Climate Adaptation: Risk Management and Resilience Optimisation for Vulnerable Road Access in Africa

Climate Risk and Vulnerability Assessment Guidelines

Council for Scientific and Industrial Research (CSIR), Paige-Green Consulting (Pty) Ltd and St Helens Consulting Ltd

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Abstract

The African Development Bank states that Africa is one of the most vulnerable regions in the world to the impacts of climate change. Most studies suggest that damage from climate change, relative to population and Gross Domestic Product, could be higher in Africa than in any other region in the world. In the past four decades, African countries experienced more than 1 400 recorded weather-related disasters (meteorological, hydrological and climatological). These disasters resulted in the death of more than 600 000 people (95 per cent due to droughts), left 7.8 million people homeless (99 per cent due to flooding and storms) and affected an estimated 460 million people.

To help address this significant threat to Africa's development, the Africa Community Access Partnership (AfCAP), a research programme funded by UKAid, 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 among participating countries. The output should assist in the future development of a resilient, climate-proof road network that reaches fully into and between rural communities.

The study reported on here addressed the issues of appropriate and economical methodologies for vulnerability and risk assessments; prioritisation of adaptation interventions; and optimisation of asset resilience in the context of rural access low-volume roads. In addition, it is meant to provide evidence of cost and economic and social benefit links to rural communities arising from more resilient rural access in order to support wider policy adoption across Africa.

In this guideline, users are led through the process of conducting a climate risk and vulnerability study at national/regional and project level by 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 the impacts of climate change.

This report is followed by the Engineering Adaptation Guidelines that focus on engineering adaptation options related to the various climatic hazards identified in this guideline.

Keywords

Capacity building; Change management, Climate adaptation; Climate change; Climate impact; Climate resilience; Climate risk; Climate variability; Risk; Rural access; Vulnerability.

Research for Community Access Partnership (ReCAP)

Safe and sustainable transport for rural communities

ReCAP is a research programme, funded by UK Aid, with the aim of promoting safe and sustainable transport for rural communities in Africa and Asia. ReCAP comprises the Africa Community Access Partnership (AfCAP) and the Asia Community Access Partnership (AsCAP). These partnerships support knowledge sharing between participating countries in order to enhance the uptake of low-cost, proven solutions for rural access that maximise the use of local resources. The ReCAP programme is managed by Cardno Emerging Markets (UK) Ltd.

www.research4cap.org

Glossary (based on the Intergovernmental Panel on Climate Change, IPCC, 2018)

Accessibility	The ease for population groups to reach or participate in service activities using a transport network.
Adaptation	In human systems, the process of adjustment to actual or expected climate and its effects, in order to moderate harm or exploit beneficial opportunities (i.e. actions that reduce hazard, exposure and vulnerability). In natural systems, the process of adjustment to actual climate and its effects; human intervention may facilitate adjustment to expected climate and its effects.
Adaptive Capacity	The ability of systems, institutions, humans and other organisms to adjust to potential damage, to take advantage of opportunities, or to respond to consequences.
Adaptation Needs	The circumstances that arise when the anticipated risks or experienced impacts of climate change require action to ensure the safety of populations and the security of assets and resources, including ecosystems and their services.
Adaptation Options	The array of strategies and measures that are available and appropriate for addressing adaptation. They include a wide range of actions that can be categorized as structural, institutional, ecological or behavioural, amongst many others
Build back better	An approach to post-disaster recovery that reduces vulnerability to future disasters and builds community resilience to address physical, social, environmental, and economic vulnerabilities and shocks
Capacity Building	The ability to enhance the strengths and attributes of, as well as the resources available to, an individual community, society or organisation in response to change.
Change Management	A collective term for all approaches to preparing and supporting individuals, teams, and organisations in making organisational or institutional changes in order to equip them to address and resolve new or recurring challenges impacting on them and their stakeholders (e.g., impacts of climate variability and change on their operations).
Climate Change	Climate change refers to a change in the state of the climate that can be identified (e.g., by using statistical tests) by changes in the mean and/or the variability of its properties and that persists for an extended period, typically decades or longer. Climate change may be due to natural internal processes or external forcings such as modulations of the solar cycles, volcanic eruptions and persistent anthropogenic changes in the composition of the atmosphere or in land use.
Climate Variability	Climate variability refers to variations in the mean state and other statistics (such as standard deviations, the occurrence of extremes, etc.) of the climate on all spatial and temporal scales beyond that of individual weather events. Variability may be due to natural internal processes within the climate system such as ocean-atmosphere coupling (internal variability), or to variations in natural or anthropogenic external forcing such as variations in solar output or changing concentrations of greenhouse gasses (external variability).

Disaster	Severe alterations in the normal functioning of a community or a society due to hazardous physical events interacting with vulnerable social conditions, leading to widespread and adverse human, material, economic or environmental effects that require immediate emergency responses to satisfy critical human needs and that may require external support for recovery.
Early Warning Systems	The set of technical, financial and institutional capacities needed to generate and disseminate timely and meaningful warning information to enable individuals, communities and organizations threatened by a hazard to prepare to act promptly and appropriately to reduce the possibility of harm or loss. Dependent upon context, Early Warning Systems may draw upon scientific and/or Indigenous knowledge.
Exposure	The presence of people; livelihoods; species or ecosystems; environmental functions, services, and resources; infrastructure; or economic, social, or cultural assets in places and settings that could be adversely affected by hazards.
Extreme Weather Event	An extreme weather event is an event that is rare at a particular place and time of year. Definitions of rare vary, but an extreme weather event would normally be as rare as or rarer than the 10th or 90th percentile of a probability density function estimated from observations. By definition, the characteristics of what is called extreme weather may vary from place to place in an absolute sense. When a pattern of extreme weather persists for some time, such as a season, it may be classed as an extreme climate event, especially if it yields an average or total that is itself extreme (e.g., drought or heavy rainfall over a season).
Flood	The overflowing of the normal confines of a stream or other body of water, or the accumulation of water over areas that are not normally submerged. Floods include river (fluvial) floods, flash floods, urban floods, pluvial floods, sewer floods, coastal floods, groundwater floods, and glacial lake outburst floods.
Hazard	The potential occurrence of a natural or human-induced physical event or trend that may cause loss of life, injury, or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, ecosystems and environmental resources.
Impacts (Consequences, Outcomes)	The consequences of realized risks on natural and human systems, where risks result from the interactions of climate-related hazards (including extreme weather and climate events), exposure, and vulnerability. Impacts generally refer to effects on lives, livelihoods, health and wellbeing, ecosystems and species, economic, social and cultural assets, services (including ecosystem services), and infrastructure. Impacts may be referred to as consequences or outcomes, and can be adverse or beneficial.
Impact Assessment	The practice of identifying and evaluating, in monetary and/or nonmonetary terms, the effects of [climate] change on natural and human systems.
Likelihood	The chance of a specific outcome occurring, where this might be estimated probabilistically.

Lock-in	The concept of ‘lock-in’ pertaining to climate change: decisions made now about the location, design and operation of assets will determine their long term resilience to the effects of climate change.
Mobility	The ability to move people and goods efficiently and effectively for socio-economic activities between an origin and destination using a transport network.
Resilience	The capacity of social, economic and environmental systems to cope with a hazardous event or trend or disturbance, responding or reorganising in ways that maintain their essential function, identity and structure, while also maintaining the capacity for adaptation, learning and transformation.
Risk	The potential for adverse consequences where something of value is at stake and where the occurrence and degree of an outcome is uncertain. In the context of the assessment of climate impacts, the term risk is often used to refer to the potential for adverse consequences of a climate-related hazard, or of adaptation or mitigation responses to such a hazard, on lives, livelihoods, health and wellbeing, ecosystems and species, economic, social and cultural assets, services (including ecosystem services), and infrastructure. Risk results from the interaction of vulnerability (of the affected system), its exposure over time (to the hazard), as well as the (climate-related) hazard and the likelihood of its occurrence.
Risk Assessment	The qualitative and/or quantitative scientific estimation of risks.
Risk Management	Plans, actions or policies to reduce the likelihood and/or consequences of risks or to respond to consequences.
Road Criticality	Road criticality refers to the importance of a rural access road to the communities it serves in terms of the community’s dependence on a road for accessing markets, goods and services.
Stressors	Events and trends, often not climate-related, that have an important effect on the exposed system and that can increase vulnerability to climate-related risk.
System Sensitivity	The degree to which a system is affected, either adversely or beneficially, by climate variability or change. The effect may be direct (e.g. in response to a change in the mean, range, or variability of temperature) or indirect (e.g. damages caused by an increase in the frequency of coastal flooding due to sea-level rise).
Vulnerability	The propensity or predisposition to be adversely affected. Vulnerability encompasses a variety of concepts and elements, including sensitivity or susceptibility to harm and lack of capacity to cope and adapt.
Vulnerability Assessment	A process that attempts to identify the root causes of a system’s vulnerability (to climate variability and change).

Abbreviations

°C	Degrees Celsius
ADB	Asian Development Bank
AfCAP	Africa Community Access Partnership
AfDB	African Development Bank
AM	Asset Management
AsCAP	Asia Community Access Partnership
BPC	Bipartisan Policy Centre
C-FIT	Climate Finance Impact Tool (JICA)
CCAP	Climate Change Action Plan (AfDB)
CMIP5	Coupled Model Inter-comparison Project Phase 5
CRED	Centre for Research on the Epidemiology of Disasters
CRMA	Climate Risk Management and Adaptation (AfDB)
CSIR	Council for Scientific and Industrial Research, South Africa
CSS	Climate Safeguard System (AfDB)
DANIDA	Danish International Development Agency
DFID	Department for International Development (UK)
DMC	Developing Member Country (ADB)
EBRD	European Bank for Reconstruction and Development
EU	European Union
GIS	Geographic Information System
IDA	International Development Association
IFC	International Finance Corporation
IPCC	Intergovernmental Panel on Climate Change
IRI	International Roughness Index
JICA	Japan International Cooperation Agency
MCA	Multi-Criteria Analysis
MDA	Ministries, Departments and Agencies/Authorities
NDP	Nordic Development Fund
NGO	Non-Government Organisation
ODA	Official Development Assistance (JICA)
RAMS	Road Asset Management System
ReCAP	Research for Community Access Partnership
SMS	Slope Management System
UK	United Kingdom (of Great Britain and Northern Ireland)

UKAid	United Kingdom Aid (Department for International Development, DFID)
UN ESA	United Nations, Department of Economic and Social Affairs
UNFCCC	United Nations Framework Convention on Climate Change
UNISDR	United Nations International Strategy for Disaster Reconstruction

Executive summary

Africa's development is highly dependent on an adequate and reliable roads system that can also withstand the impacts of climate change. To help address the significant threat of climate change to Africa's development, the Africa Community Access Partnership (AfCAP), a research programme funded by UKAid, commissioned a project in April 2016 to produce regional guidance on the adaptation of rural access roads to climate change. The project aims to provide pragmatic, cost-beneficial engineering and non-engineering adaptation procedures and guidance to road sector institutions through research and knowledge sharing within and between participating African countries.

The study covers climate threats and adaptation for both existing and new infrastructure. It addresses the issues of appropriate and economic methodologies for vulnerability and risk assessments; prioritisation of adaptation interventions; and optimisation of asset resilience in the context of low-volume rural access roads. In addition, it provides evidence of cost-, economic- and social-benefit links to rural communities arising from more resilient rural access to support wider policy adoption across Africa.

The study focuses on the following:

a) Demonstration of appropriate engineering and non-engineering adaptation procedures
b) Sustainable enhancement of the capacity of three AfCAP partner countries[1] (i.e. Ethiopia, Ghana and Mozambique) to deal with the likely impacts of climate change on rural road networks – these three countries represent nearly the full range of climatic systems in sub-Saharan Africa
c) Sustainable enhancement of the capacity of additional AfCAP partner countries
d) Uptake and embedment of research outputs across AfCAP partner countries.

The Handbook on Climate Adaptation[2] provides a methodology for carrying out a climate adaptation assessment for rural access roads to support socio-economic sustainability. It also focuses on those activities and actions that conventional engineering standards and procedures do not necessarily cover. The Handbook is supported by three separate guideline documents that cover the following:

- Change Management[3] – this guideline covers, inter alia, policy and planning, stakeholder and asset management, and recommendations for the formulation of strategies and programmes for improvement.
- Climate Risk and Vulnerability Assessment
- Engineering Adaptation[4] – this guideline introduces primary climatic attributes and the potential effects of these, followed by the provision of suggested adaptation measures for each infrastructure component, also highlighting the critical importance of effective drainage provision and of timely and appropriate maintenance of road assets.

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[1] The 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.

[2] Head, M., Verhaeghe, B., Paige-Green, P., le Roux, A., Makhanya, S. and Arnold, K. (2019). Climate Adaptation: Risk Management and Resilience Optimisation for Vulnerable Road Access in Africa: *Climate Adaptation Handbook,* GEN2014C. London: ReCAP for DFID.

[3] Head, M., Verhaeghe B. and Maritz, J., Council for Scientific and Industrial Research (CSIR) (2019). Climate Adaptation: Risk Management and Resilience Optimisation for Vulnerable Road Access in Africa, Change Management Guideline, GEN2014C. London: ReCAP for DFID.

[4] Paige-Green, P., Verhaeghe, B. and Head, M. (2019). Climate Adaptation: Risk Management and Resilience Optimisation for Vulnerable Road Access in Africa: *Engineering Adaptation Guidelines,* GEN2014C. London: ReCAP for DFID.

The guideline document in hand is a supporting document that deals with climate risk and vulnerability assessments related to climate change adaptation. It takes users through the steps involved in conducting a risk and vulnerability assessment at national-/regional-level, as well as a local-/project-level risk and vulnerability study when implementing new or maintaining/retrofitting existing infrastructure.

The Guideline targets governments (central ministries, provinces, districts); national institutes and research organisations; the private sector; local-level stakeholders directly affected by the activities of this project; and non-governmental organisations. Specific actors and role players are listed in the table below:

	Entity/Sector	Actors and role players
National /District level	Governments (central ministries, provinces, districts)	▪ National road and transport authorities, including road and transport ministries, departments and authorities ▪ National departments dealing with disaster management ▪ Central government agencies that have a vested interest in road infrastructure planning and development ▪ Other relevant government ministries/departments (e.g. agriculture, environment, science, social and economic development, health, education and relevant technology sectors) ▪ District representatives of central government agencies and departments ▪ Multi-sectorial units/committees ▪ Emergency services ▪ Funders of and investors in road infrastructure projects ▪ National planning commissions
	National institutes and research organisations	▪ Climate change committees ▪ Institutes dealing with meteorology/hydrology (e.g. water resources, hydrology and flood control)
	Private sector	▪ Businesses (small to large businesses operating in the sector) ▪ Funders of and investors in road infrastructure projects
Local /Project level	Local-level stakeholders directly affected by the activities of the project	▪ Local road engineers ▪ Private companies involved in road construction and/or maintenance ▪ Community representatives ▪ Local government representatives that can link with various district and central government departments and agencies
	Non-governmental organisations	▪ Community NGOs

1 Background and context

1.1 Aims and objectives

The overall project aim is to move forward from previous AfCAP research and to **sustainably enhance the capacity of AfCAP partner countries** to reduce current and future climate impacts on vulnerable rural infrastructure. The study covers climate risks and suggests adaptation to existing infrastructure as well as the development of 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 hazards.

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 the following concepts:

- Climate hazards
- Climate impacts
- Vulnerability to impact (risks)
- Non-engineering adaptations (referred to in this document as change management options)
- Engineering adaptations
- 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 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.

1.2 Scope

The Climate Adaptation regional programme aims to sustainably enhance the capacity of AfCAP partner countries to reduce current and future climate impacts on vulnerable rural infrastructure. This is 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 hazards.

In accordance with DFID's Research Business Case for ReCAP, the three guidelines set out to incorporate climate change and the associated challenges in the rural road planning, design, construction and maintenance phases. The impact that climate change, climate variability and extreme events (such as floods and droughts) may have on rural accessibility is likely to influence choices of design and associated planning decisions for rural roads. The subsequent guidelines build on this principle and support the generation of scientific evidence for decision-makers in rural road planning, design and construction.

The guidelines presented in this report accompany the Climate Adaptation Handbook and guide the user through the phases and steps of conducting a climate risk and vulnerability study at national/regional and project level by 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 support and inform decision making and prioritisation when adapting existing and new road infrastructure to deal with the impacts of climate change.

The guidelines are supported by demonstration case studies in the three AfCAP partner countries of Mozambique[5], Ethiopia[6] and Ghana[7]. These country reports are available for download from the ReCAP website (http://www.research4cap.org). These case studies were continuously used to verify and test the proposed methodologies on a national/regional and project level, as well as to refine the approach and make it practical and applicable in nature.

1.3 Overview of the Climate Adaptation Handbook

The Climate Adaptation Handbook as the overarching document provides relevant information on climate adaptation procedures for rural road access. It also offers instructions on an appropriate methodology to address climate risks and asset vulnerability so as to increase resilience in the foreseeable future. The Handbook was produced to provide relevant information on adaptive procedures for both new and existing rural road access. It was developed to cover a wide range of climatic, geomorphological and hydrological circumstances based on application in Mozambique, Ghana and Ethiopia, but it is equally applicable to any country in Sub-Saharan Africa. Although produced for low-volume roads, the principles also apply to high-volume roads, even though there will be differing priorities and design parameters.

Figure 1 Overview of Handbook and supporting guidelines

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[5] Le Roux, A., Maritz, J., Arnold, K., Roux, M., Head, M., Makhanya, S., Engelbrecht, F., Verhaeghe, B., & Paige-Green, P. (2019). Climate Adaptation: Risk Management and Resilience Optimisation for Vulnerable Road Access in Africa: *Management of vulnerability and adaptation to climate change: Mozambique,* GEN2014C. London: ReCAP for DFID.

[6] Arnold, K., Maritz, J., Roux, M., Le Roux, A., Makhanya, S., Engelbrecht, F., Verhaeghe, B., & Paige-Green, P. (2019). Climate Adaptation: Risk Management and Resilience Optimisation for Vulnerable Road Access in Africa: *Management of vulnerability and adaptation to climate change: Ethiopia,* GEN2014C. London: ReCAP for DFID.

[7] Maritz, J., Arnold, K., Roux, M., Head, M., Le Roux, A., Makhanya, S., Engelbrecht, F., Verhaeghe, B., & Paige-Green, P. (2019). Climate Adaptation: Risk Management and Resilience Optimisation for Vulnerable Road Access in Africa: *Management of vulnerability and adaptation to climate change: Ghana,* GEN2014C. London: ReCAP for DFID.

The Handbook only illustrates the fundamental principles, processes and steps required for climate resilience. Details regarding actual adaptation measures and vulnerability assessment methodologies are included in the accompanying guidelines documents that cover the following: (1) Change Management; (2) Climate Risk and Vulnerability Assessment; 3) Engineering Adaptation (see Figure 1). The Visual Assessment Manual further supports the Climate Risk and Vulnerability Assessment and Engineering Adaptation Guidelines.

1.3.1 The content of the Handbook

The methodology comprises **five stages**, with each stage covering several activities as set out in Table 1. However, it will be applied slightly differently depending on the scale, application and circumstances of its application. For instance, policy and strategy directives may either be in place or absent. Appropriate data management support systems may or may not be in place and the level of resource availability and skills to implement adaptation options will vary significantly. Because of this wide range of circumstances, the Handbook is split into two parts: Part A covers the ***Situational Analysis and Management Process*** and Part B covers the appropriate ***Methodology***.

The sections covered by ***this guideline report*** are highlighted in green in Table 1. This report is structured to support the methodology section of the Climate Adaptation Handbook (Part B) and specifically speaks to Stage 1 and Stage 2 of the five-stage process, as shown below.

Table 1 Contents and scope of the Adaptation Methodology

Part A	Situational review and adaptation management
Covers:	Problem identification (including evidence) Identification of probable causes Drivers of change (policy-driven) Change management Approach and delivery Effective data management
Part B	**Methodology**
Stage 1	***Climate risk screening (national/regional)***
B.1.1	Needs determination
B.1.2	Identification and mobilisation of stakeholder/partner involvement
B.1.3	Setting of policy, objectives and scope (network level)
B.1.4	Analysis of observed and projected climate effects
B.1.5	Data gathering and risk analysis
Stage 2	***Impact and vulnerability assessment (project/local level)***
B.2.1	Project-level climate risk screening
B.2.2	Climate-sensitive impact assessments
B.2.3	Data gathering and vulnerability assessment
Stage 3	***Technical and economic evaluation of options***
B.3.1	Identification of strategies and potential adaptation measures
B.3.2	Impact assessment of ‘do something’ and ‘do nothing’
B.3.3	Stakeholder consultations
B.3.4	Prioritisation and selection of adaptation measures

Stage 4	***Project design and implementation***
B.4.1	Development of an implementation plan (including 'Inadequate Budget' scenario)
B.4.2	Design parameters and optimisation
B.4.3	Construction supervision and documentation
Stage 5	***Monitoring and Evaluation***
B.5.1	Development of a monitoring and evaluation plan
B.5.2	Reporting on and sharing of implementation experiences

1.4 Outline of the Climate Risk and Vulnerability Guidelines

To assess climate hazards and their impact on the risk and vulnerability of rural accessibility (both at national/regional and local/project level), this report has been structured as shown in Figure 2.

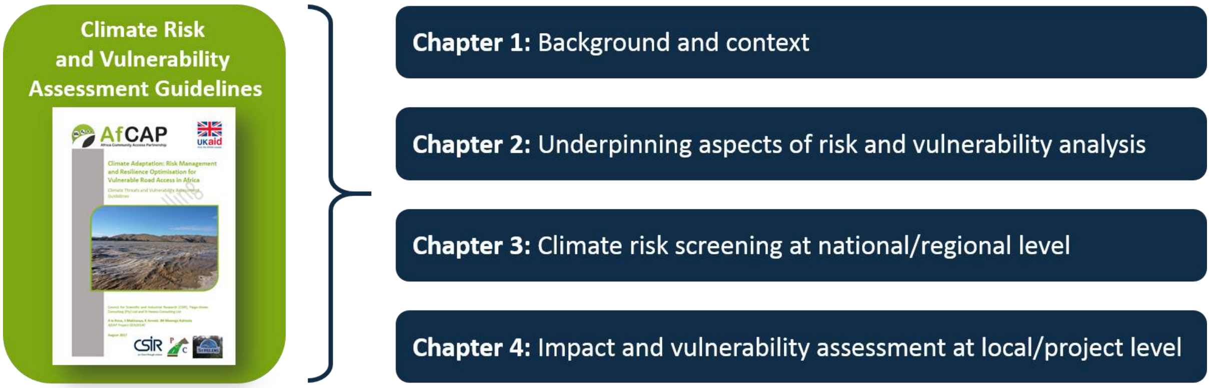


Figure 2 Overview of the Climate Risk and Vulnerability Assessment guidelines report

The following chapters have been included in this guidelines report:

- **Chapter 2** covers the underpinning aspects of risk and vulnerability analysis and sets the scene for the assessment framework/methodology proposed at a national/regional and project level.
- **Chapter 3** proposes a methodology for a rural access road risk and vulnerability assessment methodology that speaks to national decision-makers. To direct the user through the guidelines, case study material from Mozambique is used to supplement and support the methodology (also refer to steps B.1.4 and B.1.5 in the Handbook).
- **Chapter 4** proposes a methodology for rural access road risk and vulnerability assessment at a project level and is aimed at road construction and engineering professionals (also refer to steps B.2.1 to B.2.3 in the Handbook).

1.5 Purpose of the Risk and Vulnerability Assessment Guidelines

Road infrastructure is vital in supporting the delivery of essential utility services and has great strategic, political, economic and social significance. Road infrastructure is designed to 'fit' into a local environment and to withstand a defined variety of forces that could destabilise the integrity of the infrastructure. Road infrastructure design is generally based on classifications informed by up to five decades of historical climate data. With climate change, road design parameters based on historical climate data will be (and have already proven to be) inadequate, given that in this century the frequency and magnitude of extreme weather events are expected to increase. The effect of these changes could result in severe consequences for the existing rural road networks as well as for future road developments if the necessary risk management (e.g. provision of adequate maintenance), adaptation (e.g. retrofitting) and precautionary actions are not implemented in time.

The purpose of this guideline is therefore to take the user through the process of gaining a comprehensive understanding of the main climate risks that may affect the road network and how these risks translate to an increased vulnerability of both the road network and the dependent population and economies. The guidelines focus on how these approaches will differ, given the scale of analyses conducted and the different role players, methods, tools and data needed to conduct such a risk and vulnerability study. The guideline will support the user to create a series of profiles (maps and indicators) by utilising existing tools, methods and data to enhance the user's understanding of current high-risk areas in need of intervention. Utilising a series of forward-looking socio-economic principles and climate change models, this process will support the user to obtain a better understanding of plausible shifts in future risks and vulnerabilities.

The guidelines report is structured to (1) guide users through the steps involved in conducting a rapid risk and vulnerability assessment in their respective countries (national-/regional-level assessment), even though variations in the availability and quality of data are present between countries; and (2) to guide users through a local-/project-level risk and vulnerability study when implementing new or maintaining/retrofitting existing infrastructure.

The national-level assessment is geared towards providing evidence to national or international stakeholders such as funders of government road asset investment projects, while the local assessment can accommodate a higher level of detail aimed at assisting road construction and engineering professionals to prioritise suitable interventions on specific road sections – taking into account identified climate hazards.

1.6 Benchmarking and alignment of the AfCAP climate risk and vulnerability methodology

To prevent duplication, an effort was made to benchmark the AfCAP methodology against, and to find synergies with, the methodologies and screening tools used in programmes by the relevant development partners, such as the World Bank, Asian Development Bank and European Union.

Development aid initiatives in Africa are widespread, and a range of methods for assessing road vulnerability induced by climate risk already exist. The starting point for developing the proposed climate risk screening methodology was to list and comparatively assess existing methods used by international aid organisations, based on their applicability to inform road vulnerability assessments on varying scales.

Based on this investigation, the Asian Development Bank and European Union methods (which focus on outlining a study-wide approach for conducting projects in the climate adaptation domain) were valuable in aligning the flow and overall structure of the Handbook. The World Bank tool proved to be the most appropriate for national high-level overview assessments, while the proposed method outlined in this Climate Risk and Vulnerability Assessment guidelines report remains the most suitable for national-level/regional-level analysis given its ability to geospatially quantify climate-related risk and vulnerability.

Both the national-/regional-level and local-/project-level analysis methodologies were refined and harmonised to align with the compendium of proposed indicators, data and assessments of existing methodologies under each of the respective risk and vulnerability assessment sections (European Climate Adaptation Platform, n.d., ADB, 2011, World Bank, 2017). Lastly, the ROADAPT tool proposed by the CEDR (2015) (Conference of European Directors of Roads) was used to inform the local-level assessment.

World Bank tool https://climatescreeningtools.worldbank.org/ *World Bank climate screening tool*	
The Climate and Disaster Risk Screening Tool was developed to support the World Bank International Development Association (IDA) and is a way of considering and incorporating short- and long-term climate and disaster risks in national/sector planning processes and project-level investments, as well as the analysis of a country's development challenges and priorities.	
The World Bank screening tool is a non-detailed project risk screening tool which provides a project level climate change risk rating.	The World Bank tool uses an exposure-sensitivity-adaptive-capacity framework, although the tool does not explicitly or geospatially quantify risk and vulnerability and does not include identifying adaptation options in its framework.
European Union method http://climate-adapt.eea.europa.eu/ *Climate-ADAPT*	
The European Climate Adaptation Platform (Climate-ADAPT) is a partnership initiative between the European Commission and the European Environment Agency, which aims to support Europe in adapting to climate change. The platform focuses on urban adaptation for European cities, with very few guidelines for roads. The methodological framework of the Climate-ADAPT adaptation support tool consists of six steps that, used together, aid in analysing risks and vulnerability to the current and future climate, identifying and assessing adaptation options, developing and implementing a climate change adaptation strategy and monitoring its results.	
Climate-ADAPT remains a high-level six-step support tool for conducting a climate adaptation project. It needs to be customised for sector (e.g. transport or road projects).	The Climate-ADAPT tool does not geospatially quantify risk and vulnerability. Risk visualisation through maps is therefore not possible.
Asian Development Bank guidelines: *Climate Proofing Investment in the Transport Sector: Road Infrastructure (2011)*	
The Asian Development Bank guidelines for Climate Proofing Investment in the Transport Sector: Road Infrastructure Projects present a step-by-step methodology to assist project teams in incorporating climate change adaptation measures into transport sector investment projects. The guidelines are intended for use at the project level to help developing member countries in Asia and the Pacific address the increasing challenges posed by climate change, with a specific focus on adaptation in the transport sector.	
Focus solely on road infrastructure.	Quantifies risk and vulnerability in geospatial terms.
ROADAPT guidelines (CEDR, 2015) *Roads for today, adapted for tomorrow.*	
The ROADAPT (Roads for Today, Adapted for Tomorrow) guidelines and tools were proposed by the CEDR (Conference of European Directors of Roads) to be used in the Risk Management for Roads in a Changing Climate (RIMAROCC) risk assessment framework. The ROADAPT project was undertaken between 2013 and 2014 by several European nations and research institutes to better inform detailed vulnerability and socio-economic impact assessments, as well as the selection of appropriate adaptation strategies across Europe.	
ROADAPT was developed with a specific focus on adapting road construction policy to climate change.	Focuses on climate adaption of roads in the European context.

2 Underpinning aspects of risk and vulnerability analyses

2.1 The scale of impact and importance of understanding the role of climate hazards

African countries tend to be particularly susceptible to the effects of climate variability, and historical weather-related disasters have shown just how vulnerable these countries can be. A study by CRED and UNISDR (2015) suggests that 90 per cent of all global disasters are caused by weather-related events such as floods, storms, droughts and extreme temperature. Communities in Africa are projected to be some of the worst affected by climate change, in part due to their high socio-economic vulnerability, growing rural populations and high dependency on natural resources, but also due to the projected frequency and intensity increase of weather-related natural hazards (CRED & UNISDR, 2015; Engelbrecht *et al*., 2015). Between 1975 and 2015, African countries have experienced more than 1 400 recorded weather-related disasters (meteorological, hydrological and climatological). These disasters have had significant impacts on the continent's economies and in particular on rural communities and their livelihoods. The impacts of these natural hazards (floods, storms, droughts, extreme temperature, landslides and wildfires) were also felt across all economic sectors and have led to the destruction of energy, transport, water and sanitation infrastructure. Many communities and countries in Africa are dependent on natural resources to sustain their livelihoods and as a result of this dependency, exposure and vulnerability, they have been particularly at risk from losing life, livelihoods and economic activity when natural hazards do occur. The high social vulnerability and low adaptive capacity of these communities, as well as their high exposure to natural hazards, have resulted in the deaths of more than 600 000 people (95 per cent due to droughts), left 7.8 million people homeless (99 per cent due to flooding and storms) and affected an estimated 460 million people over the past four decades (CRED, 2016).

This dramatic change to the continent's climate is causing widespread damage to road infrastructure and its associated assets. Rural accessibility is being compromised in a number of countries and sub-regions for increasing proportions of the year, with both direct and indirect adverse effects on livelihoods and associated socio-economic development. The African continent is facing the potential of a USD 184 billion liability to repair and maintain roads damaged by temperature and precipitation changes directly related to projected climate change through to 2100 (Chinowsky & Arndt, 2012). Limited or non-existent funds for adaptation are challenging many African countries to identify the risks posed by climate change, to develop adaptation approaches to the projected changes, to incorporate changes into midrange and long-term development plans, and to secure funding for the proposed and necessary adaptations.

2.2 Defining the concepts

Within the context of these guidelines, risk is defined as a function of hazards, rural access road exposure and vulnerability in terms of rural community access. This was adopted from the concept framed by the IPCC WGII AR5, as illustrated in Figure 3 (Oppenheimer *et al*. 2014).

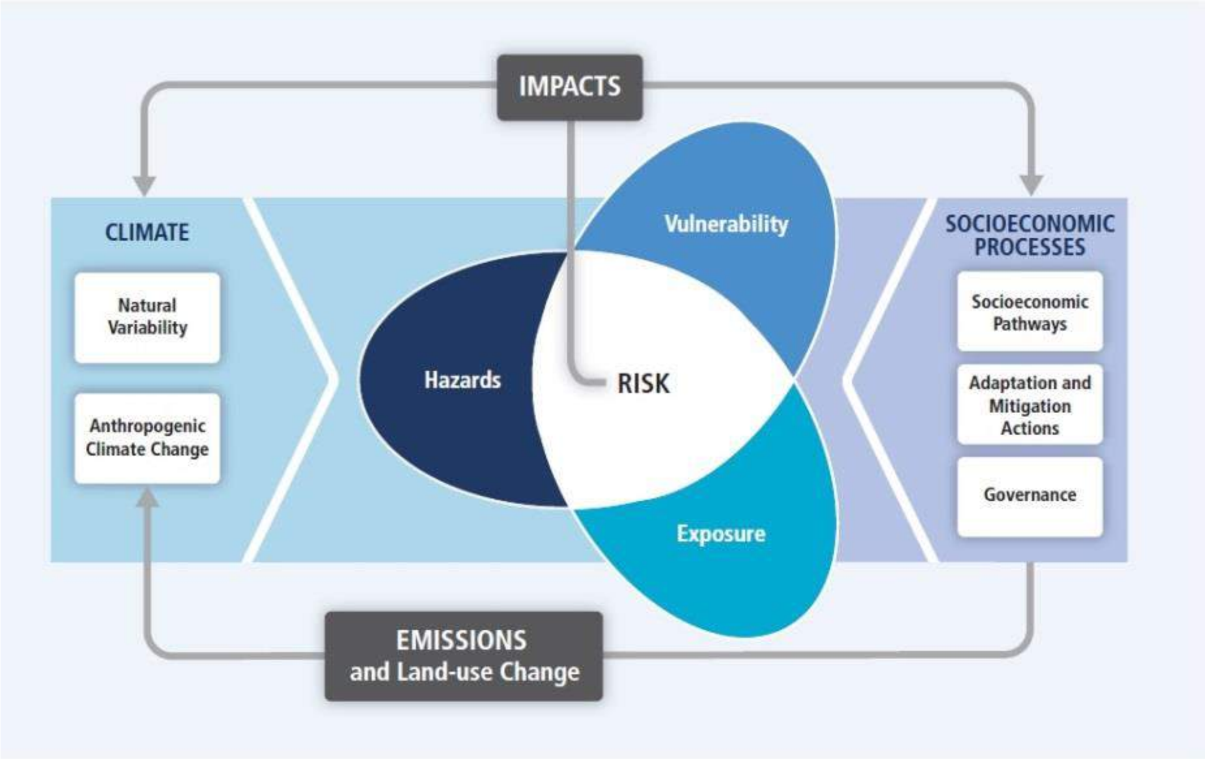


Figure 3 A conceptual framework for climate-related risk as an interaction between climate-related hazards, exposure and vulnerability of human and natural systems

Source: Oppenheimer *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 low-volume road facilities, the associated structures and road environment as well as rural communities in places that could be adversely affected directly (within the hazard footprint)
- **Vulnerability**: The propensity or predisposition to be adversely affected. Vulnerability encompasses a variety of concepts and elements, including sensitivity or susceptibility to harm and lack of capacity to cope and adapt

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

2.3 National risk and vulnerability assessments for rural access roads

A geospatial climate-related road infrastructure risk and vulnerability assessment can provide key geographic information to support decision-makers in identifying those roads that should be prioritised for repair, improvement or development in view of changing climatic conditions.

The level of detail and decision support provided by a risk and vulnerability assessment is highly dependent on the aim and scale of the study. On a national scale, a climate vulnerability, risk and adaptation strategy provides strategic level support for national road and climate policies. On a finer scale, analysis on a regional and district level plays a vital role in informing future planning and development decisions by prioritising high-risk areas, while local-scale analysis provides highly detailed project-level assessments that support project managers in adapting individual stretches of roads or road corridors.

Using visual evidence to support decision-makers' understanding of risk, vulnerability, exposure and adaptive capacity on various scales, road infrastructure risk and vulnerability assessments ultimately aim to identify critical rural road infrastructure that is most at risk from climate variability and change and livelihood dependence so as to prioritise road development adaptation options.

2.4 Actors and role players

Continuous engagement with a wide range of participants is recommended to ensure effective and efficient stakeholder communication, collaboration and involvement during the work processes. Relevant national and district stakeholders may include Ministries, Departments, Authorities (MDAs), institutions and research organisations. Additionally, specific engagement at the local level with communities, non-governmental organisations, and small to large businesses operating in the sector is also important when conducting a vulnerability assessment and selecting the most effective adaptation strategies. Table 2 identifies a variety of suggested actors and role players in various national and local sectors that may be included in consultation during the assessment process, although this list is not exhaustive.

Table 2 Actors and role players to be included in consultation during the risk and vulnerability assessment process

	Entity/Sector	Actors and role players
National /District level	Governments (central ministries, provinces, districts)	▪ National road and transport authorities, including road and transport ministries, departments and authorities ▪ National departments dealing with disaster management ▪ Central government agencies that have a vested interest in road infrastructure planning and development ▪ Other relevant government ministries/departments (e.g. agriculture, environment, science, social and economic development, health, education and relevant technology sectors) ▪ District representatives of central government agencies and departments ▪ Multi-sectorial units/committees ▪ Emergency services ▪ Funders of and investors in road infrastructure projects ▪ National planning commissions
	National institutes and research organisations	▪ Climate change committees ▪ Institutes dealing with meteorology/hydrology (e.g. water resources, hydrology and flood control)
	Private sector	▪ Businesses (small to large businesses operating in the sector) ▪ Funders of and investors in road infrastructure projects

	Entity/Sector	Actors and role players
Local /Project level	Local-level stakeholders directly affected by the activities of the project	▪ Local road engineers ▪ Private companies involved in road construction and/or maintenance ▪ Community representatives ▪ Local government representatives that can link with various district and central government departments and agencies
	Non-governmental organisations	▪ Community NGOs

2.5 Fostering organisational linkages

2.5.1 Spatial data infrastructures

Spatial data is a fast-growing resource that, when utilised efficiently, can play an integral role in the development of a country. Single agencies and sector departments on their own are unlikely to have all the required datasets needed to conduct the proposed risk and vulnerability analyses. Emphasis is thus placed on cross-sectoral collaboration through sharing the datasets and skills needed to conduct such analysis. Spatial Data Infrastructures (SDIs) provide a national platform for facilitating and coordinating the efficient and effective management, discovery and use of countries' spatial data resources (Makanga & Smit, 2010). SDIs thus promote communication and collaboration among national departmental agencies that create and maintain spatial datasets.

Given the nature of climate risk and vulnerability studies, extensive data resources from a number of cross-cutting disciplines are required. Project success is strongly linked to effective data management and participation among stakeholders, and therefore departmental collaboration in line with national SDI initiatives is recommended. The emphasis, at a national level, should be to identify and coordinate the capturing and storage of commonly shared datasets to support comparative analysis on a national level. This process involves utilising frameworks or initiatives that are either already in place or being developed (e.g. SDIs).

There are a magnitude of policies and legislation that might hinder or enhance the availability and sharing of geospatial data (such as the sources identified and proposed in this study). Several factors also influence the distribution and exchange of key information datasets (human and institutional capacity, the regulatory environment, etc.).

According to the SDI-Africa Implementation Guide (UNECA, 2003), the following should be considered:

- Policies or legislation relating to the right to access information held by public and private sectors
- Pricing policies for data captured by using public and/or private funding
- Spatial data use policies regarding ownership or custodianship
- Local and international legislation affecting the obligation of countries to undertake and maintain certain datasets (commitments to the IPCC through national communication documents, reporting on the UN's SDGs, etc.)

SDIs are commonly used for spatial data management globally, and the practice is starting to take root in Africa. In some African countries, SDIs are still operating on an informal basis and they are not officially sanctioned through government mandates. In these cases, it is hoped that activities will contribute to a formal National Spatial Data Infrastructure (NSDI) once governments are fully willing to participate in and take ownership of NSDI initiatives (Makanga & Smit, 2010).

For the sake of effective management, it is recommended that data handling within any climate risk and vulnerability project be in line with national SDI initiatives (if officially mandated), or in their absence, to informally support interdepartmental sharing and collaboration practices. Furthermore, data collection and dissemination should support the rural accessibility indicators proposed under the sustainable development goals (SDGs), as well as the countries' needs at large.

2.5.2 Road Asset Management System (RAMS)

Comprehensive, accurate information that supports efficient road management decision support systems is indispensable when it comes to effective road management (both at a strategic and operational level), and inter-agency and intra-agency systems are vitally important in this regard. Inter-agency systems such as national SDI frameworks support communication, coordination and collaboration between the work processes undertaken by different national departmental agencies, and their value and importance have been discussed in the previous section.

Equally essential are intra-agency systems, as they are needed to enable the national road authority to manage the road network within its jurisdiction effectively. To support this, a comprehensive Road Asset Management System (RAMS) should be implemented. The RAMS should include the structured processes or procedures whereby road information and data should be gathered, retained, manipulated and/or supplied, manually or by computer, to enable effective and efficient asset management. To facilitate intra-agency linkages on a nationwide scale, both vertically and laterally, road asset information should ideally be captured centrally in a national 'nationwide' information system.

The International Infrastructure Management Manual (IIMM, 2011) describes the objective of asset management as follows: *The objective of asset management is to meet a required level of service, in the most cost-effective manner, through the management of assets for present and future customers.*

A road asset management system, therefore, needs to consider the following:

- The policy of the road administration (which in turn should consider government policy)
- Customer needs through defined levels of service for road assets
- The resources (physical and human), processes and tools required (and available) to monitor and meet these levels of service
- Mechanisms to plan for the future and deal with unexpected impacts on the road infrastructure

Embedding 'climate adaptation' in road asset management systems would be an appropriate mechanism for planning for the future and for dealing with unexpected impacts on the road infrastructure. It would also enable the road authorities to deal with the impact of climate change on the road network. This will support prioritisation and decision making based on a broader spectrum of attributes in addition to present road conditions. Road condition assessors and contractors will also have to be trained to identify potential environment-related risks and vulnerabilities within and outside the immediate road environment. Asset management is thus seen as an overarching business model that provides the framework for climate change initiatives to be readily implemented by a road authority, especially given the short design-life or maintenance cycles of some road assets. This enables adaptive management of evolving risks (see: Hallegatte, 2009).

The climate risk and vulnerability assessment process must link with road asset management and the RAMS. The RAMS should be the source of road network information that is required for the risk and vulnerability assessment process. The outputs from this process must feed back into the RAMS to be used as additional indices in conjunction with the regular indices (e.g. the Visual Condition Index) when calculations are made to prioritise roads in terms of maintenance or adaptation needs. For this reason, in order to embed climate vulnerability in road adaptation planning, these guidelines (see Chapters 3 and 4) suggest a compendium of indicators to be included in the RAMS.

In addition to the proposed indicators, the following critical aspects need to be considered when capturing and maintaining spatial data for input into a RAMS:

- Geographical referencing standards
- Data content (alignment with the country's development needs and goals)
- Scale and/or resolution of data capture
- Metadata and data indexing

3 National-/regional-level climate risk screening

In subsequent sections of this chapter (also refer to Stage B.1.4 and B.1.5 in the Handbook), the core focus will be on the approach to and guidelines for conducting a national-/regional- level climate risk screening. The assessment is aimed at identifying those districts where roads should be prioritised for repair, improvement or development by providing a high-level indication of where the "riskiest" districts in each country are in terms of current and future road accessibility and vulnerability.

3.1 Communication and stakeholder involvement

Stakeholder communication and involvement should be ongoing throughout the assessment process and it should be facilitated through collaborative work sessions and workshops. These knowledge-sharing sessions should be held throughout the course of the project to enable and support both cross-disciplinary and inter-departmental coordination and collaboration – among the public sector, private sector and local stakeholders – to assess impacts, vulnerabilities and adaptation options.

Stakeholder communication and involvement should include a wide range of participants from central government agencies, all the way through to local communities. The national-/regional-level assessment may, however, be most relevant to national or international stakeholders, for instance national departments, agencies or authorities, funders of government road asset investment projects, as well as other public and private sector stakeholders that have a vested interest in road infrastructure planning and development. Engaging stakeholders who are directly affected by the activities of the project allows for more effective decision making, as well as making the development of the work process more transparent. The results of the national-/regional-level assessment should be used to guide discussions around road adaptation prioritisation with relevant stakeholders.

Continuous engagement with a wide range of participants is recommended to ensure effective and efficient stakeholder communication, collaboration and involvement during the work process. The following stakeholders should be included in ongoing open dialogue:

- Central government agencies with a vested interest in road infrastructure planning and development
- National planning commissions
- National transport sector stakeholders, including road and transport ministries, departments and agencies/authorities (MDAs)
- Funders of and investors in road infrastructure projects
- Other relevant government ministries/departments (e.g. agriculture, environment, science and the relevant technology sectors)
- National research institutes
- Technical and academic universities
- Climate change committees
- Science academies
- Institutes dealing with meteorology/hydrology (e.g. water resources, hydrology and flood control)
- Emergency services and/or the national departments dealing with disaster management
- Relevant businesses and NGOs
- Local-level stakeholders directly affected by the activities of the project (this should reach down all the way to affected community groups)

3.2 Piloting a national-/regional-level risk and vulnerability assessment

3.2.1 Overview of the AfCAP risk and vulnerability assessment methodology

The aim of the national-/regional-level risk and vulnerability assessment is to facilitate the identification of districts where roads are most vulnerable to a changing climate in terms of the impact on rural accessibility. This is done using the existing road network and road design principles to determine where roads could potentially be most affected by changes in climate and socio-economic patterns. The output of the national-level assessment identifies potential high-risk areas (i.e. districts 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. The methods presented in this section have been refined, applied and tested in three full-scale analyses of three AfCAP African countries, namely Mozambique, Ghana and Ethiopia. These guidelines refer as an example to the application of the guidelines in Mozambique, but the reader can also consult the study application conducted in Ethiopia (Arnold *et al.*, 2018) and Mozambique (le Roux *et al*., 2019b) as additional support and useful reference.

The methodology for undertaking a climate risk and vulnerability assessment at a national/regional level (Stage B.1.4 and B.1.5 in the Climate Adaptation Handbook) consists of five phases, each with a number of action steps (Figure 4):

Phase 1: Identification of hazards affecting the vulnerability of roads

- Step 1.1: Identify current climate hazards that are affecting the vulnerability of roads (based on historical data)
- Step 1.2: Understand future climate hazards that will likely affect the vulnerability of roads (based on projected climate data)

Phase 2: Data collection and preparation

- Step 2.1: Data collection
  - What data to collect
  - Where to collect data
- Step 2.2: Data preparation

Phase 3: Data analysis

- Step 3.1: Determine road exposure to identified hazards
- Step 3.2: Determine road criticality (based on rural accessibility)
- Step 3.3: Determine most vulnerable districts
  - Most vulnerable districts under current climate and socio-economic conditions
  - Future vulnerable districts under a changing climate and growing population

Phase 4: Embedment in the Road Asset Management System

- Step 4.1: Consider climate hazards indicators to be included in the RAMS
- Step 4.2: Export data to the RAMS
- Step 4.3: Analyse data in the RAMS

Phase 5: Climate adaptation (in terms of prioritisation)

- Refer to Change Management and Engineering Adaptation Guidelines

The analysis can be done for both the current situation and the projected future scenarios (where future refers to the mid-term (2050) or long-term (2100) future which are relevant to longer-lived assets such as bridges and major flood/coastal defence). In the above framework, the current and future scenarios are presented concurrently, but they can also be done as two successive analyses.

As a solution to the challenge of spatial data availability and quality as well as the multi-faceted nature of the risk and vulnerability analysis, a semi-quantitative indicator-based risk assessment method is outlined. An indicator-based risk method entails reducing a complex problem into key factors (or dimensions), identifying variables that characterise those factors and using mathematical and decision-theoretic techniques to quantify and aggregate the variables into measurements that are intuitive and accessible to practitioners and decision-makers (Satta, 2014). This approach is therefore motivated by the ease with which it can be applied to the different rural access road and climate typologies of different countries or regions. Another benefit is that it 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.

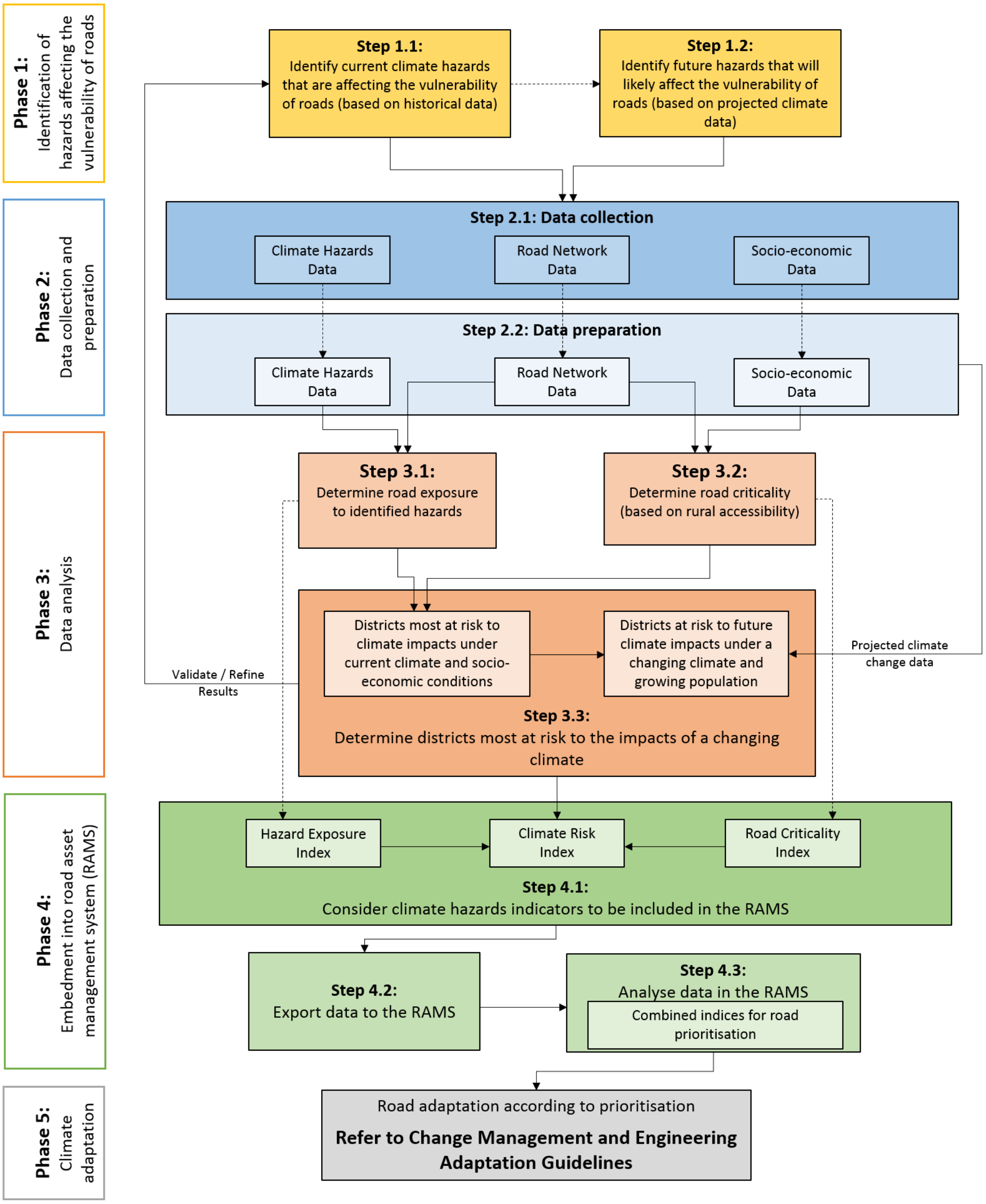


Figure 4 Framework for conducting a detailed national-level rural access risk and vulnerability assessment

3.2.2 National-/regional-level risk and vulnerability analysis steps and guidelines

Phase 1: Identification of hazards affecting the vulnerability of roads

Aim:

The aim of this phase is twofold: firstly, to analyse historical climate data to identify the current climate hazards that most affect the vulnerability of roads: and, secondly, to use the identified current climate hazards to inform the investigation into the future hazards that will likely affect the vulnerability of roads under projected climate change conditions.

The natural environment (mainly climate) constitutes the principal threat to the lifespan of low-volume rural road networks. Exposure to extreme meteorological events increases the overall vulnerability of rural access roads – either individually, or in combination. To make informed decisions for both current and future road planning policies and adaptation options, it is important to investigate how the hazards affecting the vulnerability of roads may change, since future road projects may be faced with very different climate mitigation requirements than is currently the case.

General recommendations for this phase:

- It has become increasingly important for road infrastructure decision-makers to make well-informed long-term planning judgements, based not only on current climatic conditions but also on the most likely future climate change scenarios, given that the infrastructure of today's roads will be exposed to these changing environments during their lifespan.
- Historical climate records have in the past provided a good enough indication of future climate hazards. With climate change, however, road design parameters based solely on historical climate data will be insufficient for the lifespan of the road, given that in this century the frequency of extreme weather events is expected to increase. If they are not taken into account, these changes could have severe consequences for existing rural road networks as well as for future road developments. It is also essential that the necessary mitigation, adaptation and precautionary actions are timeously implemented.
- To formulate a current and future national climate hazard picture, country-specific information should be gathered from a range of sources including but not limited to the following:
    - Country-level assessment reports, data and statistics from relevant country-specific meteorological departments and/or disaster management offices.
    - Cross-disciplinary and inter-departmental knowledge-sharing workshops between active role players in the road planning domain.
    - Reports by international climate and climate change authorities such as the Intergovernmental Panel on Climate Change (IPCC) and The Nature Conservancy (TNC).

Step 1.1: Identify current climate hazards that are affecting the vulnerability of roads (based on historical data)

Aim:

The aim of this step is to determine which climatic hazards most affect the vulnerability of rural access roads (based on historical trends), and which of these factors should be included in the current scenario risk and vulnerability assessment.

Recommendations:

- This step is concerned with identifying the main current climatic hazards to road vulnerability; investigation on a national or regional scale is therefore sufficient.
- African countries tend to be particularly vulnerable to the effects of climate variability. Analysing historical climate and disaster data such as EM-DAT data is therefore an important starting point in understanding the current hazards that affect vulnerability.

EM-DAT is a global open database on natural and technological disasters, dating as far back as the year 1900. It is maintained by the Centre for Research on the Epidemiology of Disasters (CRED). The following aspects are important to consider when using EM-DAT:
Purpose of data collection: International and national humanitarian action, disaster preparedness, vulnerability assessment and prioritisation
Spatial resolution: Country-level (sub-nationally affected districts are indicated)
Recording of dates: Date when a humanitarian emergency was declared, not the period (start and end dates) of disasters
Recording criteria: 10 or more people dead/ more than 100 people affected/ declaration of a state of emergency or request for international assistance
Limitations: Classification of the disaster type can be challenging when there are associated/ secondary disasters in a single event. Events with wider extents spatially (or in time) may be recorded as multiple events. For recorded disasters, actual data like the number of deaths, those affected, and extent of damage may be missing.

- Documents, data and statistics from country-level assessments that indicate the type, frequency and intensity of historical climate-induced disasters should be sourced to formulate a national climate hazard picture. In order of priority, the following are suggested as resources for obtaining this information:
    - Firstly, it is assumed that national data on historical climate hazards are maintained and archived by the relevant national meteorological department and/or disaster management office. As a starting point, data should be sourced from these national authorities.
    - Secondly, technical reports by the Intergovernmental Panel on Climate Change (IPCC) and The Nature Conservancy (TNC) can be consulted for background information.
    - Lastly, knowledge-sharing workshops should be conducted with active role players such as the national meteorological department and disaster management office.
- The investigation into historical climate data archives, country-level assessment reports and knowledge-sharing workshops inform the process of identifying the climate hazards with the greatest effect on the vulnerability of roads. From this inquiry, the driving forces of vulnerability should be identified and flagged for further analysis in this assessment process.
- Flood hazards have the greatest impact on rural road infrastructure; a 100-year flood can be assumed to damage up to 30 % and 10 % of unpaved and paved roads respectively (Chinowsky & Arndt, 2012).

- Two main types of climate-related impacts should be considered in the case of rural roads. These are water-related hazards (inundation by flooding and landslides) as a result of rainfall extremes, and road and structure degradation as a result of incremental changes in average rainfall and temperature.
- Other common climatic-induced hazards that may be considered include storms, droughts, wind and wildfires if determined to be of high frequency, magnitude and extent.
- Finally, the results of the climate hazard investigation should be mapped.

The following climate parameters and data can be assessed to determine the greatest climate hazard(s):

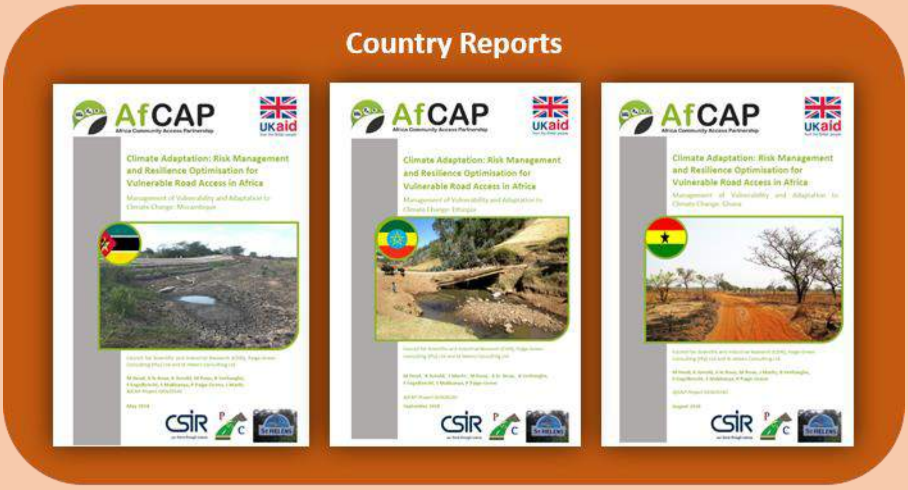
- Sea level rise, coastal erosion and wave action (for coastal roads)
- Precipitation intensity and slope angles (for mountainous regions)
- Peak rainfall events (for designing drainage and protecting infrastructure)
- Profiles of past extreme weather events
- Changes to the onset of rainy seasons (for road maintenance and construction scheduling)
- Wind speed (for erosion and wildfire hazard assessments)

Supporting Resources

The **Mozambique Country Report** (see Le Roux *et al*., 2019a), and **peer-reviewed paper** (see Le Roux *et al*., 2019b), detail the application of processes, principles and recommendations set out in the Climate Adaptation Handbook as well as the relevant supporting Guidelines. These resources illustrate the implementation of this framework methodology in supporting the management of vulnerability and adaptation to climate change in Mozambique.

Two additional country reports, the **Ethiopia Country Report** (see Arnold *et al*., 2019) and the **Ghana Country Report** (see Maritz *et al*., 2019) further outline the application of this framework in African cases that are regionally diverse.

These country reports are available for download from the ReCAP website (http://www.research4cap.org).

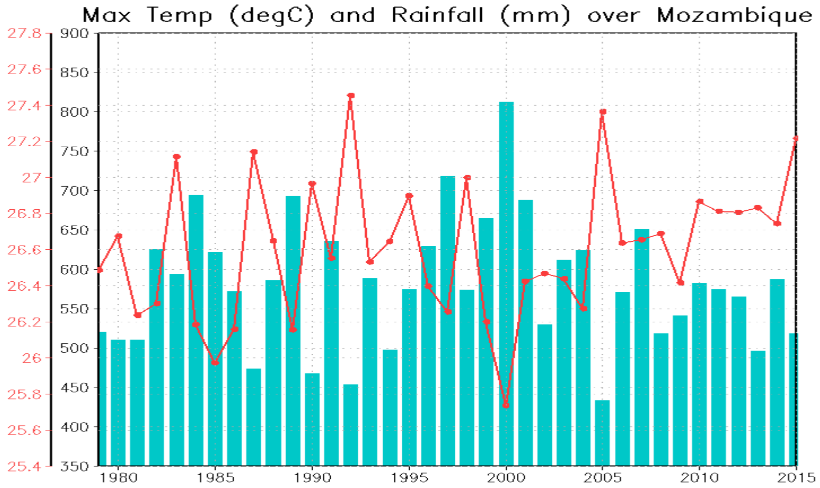


Example action (Mozambique's current situation):

From the Mozambican case study (see Le Roux *et al.*, 2019a), the following data were sourced to access and identify the main climatic hazards and their trends:

- Weather variability and trends
- Hazard frequency and impact (1978–2018)

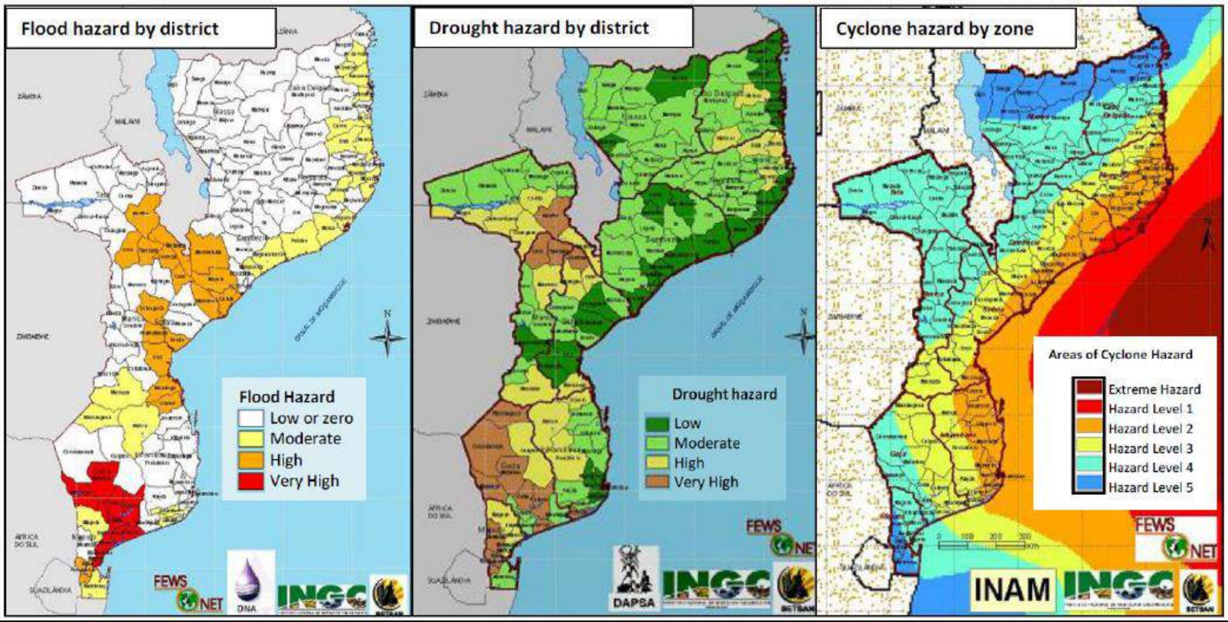
Mozambique: weather variability and trends



Data set	Period	Temperature trend (°C/century)	Rainfall trend (mm/century)
CRUTEMP4v	1961-2010	2.1	Not available
ERA interim	1979-2015	2.4	Not significant

Data source: ERA interim and CRUTEMP4v

Mozambique: hydro meteorological hazard-related risks



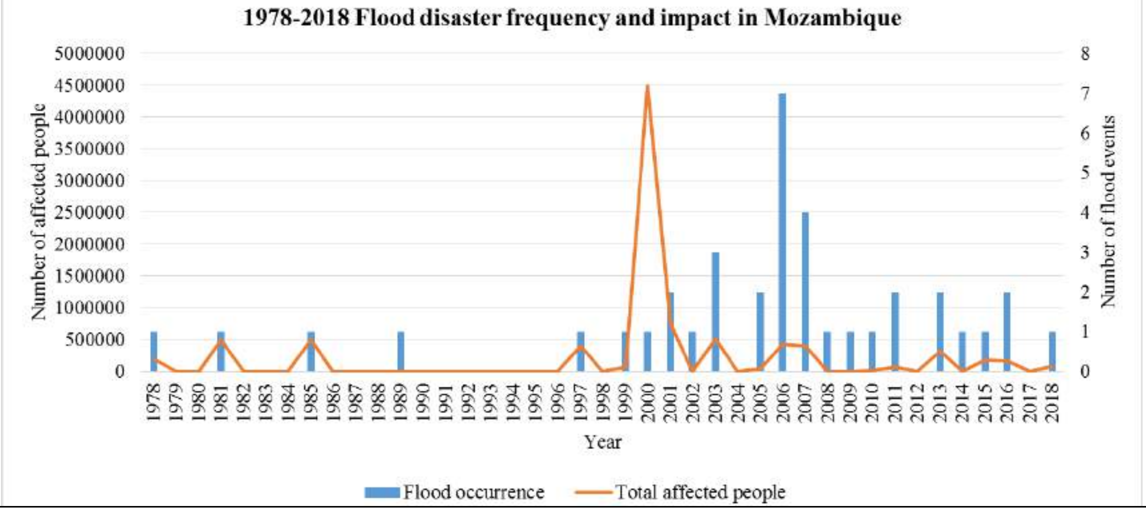
Data source: UNDP & INGC (2010)

Hazard frequency and impact in Mozambique (1978–2018)

Hazard	Number of events (1978–2018)	Total deaths	Total affected
Drought	13	100,068	20,057,500
Coastal flood	2	83	649,329
Flash flood	1	5	300
Riverine flood	20	1,287	6,806,839
Other flood	8	136	1,262,285
Landslide	2	104	2,800
Convective storm	2	24	1,700
Other storms	4	17	5,117
Tropical cyclone	16	552	4,434,260
Wildfire	1	49	3,023
Total	**69**	**102,325**	**33,223,153**

Data source: Calculated using EM-DAT data (CRED, 2019)

Flood disaster frequency and impact in Mozambique between 1978 and 2018



Data source: Calculated using EM-DAT data (CRED, 2019)

From the Mozambique case study, floods and storms are the most frequent climate hazard that the country has to deal with, and the hazards most damaging to road infrastructure and rural accessibility. The country experiences the highest frequency of land-falling tropical cyclones and pressure-lows of any African country, which are associated with widespread flooding.

Flood disasters have also been occurring at increasing frequency and greater intensity across the country over the last four decades. Based on this analysis, flooding disasters were identified as the most frequent climate hazard in Mozambique, and the hazard most damaging to road infrastructure and rural accessibility.

Step 1.2: Identify future hazards that will likely affect the vulnerability of roads (based on projected climate data)

Aim:

To make informed decisions for future planning purposes, it is important to understand which climate hazards will threaten the future vulnerability of rural access roads under changing climate conditions, epically when considering longer-lived assets such as bridges and major flood/coastal defence. It is therefore also important to understand how climate hazards are projected to change in the mid-term (2050) to long-term (2100) future. This is done by conducting forward-looking scenario studies using climate-modelled/projected data.

Recommendations:

- The results of Step 1.1 (which identified current hazards affecting the vulnerability of roads) should inform the starting point for conducting forward-looking investigations into how climate hazards are likely to change in the future.
- Mid-term (2021–2050) future projections may be less uncertain than long-term (2050–2100) future projections.
- Future climate assessments should ideally be the result of high-resolution physical climate change modelling outputs.
- To determine the likely main effects of climate change, the following examples of future climate projections and change analysis are suggested:
    - Projected changes in climate with regard to temperature and rainfall, including changes in extreme events
    - Projected changes in sea level rise and wind velocity in coastal environments
- Finally, the results of the future climate hazard investigation should be mapped.

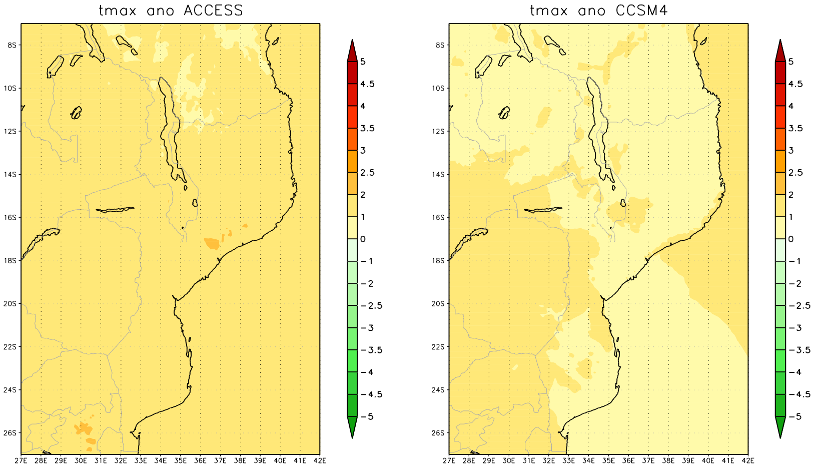
Example action (Mozambique's mid-future situation (2050)):

From the Mozambican case study (see Le Roux *et al.*, 2019a), the following projections indicate possible future climate scenarios for the country:

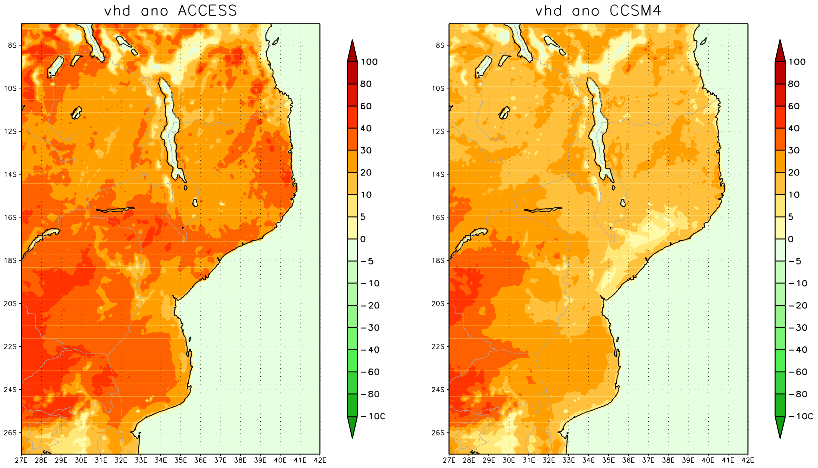
- Projected changes in annual average maximum temperatures
- Projected changes in average rainfall and extreme rainfall events

Projected changes in annual average maximum temperatures (top) and changes in very hot days (bottom) (2021–2050 relative to 1961–1990 under low mitigation (RCP 8.5) scenario)

Temperature:



Very hot days:

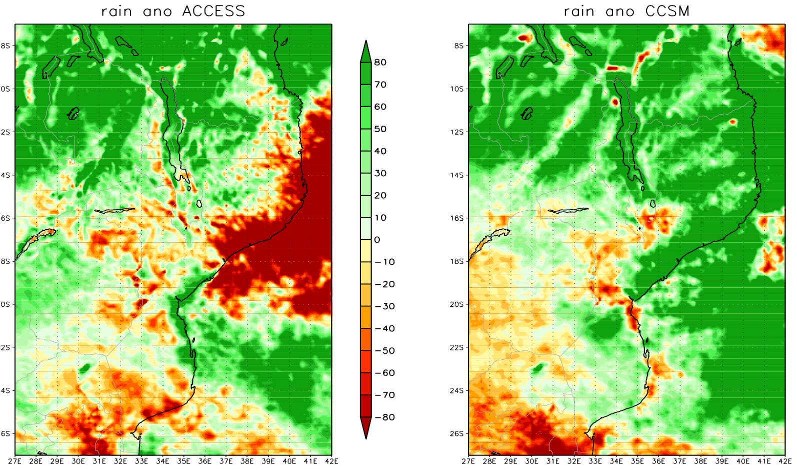


Source: Downscaled climatology from ACCESS1-0 (left) and CNRM-CM5 (right) climate models. Produced by the CSIR, South Africa.

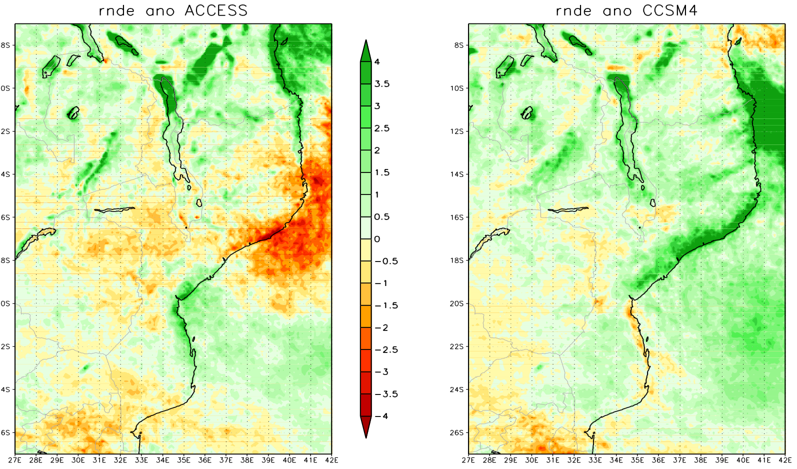
From the Mozambican case study (see Le Roux *et al.*, 2019a), conformal-cubic atmospheric model (CCAM) mid-future projected changes in annual average maximum temperatures (°C, top) and the annual number of very hot days (number of events per grid point per year, bottom) over Mozambique, for the ACCESS1-0 (left) and CNRM-CM5 (right) downscalings. The projections are for the period 2021 to2050 relative to 1961 to1990 under a low mitigation scenario (RCP 8.5).

Projected changes in average rainfall (top)and changes in extreme rainfall events (bottom) (2021–2050 relative to 1961–1990 under a low mitigation (RCP 8.5) scenario)

Annual Ave Rainfall:



Extreme rainfall:



Source: Downscaled climatology from ACCESS1-0 (left) and CNRM-CM5 (right) climate models. Produced by the CSIR, South Africa.

From the Mozambican case study (see Le Roux *et al*., 2019a), conformal-cubic atmospheric model (CCAM) mid-future projected changes in annual average rainfall totals (mm, top) and the annual number of extreme rainfall days (number of events per grid point per year, bottom) over Mozambique, for the ACCESS1-0 (left) and CNRM-CM5 (right) downscalings. The projections are for the period 2021 to 2050 relative to 1961 to 1990 under a low mitigation scenario (RCP 8.5).

Phase 2: Data collection and preparation

Aim:

The aim of this phase is to identify, source and collect the data necessary to perform a national-/regional-level climate risk screening. Once data has been sourced, general data preparation should be done to ensure that the data is ready for analysis by ensuring it is accurate (in terms of fitness for use) and in the correct spatial format.

General recommendations for this phase:

- The outlined national-level screening methodology is a generic semi-quantitative rapid assessment method that can be applied to any country, even though there may be variations in the availability and quality of data for different countries.
- Climate risk and vulnerability can be assessed even if the data does not align exactly with the recommendations in this guideline.
- Data requirements will be study-specific and should be adapted in that light.
- Once data has been collected, general data preparation should be done to ensure that the data is ready for analysis in a GIS. Generic data preparation steps involve the following:
  - Installing the GIS software required for analysis
  - Ensuring data is in the correct format for spatial analysis, and correcting data that is not
  - Validating the accuracy of data and editing/correcting inaccuracies
  - Creating a data repository (e.g. spatial database) to store data ready for analysis

Step 2.1: Data collection

Aim:

The aim of this step is to identify, source and collect the data necessary to do a national-/regional-level climate risk screening to identify districts where rural access is most at risk to climate threats. An endless range of vulnerability factors can be mapped and analysed in a GIS, but purpose-driven data needed for a district-scale analysis should be sourced in this step.

Recommendations:

- **What data to collect**
  A range of data should be sourced as input that supports the risk and vulnerability analysis**.** As a starting point, road network data, climate hazard data and socio-economic data need to be sourced from national authorities and/or open-source repositories. Socio-economic data are an important component of the rural access risk and vulnerability assessment since rural access is a key driver towards socio-economic development and plays a vital role in ensuring rural communities are connected to market and service centres. Datasets that support analysis, such as district boundary data and town hierarchy data, also need to be sourced.

- **Where to collect data**
  Data to support the national-/regional-level risk and vulnerability analysis should ideally be sourced from relevant country-specific national authorities who have been appointed as data custodians. Data custodians hold the copyright to the data they produce and are responsible for the accuracy and maintenance of their datasets.

  As a starting point, country-specific custodian data might be sourced from the following places:
  - National departmental authorities (e.g. national disaster management office, meteorological office or roads department office within a country)

- Road asset management systems (usually coordinated and maintained by the national roads authority)
- Countrywide SDIs (if implemented)
- Country-specific assessment reports
- Previous studies
- Commercial data vendors

In an ideal situation, an actively maintained centrally coordinated road asset management system should be in place to support the activities and data requirements of this risk and vulnerability assessment framework. A road asset management system should provide centralised access to the national road network database that contains inventory, condition and utilisation data – this database is updated and maintained regularly through national road visual assessment, monitoring and evaluation programmes. Although this is the ideal situation for obtaining road infrastructure data, conventional road asset management systems are currently not implemented consistently throughout Africa. Data on the road and asset conditions is not collected comprehensively or routinely in most Sub-Saharan African countries, and where data is collected, it may be found that it is only sporadically captured (based on limited visual assessment and some measurements) and archived in simple spreadsheet-based systems. There is, therefore, a need to standardise road asset management systems in line with international road asset data capture and information management practices.

If country-specific custodian data (maintained by a relevant national authority) is not available or cannot be sourced, open-source, freely available data can be used as a substitute so as to facilitate the repeatability of this method in different countries (see Table 3 for suggested data to perform national-/regional-level risk and vulnerability analyses, as well as possible open data sources). It should also be noted that international agencies are increasingly placing (global) data sets in the public domain. For a compendium of such assets see Wilby (2018).

Data not found as GIS datasets must be created manually. Input data that are known but not mapped (e.g. expert or and indigenous knowledge (such as flood extents/depths)) can be digitised directly into a GIS. In some extreme cases, it might be necessary to undertake new data collection or to create data that does not exist yet. Input data that are unknown would have to be created by means of desktop analysis studies or fieldwork. A fieldwork approach is however not recommended as a starting point, given the magnitude of the task on a country-wide scale.

It is therefore recommended to source and use national-scale GIS datasets in the following order of priority, depending on availability:

1st choice Data from country-specific national authorities who have been appointed as data custodians and/or the road asset management system

2nd choice Open source data repositories

3rd choice New data collection/creation methods

- Data created by digitising directly into a GIS based on expert knowledge
- Data captured through fieldwork and climate-sensitive visual assessment
- Data created by means of desktop analysis studies
- Data created by expanding the attribute columns of existing data

Step 2.2: Data preparation

Aim:

Once data has been sourced, data preparation should be done to transform the data from its original state into variables for rural road-specific hazard assessment.

Recommendations:

Key components of data preparation under each of the dataset categories (road network data, climate hazard data, and socio-economic data) are discussed.

- **Road network classification**
  This involves the preparation of a classified road attribute geospatial layer. Road attributes should preferably be in accordance with the proposed Asset Management System guidelines and they should include (but are not limited to) the following data:
  - The current condition of roads in the road network, rated according to the five classes of very poor, poor, fair, good and very good
  - A time-series element built into the database to monitor and track the impacts of climate hazards and/or new investments temporally
  - The length of road network per rural district
  - Road facility types as proportions of the total road network

  Road facility types refer to engineered versus non-engineered earth roads, and to paved versus gravel roads. In the absence of these specific classes, an indication of the proportion of paved versus unpaved road would suffice. Because of the nature of road facility data, it is proposed that this data be collected from the national road authorities as the custodians of these layers. These authorities are also responsible for updating and maintaining the datasets.

- **Climate hazards and incremental degradation impacts**

  Climate modelling outputs need to be assessed and transformed into workable datasets to support the risk and vulnerability analysis at the national-/regional-level.

- **Socio-economic vulnerability**
  Socio-economic datasets are essential for evaluating asset criticality in terms of rural area accessibility and remoteness. Socio-economic data should be sourced to prioritise districts according to their road criticality, and data to support this assessment includes the following:
  - Population distribution and density
  - Population living without road access
  - Hierarchy of towns
  - Essential service facility data (health and education facilities)
  - Market locations or GDP production centres

- **Supporting data**

  Finally, administration datasets that support the risk and vulnerability assessment should be sourced. These include district-level boundary data. Depending on the nature and scale of the sourced datasets, aggregation to district level may be necessary.

Table 3 outlines the possible data required to perform a national-/regional-level risk and vulnerability analysis, together with the suggested national authorities responsible for maintaining specific custodian data, or, in the absence of such data, open-source data repositories where data can be sourced freely.

Table 3 Suggested data to perform national-/regional-level risk and vulnerability analyses, as well as possible open data sources

Assessment components	Data type	Country-specific data sources	Open-source data
Road network classification	Road network data (Street centre lines with attributes)	National road agency or authority National road asset management system	DIVA-GIS
Climate hazards assessment	Historical climate data (National scale)	National disaster management department National meteorological department	EM-DAT
	Climate-related hazards data (e.g. flood incidents data on district scale)	National disaster management department National meteorological department National environmental department	Dartmouth Flood Observatory
	Projected climate data (Fine spatial resolution, e.g. 8 km resolution in the horizontal in Mozambican case study)	National meteorological department	
Socio-economic analysis	Current population data	National statistical office	WorldPop
	Hierarchy of settlements data	Surveyor-general's office	DIVA-GIS
	Projected population data	National statistical office	UN ESA
Supporting geographic data processing	Administrative boundaries (e.g. district boundaries)	Surveyor-general's office	DIVA-GIS
	Satellite images	National space agency	Landsat (USGS EROS) ESRI images

Phase 3: Data analysis

Aim:

The aim of this phase is to analyse the spatial data collected during the data collection and preparation step using GIS (geographic information system) software and principles. The advantage of using a GIS is that all data is in a spatial format, which allows the analysis results to be easily extracted to maps for further evaluation and interpretation.

The data analysis phase consists of three steps. The analysis outputs from Step 3.1 (road exposure) and Step 3.2 (road criticality) become the data inputs for Step 3.3 (determining which districts are most at risk in terms of current and future road vulnerability and accessibility).

General recommendations for this phase:

- It is recommended that data analysis be done spatially using GIS software. A variety of GIS software is available, including proprietary and open source (freely available and downloadable off the internet) options such as ESRI ArcGIS and QGIS respectively.
- The person appointed to do the spatial data analysis would benefit from prior experience in spatial data analysis and knowledge of fundamental GIS principles.
- Data should be pre-processed in line with the recommendations in Phase 2 before the analysis phase begins.

Step 3.1: Determine road exposure to identified hazards

(Based on road network condition (resilience) and exposure to climate hazards)

Aim:

The aim of this first data analysis step is to conduct a road exposure and vulnerability assessment by determining which districts are most vulnerable to climate risk, and by establishing the current condition of the roads in hazard-prone districts. This information can then be used to derive a hazard exposure index. When mapped with road condition data, hazard exposure index can be used to indicate where roads in poor condition are located in districts exposed to severe climate hazards (areas which are more at vulnerable to climate impacts).

The amount of data available for the country regarding the type and quality of roads will determine how far a classification of at-risk roads can be made. For example, if data is only available regarding whether a road is paved or not, then a summary of the total amount of "risky" unpaved roads will be made, but if more data is available, then a more detailed classification can be done.

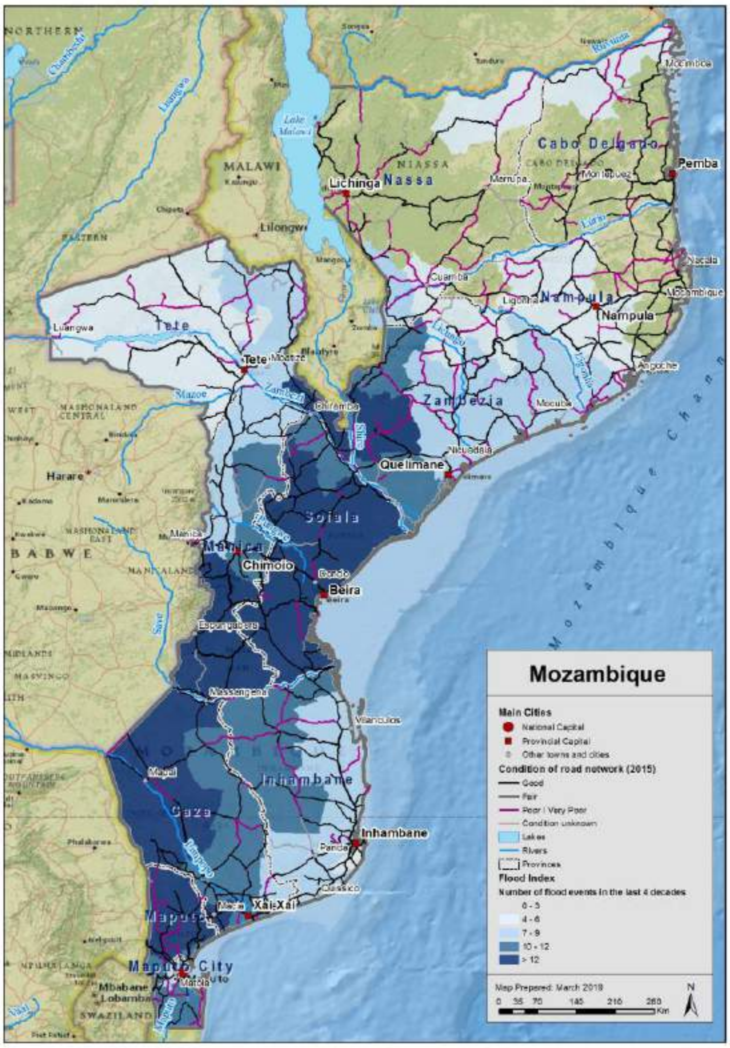
Recommendations:

- Determine districts most affected by historical climate hazards.
  - For example, aggregate the number of climate hazard events, such as severe flooding events in the past four decades, per district.
- Overlay road network condition data with the districts most affected by climate hazards.
- Map the results of the road exposure to identified hazards (based on road network conditions (resilience) and exposure to climate hazards).

Example action (Mozambique's current situation):

From the Mozambican case study (see Le Roux *et al*., 2019a), the following map was produced indicating the districts most at risk to flood exposure (flood-prone areas and road network condition).

Mozambique: road exposure to flooding risk



Flood events in the past 4 decades		Flood Exposure Index
□	0 – 3	5
░	4 – 6	4
▒	7 – 9	3
▓	10 – 12	2
█	> 12	1

Data source: CSIR custom analysis using data from the National Roads Administration (ANE) Mozambique, Dartmouth Flood Observatory (2019) and DIVA-GIS (2019)

From the Mozambican case study (see Le Roux *et al*., 2019a), given the countries location in relation to the Intertropical convergence zone (ITCZ) (a region often hit by tropical cyclones) and the lower Limpopo flood plains north of Maputo, large-scale floods occur mostly in the central and southern parts of the country. Condition surveys from 2015 suggest that a large number of the roads in these flood-prone areas are considered to be in poor or very poor condition. Roads where the condition is poor and exposure to floods is high should be prioritised.

Step 3.2: Determine road criticality – Rural accessibility and remoteness

Aim:

The aim of this step is to determine road criticality in terms of rural accessibility. At the district level, a criticality assessment is used to evaluate the importance of rural access roads to the communities (districts) they serve (e.g. the number of people a road serves and/or the number of people without access).

The basis of prioritising roads for maintenance, upgrading or expansion is often subjective and depends on each region's policy imperatives. Therefore, to allow the criticality assessment to have a region-specific focus, it is considered as an annexe to the road asset vulnerability index.

Recommendations/Considerations:

- Road exposure and vulnerability are considered a dimension in the criticality assessment, while other dimensions include road capacity and function.
- A rural access index and/or a remoteness indicator should be calculated.
    - The Rural Access Index (RAI), which was developed by the World Bank, measures the rural population living within 2 km (20 to 25 minutes of walking time) from an all-weather road passible by a four-wheeled vehicle as a proportion of the total rural population (Roberts *et al*., 2004; Vincent & Civil Design Solutions, 2018).

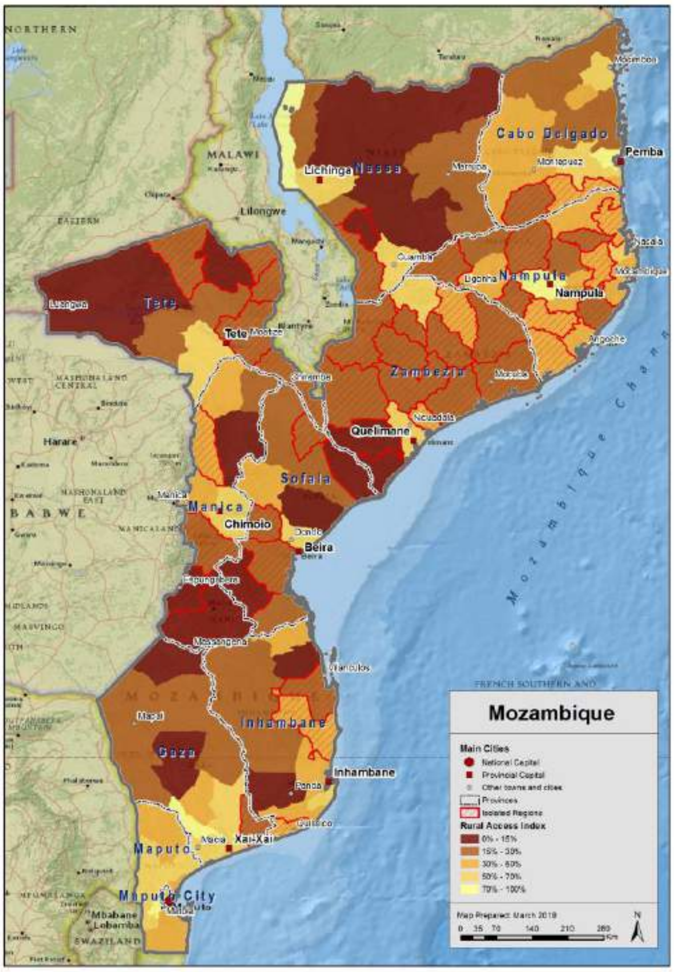
      Some of the factors to be considered in a rural access index include:
        - Population distribution and density
        - Road network density (coverage)
        - Population within 2 km of an access road
        - Population without road access (in terms of both number of people and percentage of population)
        - Availability of alternative routes
    - 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 associated with an urban setting.

      Some of the factors to be considered in a remoteness indicator include:
        - Hierarchy of towns
        - Essential service facility data (health and education facilities)
        - Market locations or GDP production centres
    - An example of a remoteness index that was successfully implemented in an African context is the remoteness index of South Africa (Mans, Le Roux, Maritz & van Huyssteen, 2016).
- These variables form the basis of a rural access and/or remoteness indicator by quantifying the road function dimension of the criticality assessment.
- A consolidated view of asset criticality per district is formed by aggregating the road exposure, vulnerability index and rural access index, and this can be mapped.
- The importance of weighting in the aggregation step depends on the need to accommodate preferential information. Country-specific, multi-criteria analysis is a useful tool to evaluate the overall rural access road risk, given different views on the importance of the various components.
- Finally, the results of the road criticality analysis depicting the most isolated districts should be mapped.

Example action (Mozambique's current situation):

From the Mozambican case study (see Le Roux *et al*., 2019a), the following maps were produced indicating road network density and condition, as well as overall road criticality per district (rural accessibility and isolation).

Mozambique: road criticality (rural accessibility and isolation)



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

−

Criteria	Isolation Factor
Districts where more than 60% of the population lives further than 2km from an access road, and where this accounts for 100,000 people or more	1
All other districts	0

=

Road Criticality Index

Data source: CSIR custom analysis using data from the National Roads Administration (ANE), WorldPop (2013) and DIVA-GIS (2019)

From the Mozambican case study (see Le Roux *et al*., 2019a), large parts of the country are faced with inadequate road access based on the calculation of the rural access index (RAI).

Step 3.3: Determine districts most at risk to the impacts of a changing climate

Sub-step 3.3.1: Districts most at risk to climate impacts under current climate and socio-economic conditions

Aim:

The aim of this assessment is to identify those districts that are at most risk under current climate and socio-economic conditions. The data inputs for this step are the analysis outputs from Step 3.1 (road exposure) and Step 3.2 (road criticality). Roads in poor condition in these most at risk districts should be prioritised for adaptation.

Recommendations:

- From the analysis done up to this stage, the most at risk districts can be identified by aggregating the road exposure (hazard exposure index) and road criticality (road criticality index) analysis results. The overlap between high road exposure and high road criticality indicates in which districts the roads are most at risk to climate hazards.
- These results can be used to map the districts most at risk under current climate and socio-economic conditions.

AfCAP

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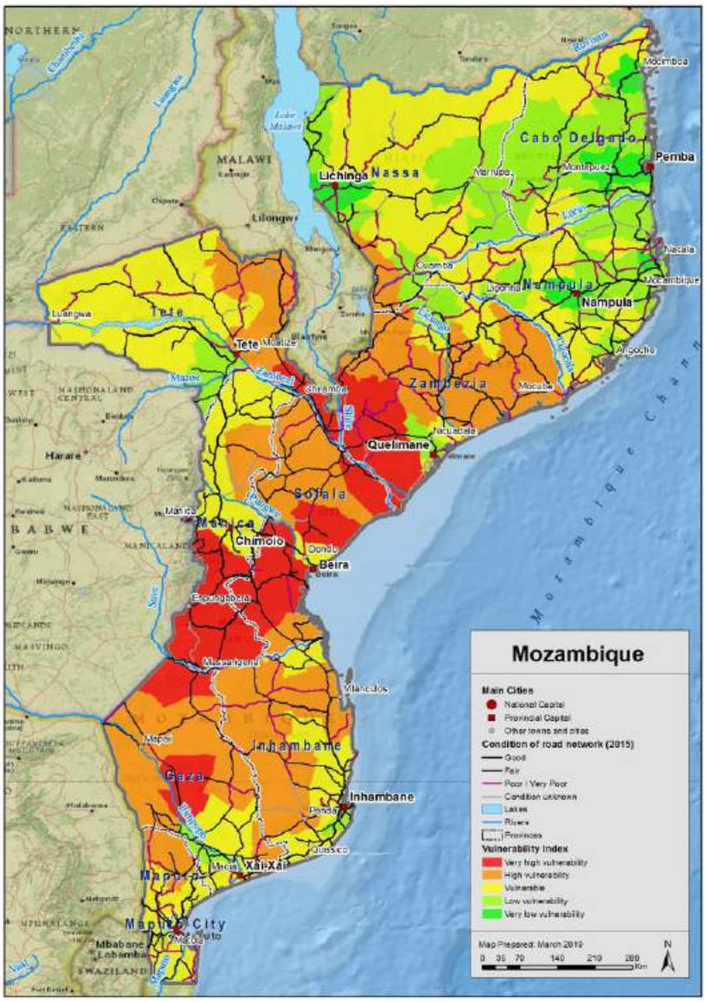
Climate Adaptation: Risk Management and Resilience Optimisation for Vulnerable Road Access in Africa

Example action (Mozambique's current situation):

From the Mozambican case study (see Le Roux *et al.*, 2019a), the following map was produced to indicate the districts most at risk to climate impacts under current climate and socio-economic conditions. Based on the outcome of the climate risk index analysis, the districts in orange and red can be considered to be at higher risk to the impact of changing climate while the districts in shades of green indicate lower vulnerability to climate risk.

Mozambique: Climate Risk Index
(districts most at risk to climate impacts under current climate and socio-economic conditions)



Flood Exposure Index
5
4
3
2
1

+

Criticality Index		
Rural Access Index	**-**	Isolation Factor
5		1
4		
3		0
2		
1		

=

Current Climate Risk Classification		Climate Risk Index
🟩	Very Low Risk	8 – 10
🟩	Low Risk	7 – 8
🟨	Moderate Risk	5 – 6
🟧	High Risk	3 – 4
🟥	Very High Risk	1 – 2

Data source: CSIR custom calculation, National Roads Administration (ANE)

From the Mozambican case study (see Le Roux *et al.*, 2019a), a climate risk index was calculated. Here, areas in red and orange depict high risk given their exposure to frequent and severe flooding (flood exposure) as well as districts where road criticality is key due to high isolation. This is where roads are at high risk to a changing climate in terms of the impact on rural accessibility and areas that should be prioritised for road adaptation. The index gives preference to districts where larger amounts of people are without adequate access to a road network.

Sub-step 3.3.2: Districts at risk to future climate impacts under a changing climate and growing population

Aim:
The aim of this assessment is to identify those districts that are most vulnerable to future changing climate conditions in terms of the impact on rural accessibility. Roads in vulnerable districts that are expected to be most affected by changes in climate with regard to temperature and rainfall (including changes in extreme events) should be prioritised for adaptation.

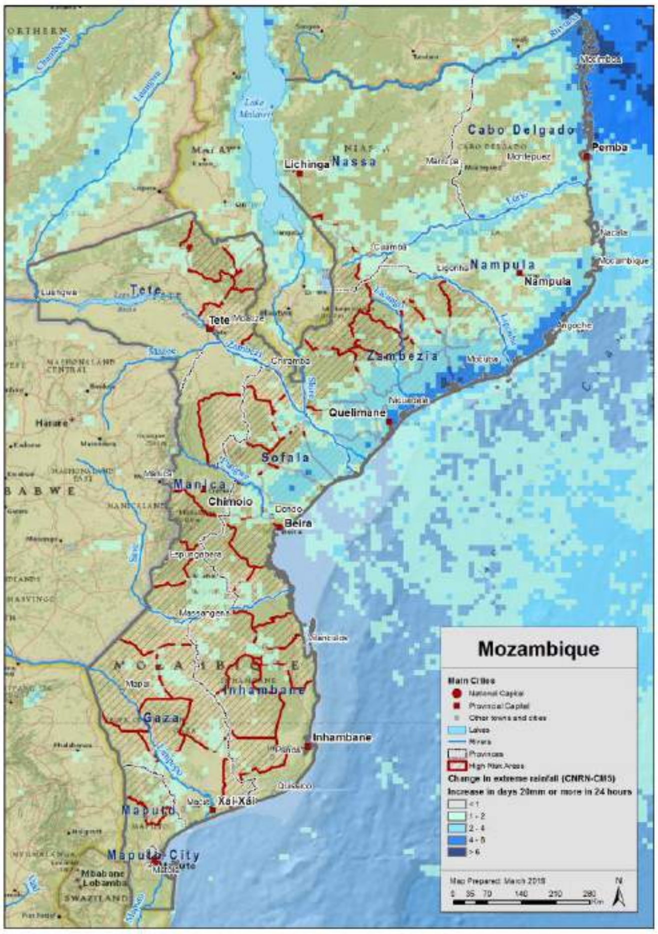
Recommendations:

- Future vulnerable districts can be identified by combining the results of the most vulnerable districts under the current climate and socio-economic conditions with projections of future climate change and population distribution.
- The overlap between high future road exposure due to projected climate change and/or increased criticality resulting from population distribution change, for the most vulnerable districts, indicates where already vulnerable roads will become even more vulnerable under changing future conditions.
- To show a range of uncertainty for the projected climate changes, it is recommended that a suite of climate change models are for comparative purposes (e.g. The ACCESS1-0 and CNRM-CM5 climate downscaling's were chosen in the Mozambique case study).
- Exposure of road network and vulnerable communities to increases in extreme rainfall events can be used as a proxy for both direct damage (e.g. erosion) of (unpaved) roads and flood risk.
- For road adaptation, increases in temperature extremes need to be taken into account for softening of bitumen, expansion of concrete and loss of soil moisture which has secondary effects including increased susceptibility to cracking and erosion. Exposure of the road network to increases in the number of very hot days can be used as a proxy for change in temperature extremes.

Example action (Mozambique’s mid-future situation (2050)):

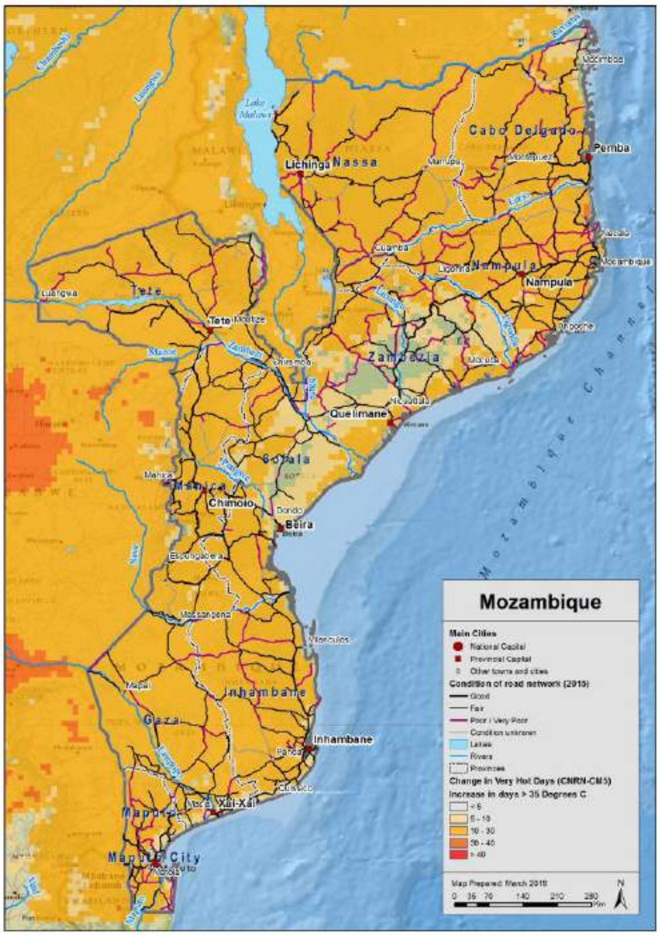
From the Mozambican case study (see Le Roux *et al.*, 2019a), the following maps were produced showing the most vulnerable districts:

- Exposure of road network and vulnerable communities to increases in extreme rainfall events
- Exposure of the road network to increases in the number of very hot days

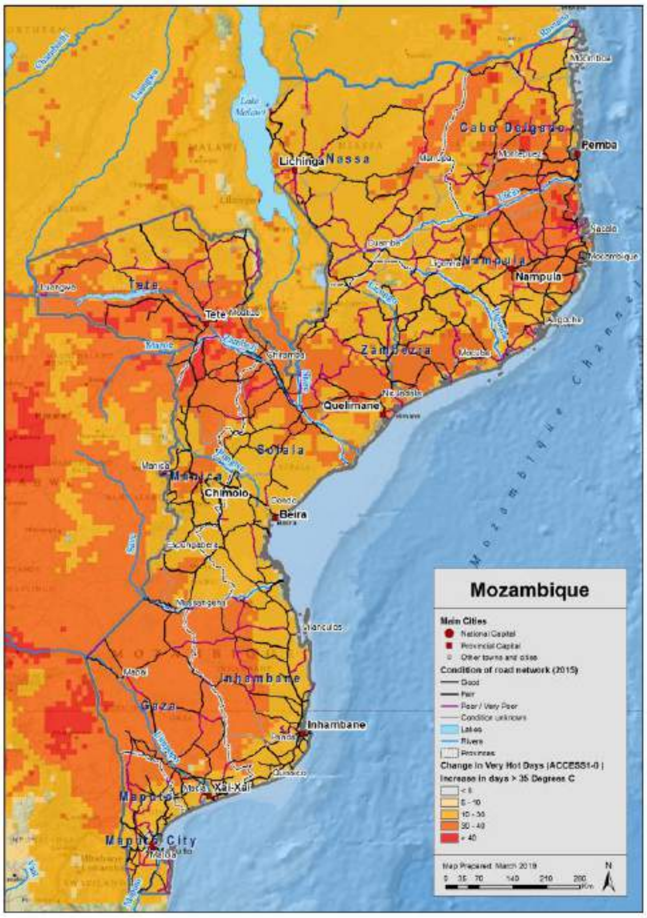
<table>
<tr><th colspan="2">Mozambique: exposure of vulnerable regions to increases in extreme rainfall events</th></tr>
<tr><td>
</td><td>
</td></tr>
<tr><td>Source: CNRM-CM5 downscalings (CSIR)</td><td>Source: ACCESS1-0 downscaling (CSIR)</td></tr>
</table>

From the Mozambican case study (see Le Roux *et al.*, 2019a), The CNRM-CM5 (Left) and ACCESS1-0 (Right) downscalings for the near-future period of 2021–2050 were used to map the projected change in the annual number of extreme rainfall days over Mozambique, together with the districts classified as being at high and very high risk to climate impacts as an example of the risks that extreme rainfall events may plausibly pose to Mozambique in the future. The ACCESS1-0 and CNRM-CM5 climate downscaling's were chosen to show a range of uncertainty for the projected climate changes.

Mozambique: exposure of road network to increases in very hot days



Source: CNRM-CM5 downscalings (CSIR)



Source: ACCESS1-0 downscaling (CSIR)

For road adaptation, increases in temperature extremes need to be taken into account for softening of bitumen, expansion of concrete and loss of soil moisture which has secondary effects including increased susceptibility to cracking and erosion. From the Mozambican case study (see Le Roux *et al*., 2019a), The CNRM-CM5 (Left) and ACCESS1-0 (Right) downscalings for the near-future period of 2021–2050 were used to map the projected changes in the frequency of very hot days annually. These models were chosen to show a range of uncertainty for the projected climate changes.

3.3 Summary of proposed indicators

Table 4 shows a list of spatial variables considered in implementing the district indicator-based risk and vulnerability assessment method as described above. It was noted previously that data for partner countries is probably not the same in terms of quality and quantity. Therefore, this compendium outlines those variables that each partner country would be expected to have/make available in a basic data set to enable a detailed road risk assessment that goes beyond a simple climate risk analysis.

Table 4 A compendium of the indicators that are relevant for an indicator-based geospatial risk and vulnerability assessment of rural access roads to climate change

Assessment components	Possible indicators	Assessment level
		National / Regional
Road asset classification	Rural road network length (disaggregated by class if possible)	X
	Proportion or length of the network that is paved and/or unpaved	X
	% of the rural road network in a climate-resilient condition	X
Current climate hazards assessment (e.g. historical flood events)	Flood occurrence frequency and intensity	X
	Flood-prone areas	X
Climate change hazards assessment	Expected change in annual average rainfall	X
	Expected change in the annual average temperature	X
	Expected change in the average number of days per year with rainfall above 20 mm	X
	Expected change in the number of days per year above 35°C	X
	Expected change in maximum monthly rainfall	X
	Expected change in average wind speeds (in m/s)	X
	Expected change in maximum monthly wind speed (period's average)	X
	Expected change in the number of high fire danger days	X
	Expected change in the Keetch-Byram drought index	X
	Expected change in wind speeds and directions	X
Socio-economic condition (Criticality of rural access roads)	Population distribution and density	X
	% of the population living within 2 km of an access road	X
	Location of healthcare facilities	X
	Location of educational facilities	X
	Average distance to the nearest town or market	X

Phase 4: Embedment in the Road Asset Management System (RAMS)

Aim:

The aim of this phase is to embed the information pertaining to climate change risks into the Roads Asset Management Systems (RAMS) of road authorities. The World Bank report "Integrating Climate Change into Road Asset Management", published in April 2017 (Henning, Tighe, Greenwood & Bennett, 2017) recommends that climate change must be recognised as a risk to assets as well as to the delivery of services. The report further states that risk and vulnerability assessments are already commonly used for climate adaptation and that these processes should be integrated with risk management from an organisational risk perspective. The recommended way to incorporate climate change as a risk in a RAMS is to embed the vulnerability assessments and indicators quantified during Phase 3 into the RAMS of road authorities.

The embedment phase consists of three steps. The output from Phase 3 is considered in Step 4.1 to decide which of these outputs to include in the RAMS. During Step 4.2, the data is prepared so that it is in the format that is required for import into the RAMS and, in Step 4.3, this imported data is analysed in the RAMS to calculate climate hazards indicators and combined indices.

General recommendations for this phase:

- An understanding of the RAMS database structure would be required during this phase.
- It would be essential for the person appointed to do the spatial data analysis to have close interaction with the RAMS champion(s) and persons managing the RAMS.
- Changes to the RAMS database structure, such as adding of additional tables, additional field to existing tables and additional look-up values, would be required to accommodate climate adaptation data.

Step 4.1: Consider climate hazard indicators to be included in the RAMS

Aim:

The aim of this first embedment step is to consider all the outputs from the national-/regional-level risk and vulnerability analysis in Phase 3, and to decide which of these to embed in the RAMS.

During Phase 3, a road exposure and vulnerability assessment is conducted to determine which districts are most at risk from climate hazards, and the current condition of the roads in these districts. This information is then used to determine road exposure vulnerability, in other words, where roads in poor condition are located in districts exposed to severe climate hazards, which are more at risk. This is done by synthesising climate hazard and road network condition data into a single index for climate hazard exposure vulnerability.

For the purpose of embedding climate change risks in the 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. Risk assessment components and possible indicators quantified during Phase 3 that would be useful for prioritisation in the RAMS are those listed in Table 4 under the headings *Current Climate Hazards* and *Climate Change Hazards.*

Recommendations:

- Determine for which current climate hazards and future climate change hazards indices should be calculated, based on what type of historical climate hazards occurred and what types are predicted for the future for the district in which the road falls.
- Decide which of these indices represent significant risks for the road network and road structures (bridges, culverts, embankments, etc.), which would generally be an increase in

precipitation and an increase in the intensity of rainfall, which could lead to more floods and an increase in very hot days.
- Focus on these identified indices in Step 4.2.

Step 4.2: Export data to the RAMS

Aim:

The aim of this step is to allocate the district climate hazard and climate change indices determined in Step 4.1 to the road network and then to export these to the RAMS. As these indices are determined per district, the same index per indicator would be allocated to all roads in a district.

For the purpose of a RAMS, a road network is broken up into road links and nodes. Data (attributes) is then stored per road link. This includes inventory and condition data. The district climate hazard and climate change indices would be a third class of data in the RAMS, namely Climate Adaptation Data. The various indices would have to be stored per road link in the RAMS database.

Recommendations:

- Allocate indices for significant historical climate hazards to each district, based on the analysis carried out during Phase 3.
    - For example, aggregate the number of climate hazard events, such as severe flooding events in the past four decades, per district and assign an index to each district.
- Overlay road network inventory data with each climate hazard index at the district level and assign the district index to all roads per district.
- Overlay road network inventory data with each climate hazard index at the district level and assign the district index to all roads per district.
- Repeat the same process for climate change hazards.
- Export the data from the GIS in a format that can be imported into the RAMS database.

Step 4.3: Analyse data in the RAMS

Aim:

The aim of this step is to use the district climate hazard and climate change indices imported into the RAMS in Step 4.2 for prioritisation analysis using the RAMS. This step does not form part of the Climate Risk and Vulnerability Assessment but is included here for the sake of completeness.

The individual indices, such as a flood prone index, can be used to rank roads and structures in terms of priority for maintenance or adaptation, or the indices can be included in the calculation of a combined climate hazard or climate change index that can then be used to rank the roads and structures.

At the next level, the combined climate hazard or climate change index can be combined with condition indices, such as the Visual Condition Index, which would lead to a ranking of roads and structures in terms of priority for maintenance or adaptation, taking both climate factors and current condition into account.

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.

4 Local-/project-level assessment of climate risk and vulnerability of rural access roads

4.1 The purpose of a local-/project-level road vulnerability assessment

The national-/regional-level vulnerability assessment discussed in Chapter 3 is a top-down geospatial indicator-based approach. The aim is to identify districts of higher priority in terms of road infrastructure deficiencies, the need for climate-proofing and the criticality of improved access as a stimulus for community development and resilience. The purpose of a local climate vulnerability assessment for rural access roads is to identify specific hazards that currently affect particular road segments and to assess how likely it is that such hazards would intensify (or diminish) in the future. Typical climate-related hazards for rural access roads are illustrated in Figure 5.

Figure 5 Damage to road infrastructure due to climate-related environmental stresses

A local climate vulnerability assessment for roads can be used in the following ways:

- To inform engineering design decisions from the road segment level up to the catchment level of a road network
- To identify additional data that needs to be included in road asset management systems for monitoring climate and environmental risks

- To identify other factors that aggravate the effects of climate change on roads and that can be managed through changes in the practices of communities, industry and policy makers

One of the greatest challenges in carrying out such an analysis in resource-stricken countries is data availability. This is the case at the district level, but even more so at the local level where high-resolution spatial data is required to produce information that can support engineering design decisions for the climate adaptation of specific road segments. For example, detailed local data on current and historical climate hazards are typically not easily available in a digital format.

In this chapter, the user is guided in terms of the principles of conducting a local-level road vulnerability assessment. Section 4.2 discusses communication and stakeholder involvement in local assessments owing to the required awareness needed about the local environment and state of the roads. Local stakeholders are involved in the collection of data and in the uptake of recommendations. Section 4.3 provides guidance on the method proposed for assessing local road vulnerability to climate hazards, including a step-by-step guideline on data sourcing, storage and manipulation within a geographic information system. Concluding remarks and a compendium of indicators that are relevant for undertaking a vulnerability assessment of road infrastructure to climate are included in Section 4.4.

4.2 Communication and stakeholder involvement

The users of these local vulnerability assessment guidelines are envisaged as being mainly local and sub-regional road authorities. The pool of stakeholders is wider, as it includes all parties who are affected by road infrastructure maintenance and upgrading decisions. Such parties include development partners, non-governmental organisations and government departments in charge of transport, environmental affairs, emergency and disaster management, the economy and social development. Stakeholders are also important sources from which to gather local-level data and for stimulating the development of community-led enterprises that can assist in the construction and maintenance of roads.

Rural communities that depend on access roads are also identified as stakeholders. They derive benefits from having roads that are climate-resilient, but they are also affected by the passage of roads through their environment, which often results in changes in settlement patterns, culture and safety (World Bank, 1997; Escobal & Ponce, 2002; Hettige, 2006). It is therefore important that communities understand factors that render roads in their community vulnerable to climate hazards. These communities also offer a unique informative view on historical hazards that have affected their access roads and as such should be consulted as part of the local risk assessment screening. The benefits that increased community awareness have for road authorities include receiving early warning about emerging structural damage on the roads, reduction of climate impacts through modification of land-use practices, and frequent clearing of debris and vegetation from culverts, bridges and other water drainage structures. Communities are also well positioned to implement change management recommendations aimed at eliminating land-use practices that aggravate the impacts of climate on nearby roads.

Local road vulnerability assessment users include:
District road engineers or assessors who perform and use the results of these assessments in maintaining and further developing the road networks.

Local road vulnerability assessment stakeholders include:

- Government agencies and departments with a vested interest in road infrastructure planning and development such as transport, disaster management, environment, agriculture, tourism, health and education
- Private companies involved in the construction and maintenance of roads

- Communities dependent on the road
- Investors in road infrastructure projects

4.3 Methods for local assessment of road vulnerability to climate hazards

4.3.1 Overview of the local road vulnerability assessment framework

The local-/project-level risk and vulnerability assessment for rural roads differs from the national-/regional-level assessment in two ways. Firstly, the local assessment accommodates the possibility that local-level spatial data on historical hazards (or disasters) will in most cases not be available, in contrast to the availability of EM-DAT disaster data used for the national-/regional-level assessment. In cases where these datasets are actually available at the local level, they will be used as weights when quantifying road vulnerability to specific climate hazards. For example, if the area is flood-prone, spatial layers for rainfall variables will be given more weight in quantifying vulnerability in terms of the five specific risks. If there is no reliable historical disaster dataset, then the climate variables can be considered uniformly. Secondly, the assessment considers the vulnerability of rural roads to specific climate-related risks and these can be mapped for particular road network catchments. Disaggregation of vulnerability according to risks is necessary at the local level because the aim is to provide information that the engineers can use when making design-related decisions.

The methodology for undertaking a climate risk and vulnerability assessment at a local or project level also consists of five phases, each with a number of action steps (Figure 6):

Phase 1: Contextualisation of the local area
- Step 1.1: Collect and prepare local-level data

Phase 2: Climate-sensitive visual assessment
- Step 2.1: Capture data through fieldwork and community participatory mapping

Phase 3: Climate-sensitive road vulnerability analysis
- Step 3.1: Assess road condition deficiency
- Step 3.2 : Assess road maintenance
- Step 3.3: Assess road criticality
- Step 3.4: Calculate road vulnerability index

Phase 4: Embedment into road asset management system (RAMS)
- Step 4.1: Export data to the RAMS
- Step 4.2: Communicate with stakeholders

Phase 5: Climate adaptation
- Adapt road according to prioritisation and climate-sensitive engineering designs (Refer to Change Management and Engineering Adaptation Guidelines)

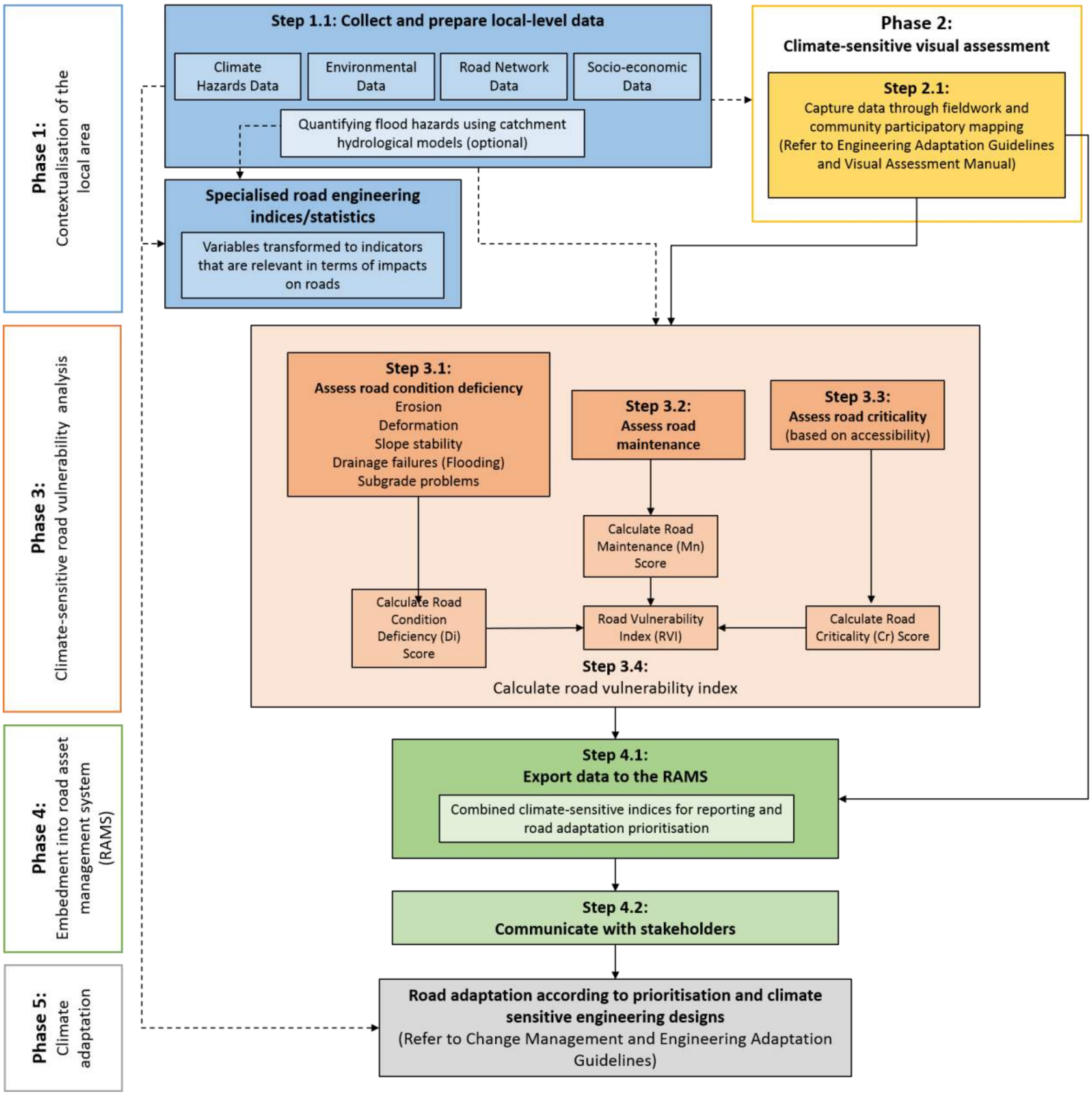


Figure 6 A conceptual framework for the local vulnerability assessment of rural access roads

4.3.2 Local-level risk and vulnerability analysis steps and guidelines

Phase 1: Contextualisation of the local area

Aim:

The aim of this phase is to contextualise and give some background of the local area where road engineers will carry out climate-sensitive visual assessments. This is done by identifying, sourcing and mapping data that will aid in contextualising the environment around the roads being assessed. A local climate-sensitive assessment requires attribute data about the road segment being assessed and the surrounding environment (vegetation, soil and water catchment areas), including hazards that have affected and may continue to affect that particular road. Gathering data on the availability of alternative routes when the road is inaccessible and obtaining clarity about the use of the road by the community is also important.

General recommendations for this phase:

- Using a GIS facilitates the efficient management of all the input and output data, enables easier communication with stakeholders through maps and allows for the data to be easily shared for further evaluation and applications.
- Data quality in terms of availability, completeness and correctness has an influence on the margin of error associated with the results of the assessment. Decision making can be challenging if output uncertainty is high. Data availability, especially at this level of detail in terms of attributes and spatial resolution, is typically a problem in resource-constrained countries.
- At a project/ local level, an important analysis component of the risk and vulnerability analysis is a hydrological model. This model can be implemented outside the GIS environment; however, the results can be imported into a GIS for visualisation and further analysis.
- Where there are modifications to the general methodology to accommodate the available data, it is good practice to document these changes and the perceived limitations or effects on outputs.

Step 1.1: Collect and prepare local-level data

Aim:

The aim of this step is to identify, source and collect the necessary data to support a local-level climate-sensitive visual assessment. Categories of data, as described in Figure 6 and Table 5, include climate, environment, road attributes and socio-economic factors. Local road authorities and government departments would be the custodians of local spatial data for these categories, whereas most of the gridded data such as climate projections, population, land cover and elevation can be sourced from global open source repositories as recommended in the national-level assessment in Section 3.2.2 (Step 2.1).

Recommendations with regard to data collection:

- District road authorities, local government departments and communities are an important source of information. Ideally, this information would have been collected during the surveying of roads by district engineers, which would mean the data can be extracted from the RAMS of roads department.
- If a national-level assessment was done prior to the local assessment, then GIS layers can be extracted for that district, including the current and future hazards that were identified. However, in a national-level assessment, some hazards that directly affect particular roads in the district are likely to be missed in country-specific departmental reports and international databases such as EM-DAT. Community engagement is therefore recommended, as local communities are seen as experts in terms of knowledge of their immediate environment and they may have in-depth knowledge and information about what hazards most frequently affect their environments and road accessibility. Where feasible, indigenous knowledge should be accessed and corroborated.
- It is also important to consider information on historical and future climate and environmental hazards that have had or may have an impact on roads (including the road of interest within a district). In the case of a local assessment, this information can be soused from local level reports or data (if available), community participatory mapping or indigenous knowledge, and would be used as weights when integrating the various climate data layers to calculate threat-specific vulnerability.

Table 5 Data sources and variables to consider for a local climate vulnerability assessment for rural roads

Description	Climate	Environment	Roads	Socio-economic
Data sources	▪ National meteorological office; Climate modelling groups (simulations and projections)	▪ Environment and disaster management government departments; Communities; International organisations (earth observation data)	▪ Road Asset Management System (RAMS) ▪ Road authorities; private road construction companies	▪ Government departments; National statistics offices; International organisations (World Bank, United Nations)
Data types	▪ Historical and projected time series points or raster datasets ▪ Point data (weather station observations) ▪ Raster data (climate simulation model outputs)	▪ Raster data for continuous surfaces ▪ Vector and point data for the location of objects	▪ Vector (street centre lines) data	▪ Vector data (administrative polygons)
Variables (raw / unprocessed)	▪ Rainfall ▪ Temperature ▪ Wind speed and directions	▪ Land cover and use ▪ Topography (elevation, slope) ▪ Soil (type, observed erosion) ▪ Hydrology (location of water bodies, catchment boundaries/extent, coastal lines) ▪ Unusual recent events (temporary flooding, erosion, siltation, slope failures)	▪ Road surface type ▪ Road surface level ▪ Road width ▪ Traffic loads ▪ Alternative routes ▪ Location of water drainage features (culverts, bridges, road ponds) ▪ Maintenance frequency for road surfaces and drainage infrastructure ▪ Recent failures of roads or structures	▪ Population distribution ▪ Location of markets or distance to the nearest town ▪ Location of public facilities ▪ Land use (main economic activities)
Variables (after pre-processing)	▪ Design flood estimates ▪ Design rainfall estimate ▪ Annual average rainfall intensity ▪ Frequency of extreme rain events per year (>20mm/24 h) ▪ Annual average temperatures	▪ Elevation, slope and aspect derived from the DEM ▪ Vegetation cover density on road embankments ▪ Proximity of forest or tall trees to the road ▪ Distance of road to water bodies ▪ Length of longest watercourse	▪ Location of drainage systems along the road ▪ Road surface level indicator ▪ Location of erosion protection works ▪ Road base material ▪ Geotechnical information of road base and embankments	▪ Travel distance to market/town ▪ Travel distance to school ▪ Travel distance to healthcare centre ▪ Remoteness indicator ▪ Access distance to ‘all-weather’ road

Description	Climate	Environment	Roads	Socio-economic
	▪ Annual average frequency of very hot days (daily temp > 32 degrees Celsius) ▪ Annual average frequency of excessive wind speeds	▪ Catchment area/extent	▪ Location, type and size of observed cracking along the road ▪ Maintenance frequency of drainage system	

Once data has been sourced, it needs to be transformed from its original state into variables for the climate-sensitive road vulnerability assessment.

Recommendations with regard to data preparation:

- Data from local sources are likely to not be in a GIS format; hence, appropriate steps should be taken to digitise the data in a GIS, or to map the data obtained from community participatory mapping exercises.
- In the local/project assessment, vulnerability to specific risks is considered separately, which is different to the national/regional assessment where districts are given a single overall vulnerability score based on the combination of all risks. For example, the vulnerability of the road to the erosion of embankments and foundations is considered separately from its vulnerability to surface flooding through drainage deficiencies. Thereafter, a compound Road Vulnerability Index is calculated for each road segment and then for the road entirety.
- When considering climate change variables in general, there needs to be a consensus among stakeholders on the following aspects:
    - The choice of projection period. For example, the mid-term period between the years 2021 and 2050 was chosen in the national-level assessments based on the practicalities of obtaining data on the population and economic outlook, as well as considering the lifespan of roads.
    - Choice of RCP mitigation scenario/s, climate model(s) and downscaling method(s). These need to be the same scenario/s, model(s) and downscaling method(s) that were used in the national-level assessment and should ideally be the same as those used in other infrastructure planning initiatives by government.
    - The inclusion of information on road infrastructure and land-use plans for the future scenario of the vulnerability assessment. Typically such data does not exist in databases, but can be sourced from policy and other planning documents.
- The preparation of climate data includes identifying extreme value statistics for rainfall, temperature and wind. For assessing climate impacts on roads, further statistics such as temperatures in excess of specific limits, moisture indices, etc. need to be derived. Guidelines on appropriate statistics can be sought from consultation with civil (road) and geotechnical engineering experts.
    - Transform climate variables into indicators that are relevant in terms of impacts on roads. For example, when considering the annual average frequency of excessive wind speeds, an exceedance threshold needs to be defined according to expert knowledge on conditions amenable to loss of pavement materials and unstable loading on structures.
    - Follow data management principles by documenting the lineage of climate data, from the original data that were received to the climate impact indicators.
- Socio-economic data provides a narrative about the community’s use of a particular road.

- Land use in an area is related to socio-economic functions occurring in that community. For example, most rural communities engage in agricultural activities.
- Other socio-economic variables that are recommended for use in evaluating road criticality in terms of rural accessibility and remoteness are the following:
  - Population distribution and density to evaluate differences in proximity to the road.
  - Location of cultural (religious and recreational) and essential service (health and education) facilities to evaluate whether the road provides essential access.
  - The location of markets and economic centres to evaluate whether the road provides access to them.

Data collected from the field requires capturing and then digitisation in a GIS, and includes ground survey data (visual assessment of the road and surrounding environment) and paper maps and other products from community participatory mapping.

GIS data preparation steps include the following:

- Installing the required software for data capture, transformation (e.g. in Excel) and geocoding in a GIS
- Ensuring that spatial data is in the correct format
- Validating the attribute and positional accuracy of data
- Editing incorrect cases
- Creating a data repository (e.g. spatial database) to store data that is ready for analysis
- Applying GIS processing steps to make the data uniform in terms of format, resolution and spatial extent by clipping, conversion (vector to raster), the setting of buffer limits and zonation

At this stage, data are collated within a GIS and the purpose is to map the data to support the road engineers in understanding the environment in which they will conduct the climate-sensitive visual assessment.

General recommendations for data mapping:

- When mapping data that contextualises the local environment, the following general principles of cartography are applicable:
  - Delineate/clip out the area of interest and map the road network.
  - Map out the areal extents of environmental parameters under consideration, including locations of recorded hazards, if available.
- The frequency and intensity of hazards that currently affect roads will change as a result of changes in climate; therefore, expected future climate conditions can be used to determine how hazards are likely to change so that the weights used in the current analysis would differ from those used when considering future scenarios.
- To contextualise the local environment, the following maps are suggested (as examples) (also see Figures 7–12 for example actions/analyses in the case of a road in Mozambique):
  - Delineate water catchments and watercourses in combination with topographical data.
  - Map soil types along the road network. Soil maps are useful in the context of landslides, flooding, road surface responses under dry and windy conditions, subsidence and erosion.
  - Map land-cover type and changes along the road network. The inclusion of a land-cover map of the area is important for contextualisation of the local environment.
  - Map population distribution and the location of market towns as well as education and healthcare facilities along the road network. Mapping socio-economic conditions help to contextualise the roads in the local area in terms of accessibility and criticality, and gives additional insight into the connective functions that roads fulfil for local communities in the region.

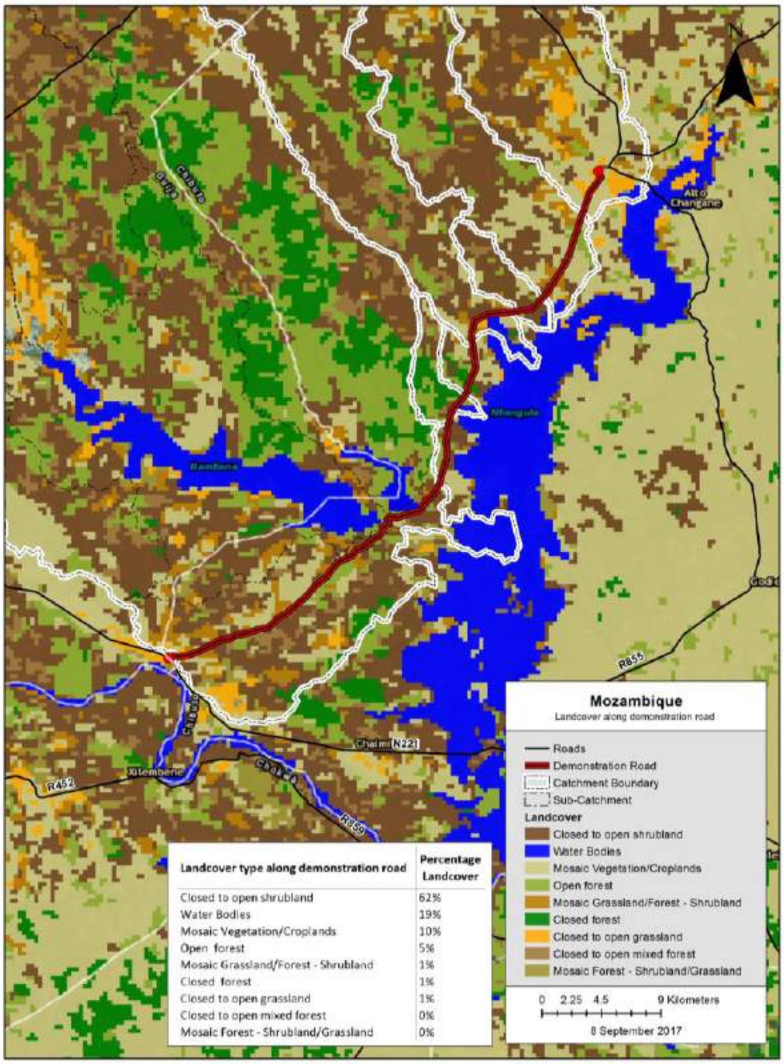
Example action (Contextualisation of the area/road between the towns of Chibabel and Maqueze in Gaza Province, northern Mozambique)

From a Mozambican case study, the following maps were produced to help contextualise the road and local environment on the rural road between Chibabel and Maqueze where a climate-sensitive visual assessment was later undertaken:

- Land cover of the natural environment surrounding the road
- Soil typology of the area surrounding and adjacent to the road
- Landscape topography of the area and a topographical cross-section of the road
- Water catchments areas along the road
- Watercourses relative to the elevation for the road
- Population distribution of communities in the area, including the location of towns, schools and healthcare facilities

These maps were assessed by the road engineers before fieldwork commenced (Phase 2). The maps were used to give the engineers a local background to and understanding of the area, so as to ensure the overall success of the climate-sensitive visual assessment and to support the data they collected in the field.

Land cover



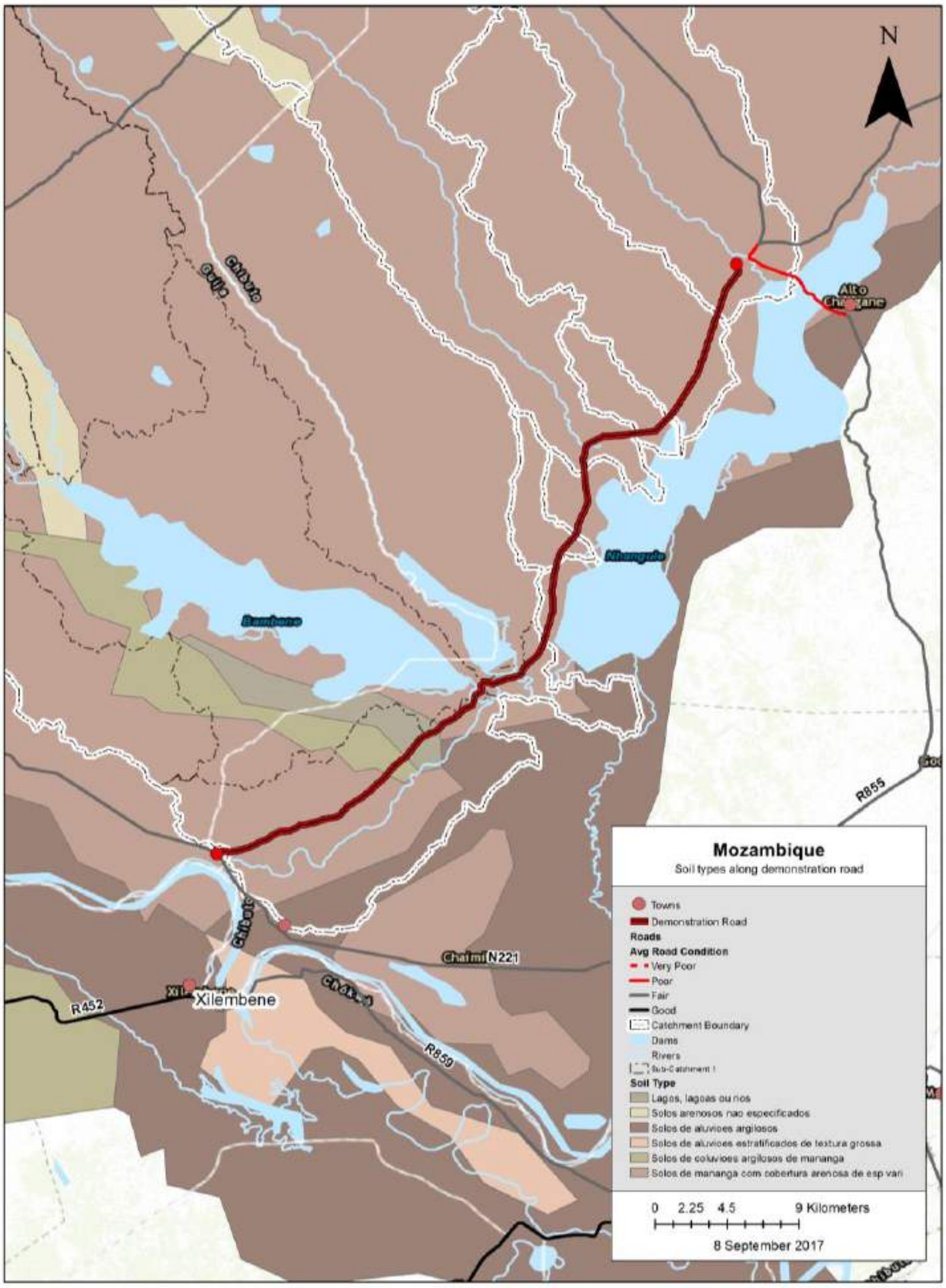
Landcover type along demonstration road	Percentage Landcover
Closed to open shrubland	62%
Water Bodies	19%
Mosaic Vegetation/Croplands	10%
Open forest	5%
Mosaic Grassland/Forest - Shrubland	1%
Closed forest	1%
Closed to open grassland	1%
Closed to open mixed forest	0%
Mosaic Forest - Shrubland/Grassland	0%

Data source: CSIR, 2017

Figure 7 Land cover around the road section between Chibabel and Maqueze in Gaza Province, Mozambique

Land use/cover is considered as a contextual variable for evaluating road exposure and vulnerability. From a Mozambique case study, Figure 7 shows the road section between Chibabel and Maqueze in the Gaza Province. One can observe from this map that the road section is located at the intersection of several water catchments, in very close proximity to the Nhangule and Bambene lakes. The vegetation cover in this area is limited to mostly shrubs and there are very few agricultural fields. Based on this land-cover information, one can assume that the road section has a high probability of flooding, given the presence of large water bodies and little vegetation cover that could be useful as a flood defence barrier. The soil typology is also indicative of an area prone to flooding.

Soil typology

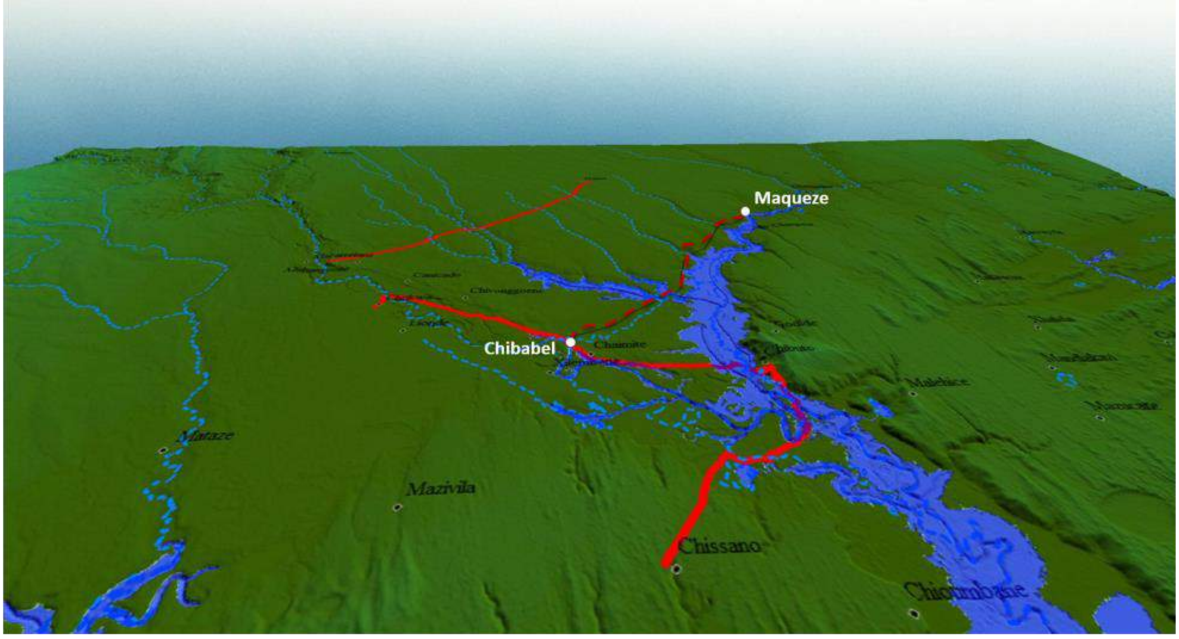


Data source: CSIR, 2017; National Roads Administration (ANE) Mozambique

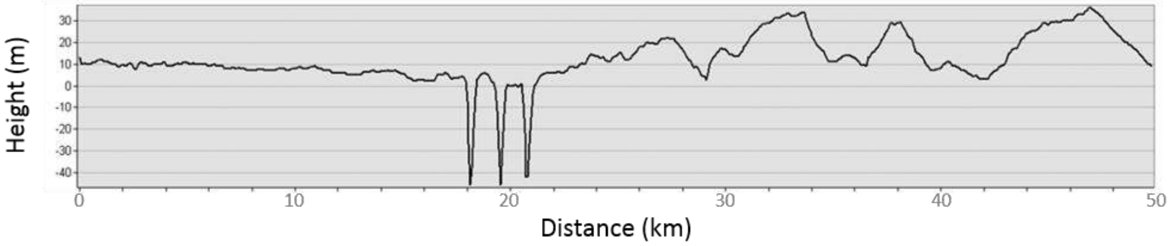
Figure 8 Soil typology in the area surrounding the road segment between Chibabel and Maqueze (Gaza Province, Mozambique)

Figure 8 is a soil map from a Mozambique case study showing that the area between Chibabel and Maqueze is dominated by alluvial soils (also known as fluvisols), which are young soils that occur as a result of river or marine deposits. These soil types are typical to areas that are prone to flooding.

Topographical cross-section of the road



Topographical cross-section of Chibabel-Maqueze road (Gaza Province, Mozambique)



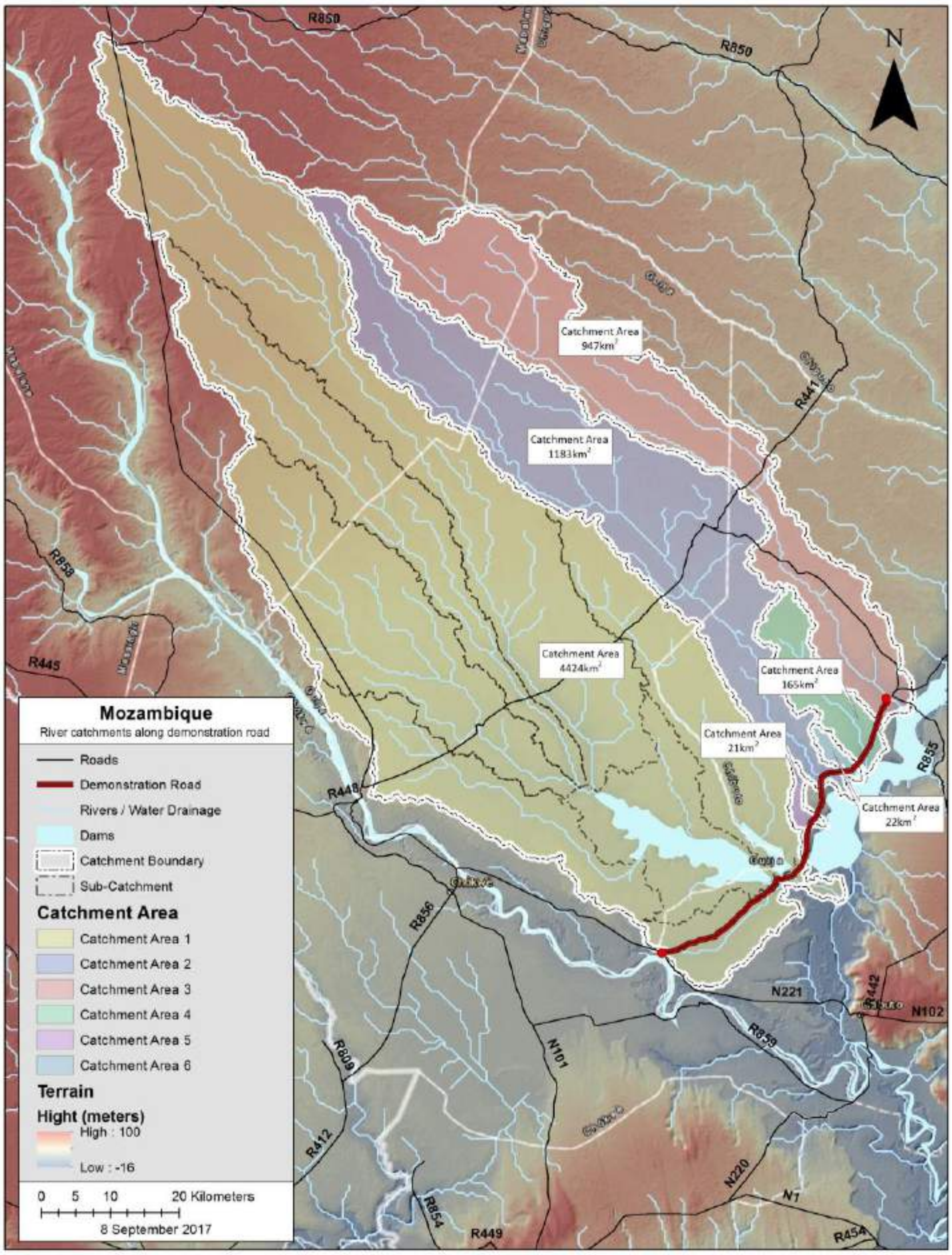
Source: CSIR custom analysis, 2017

Figure 9 Topographical landscape and cross-section of the road between Chibabel and Maqueze (Gaza Province, Mozambique)

From a Mozambique case, Figure 9 shows the 3D landscape of the area, as well as a topographical cross-section of the road between Chibabel and Maqueze. It indicates that the area is very flat, and elevations along the road vary between 0 m and 40 m.

Figure 10 is a combination of topographic relief data from a digital elevation model (DEM) and data that delineates the water catchment boundaries and the location of water bodies in the area surrounding the towns of Chibabel and Maqueze in Mozambique. The towns and villages are located on a flat, low-lying area and the road lies in an area where three large water catchment areas converge. The locations where river tributaries cross the road reserve are indicated in Figure 11. This information provides further evidence that flooding poses a significant threat to this road, and it indicates locations where flooding may pose a significant threat to the road infrastructure in terms of year-round accessibility for the local community.

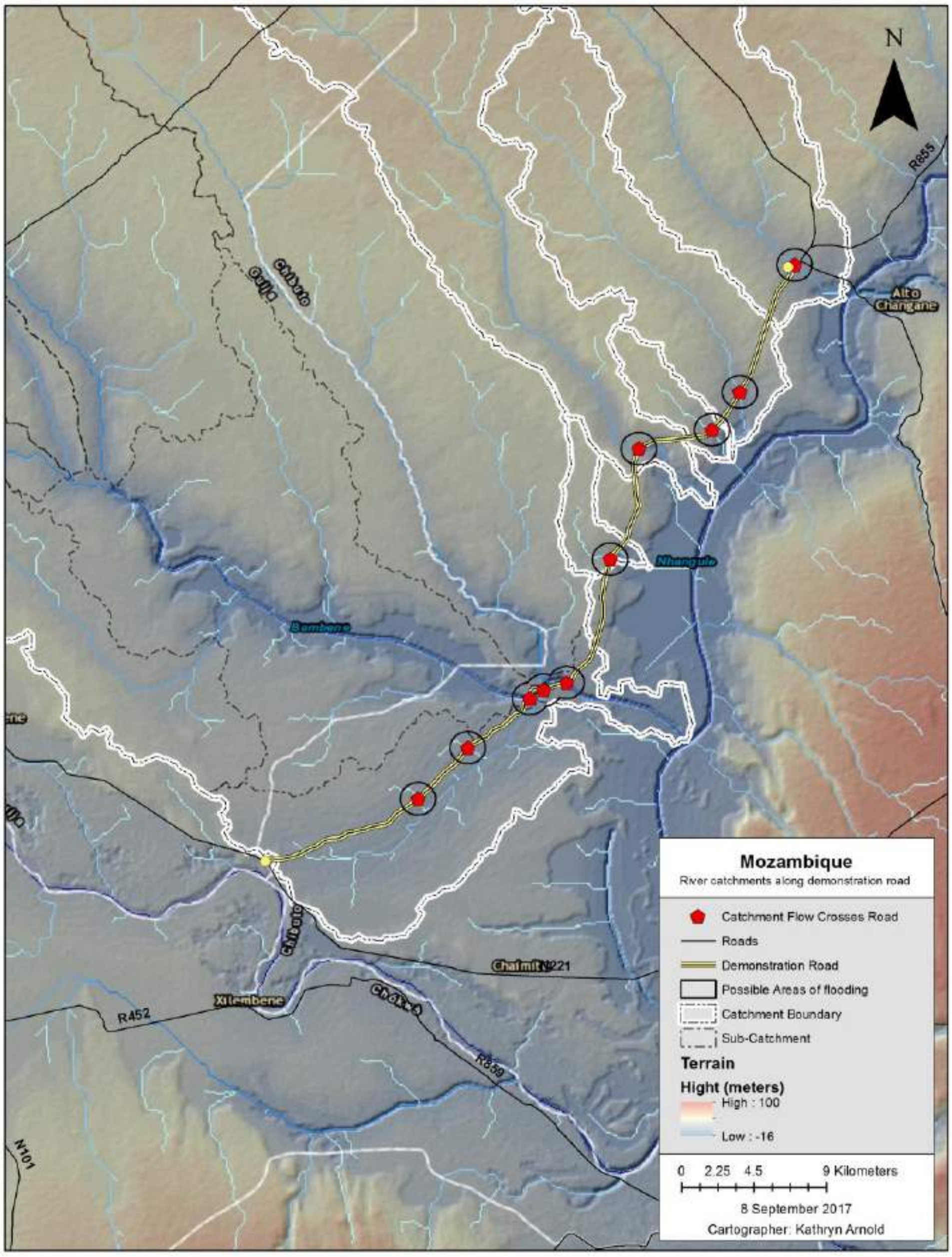
Water catchments areas



Source: CSIR custom analysis, 2017

Figure 10 A map of water catchments areas for the road between Chibabel and Maqueze (Gaza Province, Mozambique)

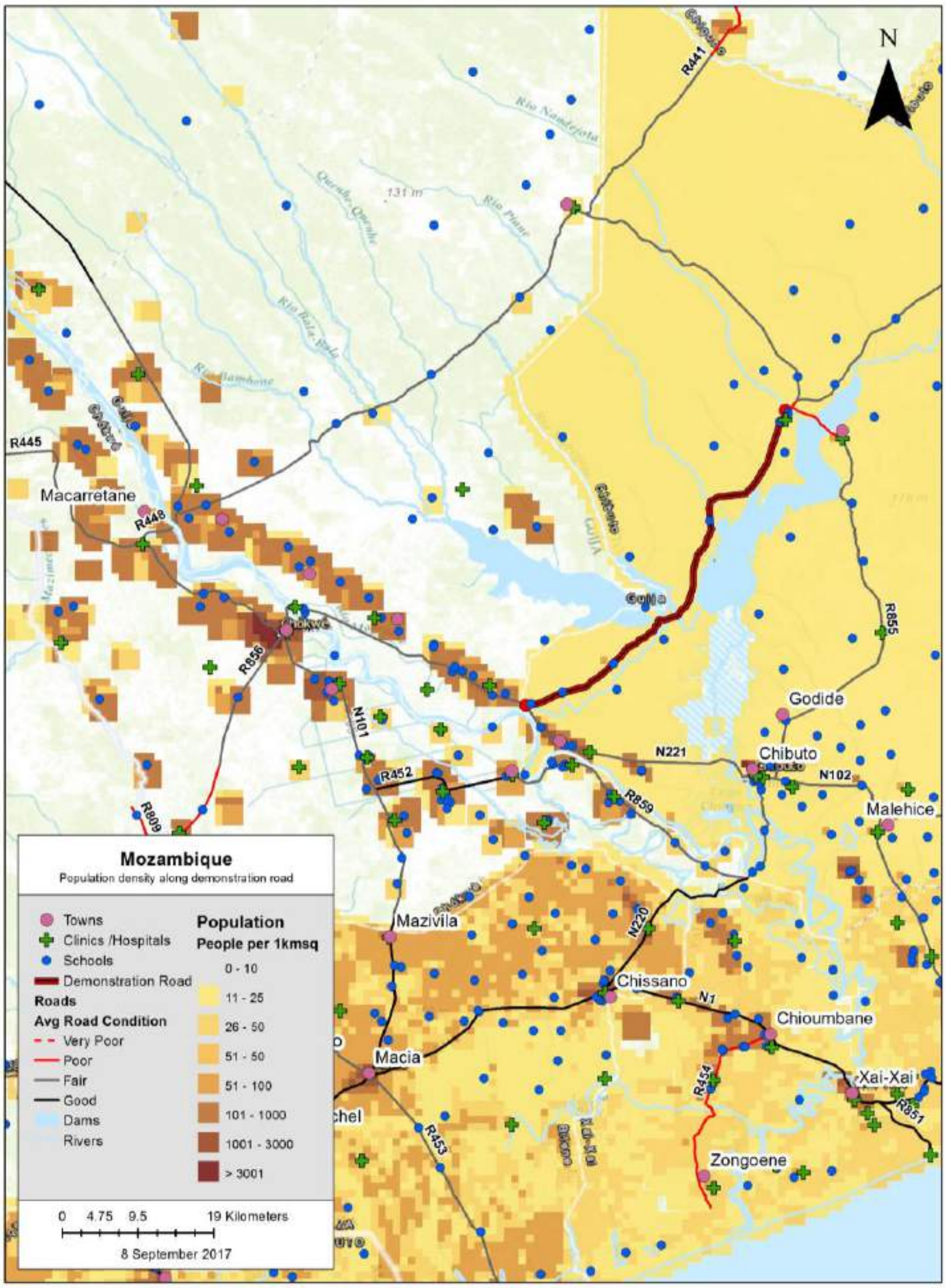
Watercourses relative to the elevation of the road



Source: CSIR custom analysis, 2017

Figure 11 A map of watercourses relative to the elevation for the road segment between Chibabel and Maqueze (Gaza Province, Mozambique)

Population distribution and the location of towns as well as education and healthcare facilities



Data source: CSIR, 2017; WorldPop, 2013

Figure 12 An indication of the population distribution and the location of towns as well as education and healthcare facilities within the catchment area of the Chibabel and Maqueze road segment

From a Mozambique case, Figure 12 shows that the road segment between Chibabel and Maqueze is a critical link to the N221 along which several towns, schools and healthcare facilities are located – both in the westerly direction towards Macarretane and in the easterly direction towards Chibuto. The areas immediately adjacent to the Chibabel–Maqueze road section are sparsely populated with no towns or healthcare facilities, but the road gives access to a number of schools.

Quantifying the flood hazard using catchment hydrological models (optional)

Flooding varies in its spatial extent, intensity and frequency and it poses the greatest risk in respect of infrastructure and economic losses. Proper planning and design of engineering projects require the estimation of design flood events (Rahman *et al*., 1998). Hence, flood frequency analysis is important in a project-level risk and vulnerability analysis, given the socio-economic and environmental impacts of floods.

The aim of the hydrological model at catchment level for local assessment would be to properly assess the flood hazard for a specific road, thus deriving parameters such as flood return periods which are inputs in road engineering and design. However, such an assessment can only be undertaken if there are resources available – specifically hydrological modelling experts and the relevant data.

In a gauged basin with appropriate observed flows, both in length and quantity, design flood estimation may be performed by means of a frequency analysis. The result of such an analysis is a return period (recurrence interval or repeat interval), which is an estimate of the likelihood of an event such as a flood or a river discharge flow to occur (ASCE, 1996; Peres & Cancelliere, 2016). It is a statistical measurement typically based on historical data, denoting the average recurrence interval over an extended period of time. It is usually used for risk analysis (e.g. to decide whether a project should be allowed to go forward in a zone of a certain risk, or to design structures to withstand an event with a certain return period).

However, for most catchments that are ungauged, the countries involved have developed standard techniques for flood estimation, ranging from statistical analysis of observed peak discharges to event modelling using rainfall runoff techniques.

It is advised that a hydrological assessment be done to help inform engineering design and adaptation parameters. The necessary experts should be consulted in this regard.

Specialised road engineering indices/statistics (to support engineering adaptation designs that are climate-sensitive)

For assessing the engineer adaptation measures to withstand the climate impacts posed by a certain road location, further statistics such as temperatures in excess of specific limits, moisture indices, etc. need to be derived. The objective is to transform the outputs of climate models into climate indicators suitable for supporting the engineering adaptation process. These statistics are used by road engineers to inform their climate-sensitive engineering adaptation designs. Guidelines on appropriate statistics can be sought from consultation with civil (road) and geotechnical engineering experts. For more information, refer to the Engineering Adaptation Guidelines (Paige-Green *et al.*, 2019).

Recommendations:

- For roads, climate assessments should be done on a high spatial resolution because of their complex and location-specific dynamic nature.
- Climate variables should be transformed into indicators that are relevant in terms of impacts on roads. For example, when considering the annual average frequency of excessive wind speeds, an exceedance threshold needs to be defined based on expert knowledge on conditions amenable to loss of pavement materials and unstable loading on structures.

- Guidelines on appropriate statistics can be sought from consultation with civil (road) and geotechnical engineering experts. To account for climate-related road degradation impacts, the following examples of climate statistics are suggested (also see Table 15):
    - Hazard occurrence frequency and the intensity of main hazard types
    - Hazard prone areas for main hazard risks
    - 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 35°C)
    - Keetch-Byram drought index
    - Maximum wind speeds and changes in direction
- Data management principles should be followed by documenting the lineage of climate data from the original data that were received to the creation of climate impact indicators.

The spatial information layers (or maps) listed above can be integrated in such a way that the following parameters can be assessed to determine the greatest climate-related hazards:

- Distance to the coast for coastal roads because of the risk posed by rising sea levels and wave heights exceeding particular thresholds
- The combination of precipitation intensity and slope for run-off and landslide risk in mountainous regions
- For the design of drainage infrastructure, the combination of watercourse maps, topography, previous flood extent, road infrastructure location and land cover (these are important considerations when assessing peak and moderate to heavy long-duration rainfall events)
- Profiles of past extreme temperature events and droughts in combination with soil and land-cover maps (these are useful in assessing erosion and loss of road surface structure or integrity as vulnerability factors)
- Changes to the intensity and duration of rainy seasons as a threat to road maintenance and construction schedules
- Deforestation and land-cover change in general for landslide risk
- Increase in vegetation cover as a modifying factor in flooding

Phase 2: Climate-sensitive visual assessment

The impact of climate change on roads requires that vulnerable sections of the road infrastructure be identified and that engineering adaptations be made to minimise potential future climate-related damage. Currently, for purposes of planning road management, maintenance and rehabilitation, visual condition assessments of the road network are usually routinely carried out at specified frequencies (yearly/twice yearly etc.). These normally look at the road condition and attempt to classify problems such as cracking, deformation, rutting, potholing, etc. by degree and extent in order to prioritise and budget for follow-up maintenance operations. Generally, the current protocol only requires the road carriageway area to be assessed. Similar assessments for Bridge Management Systems are also carried out in certain countries, and these are mostly related to the planning and management of maintenance and repair of structures (including bridges and culverts). It is, however, necessary to add to this information to provide the required inputs for climate resilience assessments and the implementation of appropriate adaptation techniques to improve the climate resilience of the infrastructure (Paige-Green *et al.*, 2019).

Aim:

The aim of this phase is therefore to conduct a local-level climate-sensitive visual assessment of the road network that accommodates the entry of socio-economic and environmental data.

General recommendations for this phase:

- In regions where only a basic assessment can be undertaken initially, the goal should be to improve data collection with the aim of improving the quality and quantity of subsequent assessments.
- Consult the Engineering Adaptation Guidelines (Paige-Green *et al.*, 2019) and the Visual Assessment Manual (Paige-Green & Verhaeghe, 2019) where the climate-sensitive visual assessment is explained at length.

Step 2.1: Capture data through fieldwork and community participatory mapping

Typically, during field surveys, road engineers or assessors collect data that are warehoused in the RAMS. Roads within a network are assessed in segments and any structural defects, as well as the overall condition of each road segment, are noted. Consideration of climate impacts on the road requires a different kind of field assessment than the standard road condition assessment because environmental and socio-economic factors beyond the road reserve need to be considered.

An example of a field assessment form that accommodates the entry of environmental data is the climate-sensitive visual assessment form (Figure 13), which is explained at length in the Engineering Adaptation Guidelines (Paige-Green *et al.*, 2019) and in the Visual Assessment Manual (Paige-Green & Verhaeghe, 2019). In addition to road and asset condition, data about prevalent weather conditions, topography and land cover and use (highlighted in red, Figure 13) can be collected using this form. The explanation of these assessment fields is provided in Table 6, and further detailed descriptions are provided in the Visual Assessment Manual (Paige-Green *et al.,* 2019).

Table 6 Explanation of data capture fields on the climate-sensitive field assessment form

Weather	
Description of prevailing weather conditions at the time of assessment	
S	Sunny
PC	Partly cloudy
C	Cloudy
R	Rainy
H	Hail
Cold	Cold

Topography	
F	Flat
R	Rolling or gentle slopes
H	Hilly
M	Mountainous

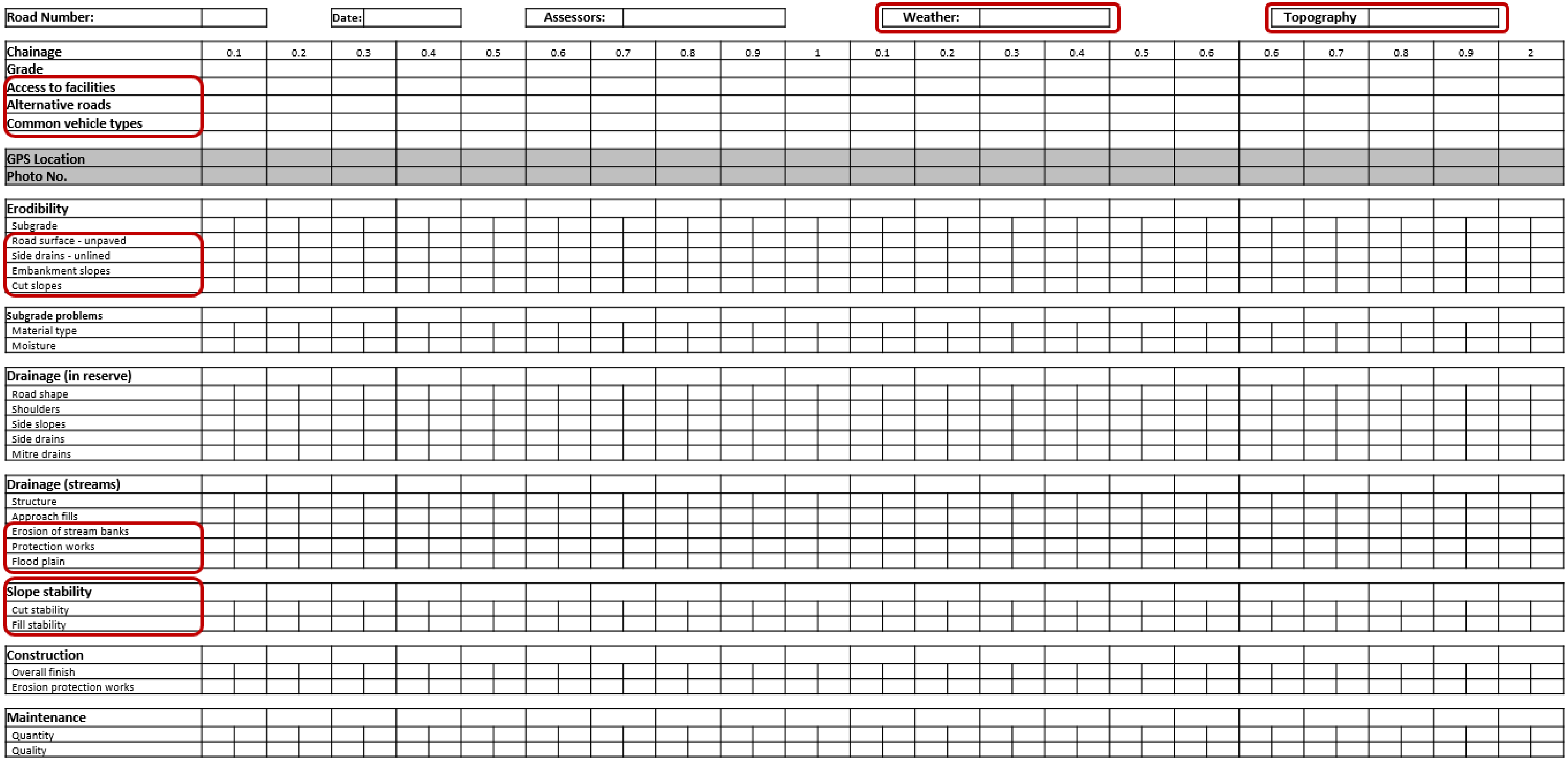
Land cover	
A	Agricultural lands
F	Forests
N	Natural landscape or grasslands
PU	Peri-urban/Urban
D	Degraded land
O	Other

In conducting a climate-sensitive road assessment, assessors can obtain information from members of the surrounding communities about historical disasters, incidences of impassibility and disruptions in accessibility, access to facilities provided by the road, and the availability and conduction of alternative routes (including travel-time implications). Communities are therefore an important source of local information on historical and current climate disasters, climate patterns, the topography, the location of water bodies and incidences of climate-related road closures. They can also give an indication of the impact on access to markets, health and education facilities, based on the expert knowledge they have about their own environment. Several methods are used to collect data from communities. In the case of road vulnerability assessment, spatial data collection methods (i.e. community participatory mapping (CPM) methods) are recommended (Forrester & Cinderby, 2011). CPM, as a means to document indigenous knowledge, is a useful source of information, especially when triangulated with independent knowledge. CPM methods such as the transect walk (World Bank, 2008) consider local residents as experts in terms of knowledge of their immediate environment and, through community mapping exercises, this information is captured spatially for further processing and visualisation by using GIS.

Integrated Approaches to Participatory Development (IAPAD) is a knowledge hub focused on sharing information on participatory mapping methodologies and processes (Last accessed August 2019, http://www.iapad.org).

In addition to community engagement and knowledge acquisition, road construction records give an indication of the quality of compaction, which is important when considering the risk of deformation. Material type and moisture content are important variables to consider as they are indicators of volumetric changes in response to climatic conditions.

By highlighting fields on the climate-sensitive visual assessment form that are relevant when considering climatic and environmental risks to rural access roads according to the Engineering Adaptation Guidelines (Paige-Green *et al.*, 2019), the assessor using the climate-sensitive visual assessment form would score each item out of five (0 being not applicable; 1–2 being acceptable and 4–5 being areas of concern). The scoring is done per 100 m segment. The form itself can be used by the engineers to make decisions regarding areas that need urgent intervention. However, for decisions about the roads to prioritise for climate adaptation, a network-wide view is necessary. Therefore, it is essential that the data captured in these forms is stored in a RAMS for easy extraction when local road vulnerability assessments (Phase 3) are performed.



Road Number:

Date:

Assessors:

Weather:

Topography

Chainage	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1	0.1	0.2	0.3	0.4	0.5	0.6	0.6	0.7	0.8	0.9	2
Grade																					
Access to facilities																					
Alternative roads																					
Common vehicle types																					
GPS Location																					
Photo No.																					
Erodibility																					
Subgrade																					
Road surface - unpaved																					
Side drains - unlined																					
Embankment slopes																					
Cut slopes																					
Subgrade problems																					
Material type																					
Moisture																					
Drainage (in reserve)																					
Road shape																					
Shoulders																					
Side slopes																					
Side drains																					
Mitre drains																					
Drainage (streams)																					
Structure																					
Approach fills																					
Erosion of stream banks																					
Protection works																					
Flood plain																					
Slope stability																					
Cut stability																					
Fill stability																					
Construction																					
Overall finish																					
Erosion protection works																					
Maintenance																					
Quantity																					
Quality																					

Figure 13 Road climate-sensitive visual assessment form highlighting those fields on that are most relevant when considering climate and environmental risks to rural access roads

Phase 3: Climate-sensitive road vulnerability analysis

Aim:

The objective in this phase is to analyse the data that were collected from the climate-sensitive visual assessment undertaken in Phase 2 to methodically provide insights about sections of the road that are prone to different road condition and maintenance deficiencies. It also aims to understand road criticality in terms of the socio-economic functions of the road in order to identify sections of the road most at risk from climate impacts. The output of this phase is the computation of a Road Vulnerability Index (RVI), calculated firstly per 100 m assessment segment and secondly for the entire road section, from node to node in the RAMS.

Step 3.1: Assess road condition deficiency

Aim:

The aim of this step is to conduct a road condition deficiency assessment, the output of which is the calculation of a Road Condition Deficiency Score (Di Score). Information on the variability of vulnerability to specific risks along the road helps in deciding where to implement specific engineering adaptation options and where changes in land-use practices may help to reduce the extent of damage resulting from adverse climate events. The vulnerability of road infrastructure to the following climate hazards is considered:

- Erosion of embankments and foundations
- Loss of pavement integrity through cracking and/or aggregate loss
- Flooding of the road surface due to drainage failure
- Deformations resulting from subgrade material and moisture defects
- Deficiencies in slope stability

The inputs required to calculate the Di score are obtained by way of the climate-sensitive field assessment (conducted during Phase 2). The road condition deficiency aspects and specific elements informing each deficiency aspect assessed are summarised in Table 7.

Table 7 Aspects and elements evaluated during condition deficiency assessment

		Elements
Aspects	**Erodibility**	Subgrade
		Road surface – unpaved
		Side drains – unlined
		Embankment slopes
		Cut slopes
	Drainage (streams)	Structure
		Approach fills
		Erosion of approach fills
		Protection works
		Flood plain
	Subgrade problems	Material type
		Moisture
	Slope stability	Cut stability
		Fill stability
	Drainage (in reserve)	Road shape
		Shoulders
		Side slopes
		Side drains
		Mitre drains
	Construction	Overall finish
		Erosion protection works

Recommendations:

Transforming defect elements

During the field assessment, the assessor evaluates each element in terms of severity and extent. These two dimensions are explained in Tables 8 and 9 respectively, as well as in the Visual Assessment Manual (Paige-Green & Verhaeghe, 2019). For each 100 m road segment, the whole range of aspects and elements listed in Table 7 would have been assessed and rated in terms of severity and extent during the climate-sensitive field assessment.

The first step in the calculation of the Di score is to combine the severity and extent ratings for each element into a single rating using the following rating/scoring rules (Figure 13):

- Any road segment with a severity rating of 5 needs urgent attention. In particular, it needs reconstruction and adaptation for improved resilience to climate hazards.
- For severity ratings from 1-4, the combined rating is the uniform geometric mean, which in this case is the square root of the product of severity and extent. The use of the geometric mean corresponds to the multiplicative nature of severity and extent in the context of deficiencies or damage.

Table 8 Description and rating values for the severity dimension

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 primary defect is extremely severe. Adaptation measures should be implemented immediately. Usually requires reconstruction.	5

Table 9 Description and rating values for the extent dimension

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

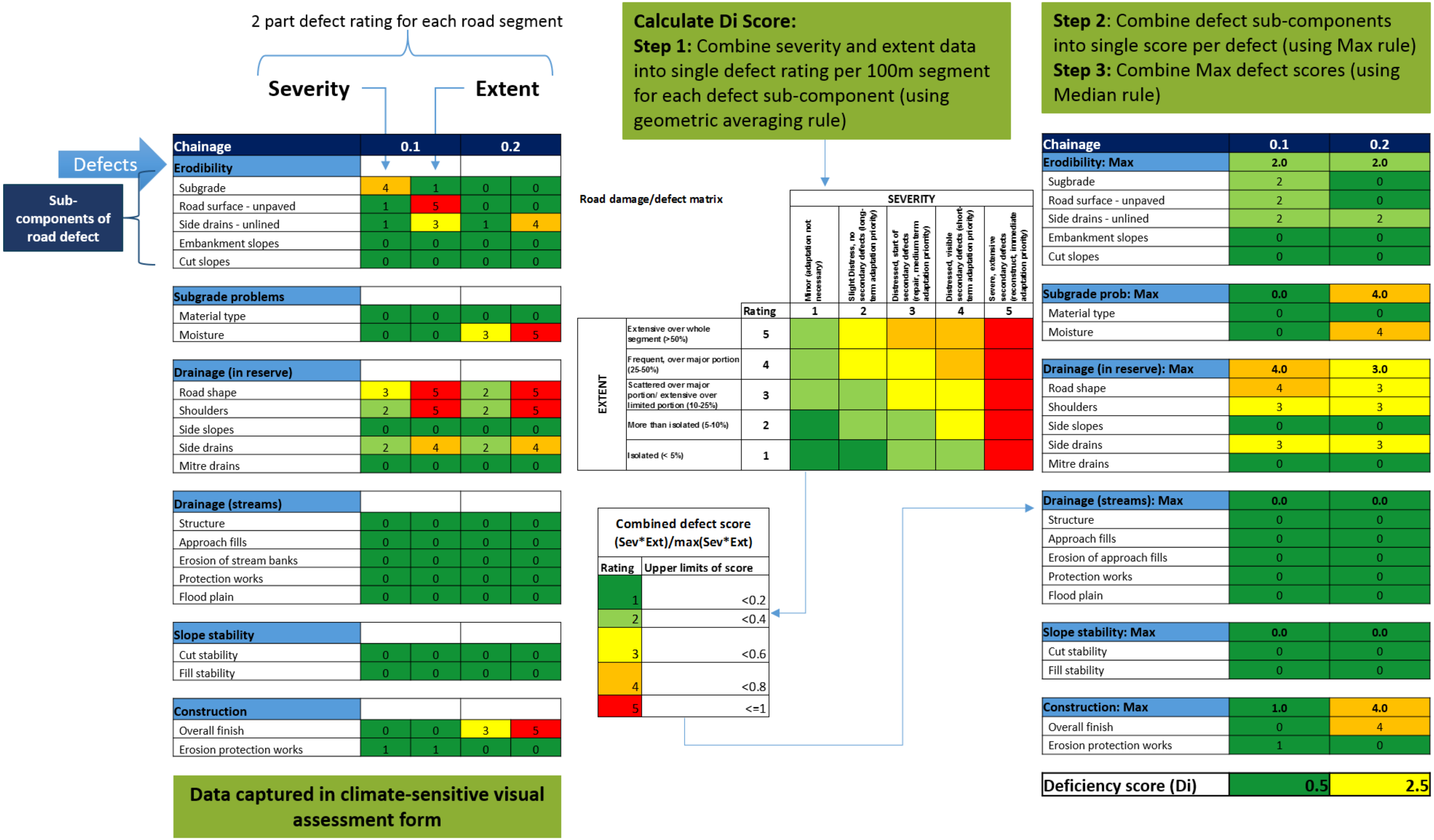
Aggregating defect element ratings

The next step in the calculation of the Di score is to aggregate the individual element ratings (now a single value – the combined value of the geometric mean of severity and extent) into a single aspect rating for each deficiency aspect. For example, the combined ratings for the elements of the erodibility aspect (i.e. subgrade; road surface – unpaved; side drains – unlined; embankment slopes; cut slopes) are aggregated to arrive at a single 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.

Figure 14 shows three aspect scores for erodibility using the maximum, arithmetic mean and the median functions to illustrate the effect of using the different functions, evaluating in particular whether the resulting scores are representative of the patterns observed at the defect level. Arithmetic averaging results in dilution or over-smoothing, whereas the median is biased towards the most frequently occurring values (zero in this case) and is insensitive to the presence of a small number of serious defects.

Calculate Di score

The final step is to calculate the Di score for each 100 m 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.



Chainage	0.1		0.2	
Erodibility				
Subgrade	4	1	0	0
Road surface - unpaved	1	5	0	0
Side drains - unlined	1	3	1	4
Embankment slopes	0	0	0	0
Cut slopes	0	0	0	0
Subgrade problems				
Material type	0	0	0	0
Moisture	0	0	3	5
Drainage (in reserve)				
Road shape	3	5	2	5
Shoulders	2	5	2	5
Side slopes	0	0	0	0
Side drains	2	4	2	4
Mitre drains	0	0	0	0
Drainage (streams)				
Structure	0	0	0	0
Approach fills	0	0	0	0
Erosion of stream banks	0	0	0	0
Protection works	0	0	0	0
Flood plain	0	0	0	0
Slope stability				
Cut stability	0	0	0	0
Fill stability	0	0	0	0
Construction				
Overall finish	0	0	3	5
Erosion protection works	1	1	0	0

Data captured in climate-sensitive visual assessment form

Calculate Di Score:
Step 1: Combine severity and extent data into single defect rating per 100m segment for each defect sub-component (using geometric averaging rule)

Road damage/defect matrix

			SEVERITY				
			Minor (adaptation not necessary)	Slight Distress, no secondary defects (long-term adaptation priority)	Distressed, start of secondary defects (repair, medium term adaptation priority)	Distressed, visible secondary defects (short-term adaptation priority)	Severe, extensive secondary defects (reconstruct, immediate adaptation priority)
		Rating	1	2	3	4	5
EXTENT	Extensive over whole segment (>50%)	5	🟢	🟨	🟧	🟧	🟥
	Frequent, over major portion (25-50%)	4	🟢	🟨	🟨	🟧	🟥
	Scattered over major portion/ extensive over limited portion (10-25%)	3	🟢	🟢	🟨	🟨	🟥
	More than isolated (5-10%)	2	🟩	🟢	🟢	🟨	🟥
	Isolated (< 5%)	1	🟩	🟩	🟢	🟢	🟥

Combined defect score (Sev*Ext)/max(Sev*Ext)

Rating	Upper limits of score
1	<0.2
2	<0.4
3	<0.6
4	<0.8
5	<=1

Step 2: Combine defect sub-components into single score per defect (using Max rule)
Step 3: Combine Max defect scores (using Median rule)

Chainage	0.1	0.2
Erodibility: Max	**2.0**	**2.0**
Sugbrade	2	0
Road surface - unpaved	2	0
Side drains - unlined	2	2
Embankment slopes	0	0
Cut slopes	0	0
Subgrade prob: Max	**0.0**	**4.0**
Material type	0	0
Moisture	0	4
Drainage (in reserve): Max	**4.0**	**3.0**
Road shape	4	3
Shoulders	3	3
Side slopes	0	0
Side drains	3	3
Mitre drains	0	0
Drainage (streams): Max	**0.0**	**0.0**
Structure	0	0
Approach fills	0	0
Erosion of approach fills	0	0
Protection works	0	0
Flood plain	0	0
Slope stability: Max	**0.0**	**0.0**
Cut stability	0	0
Fill stability	0	0
Construction: Max	**1.0**	**4.0**
Overall finish	0	4
Erosion protection works	1	0
Deficiency score (Di)	**0.5**	**2.5**

Figure 14 Worked example calculating road deficiency (Di) score for two 100m road segments

Step 3.2: Assess road maintenance

Maintenance is considered independently from the aspects included in the Deficiency (Di) Score 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. Furthermore, maintenance regimes are shaped by the availability of resources, as well as by differences in policy planning and implementation practices and therefore they are an important change management consideration. Separating maintenance from structural deficiency also enables exploration of the effect of different types of maintenance regimes, which is useful in strategic planning for the future. In most developing countries, particularly in Africa, budgets are often insufficient for the levels of maintenance required; therefore this indicator is expected to be high (ratings of 4 or 5) for most rural roads.

Aim:
The aim of this step is to conduct a road maintenance assessment, the output of which is the calculation of a Road Maintenance (Mn) Score.

Recommendations:
Like the road condition deficiency assessment, the inputs required to calculate the Mn score are obtained by way of the climate-sensitive field assessment (Phase 2). The elements of road maintenance that need to be assessed are maintenance quality and quantity (frequency) (see Table 10).

Table 10 Aspects and elements evaluated during the road maintenance assessment

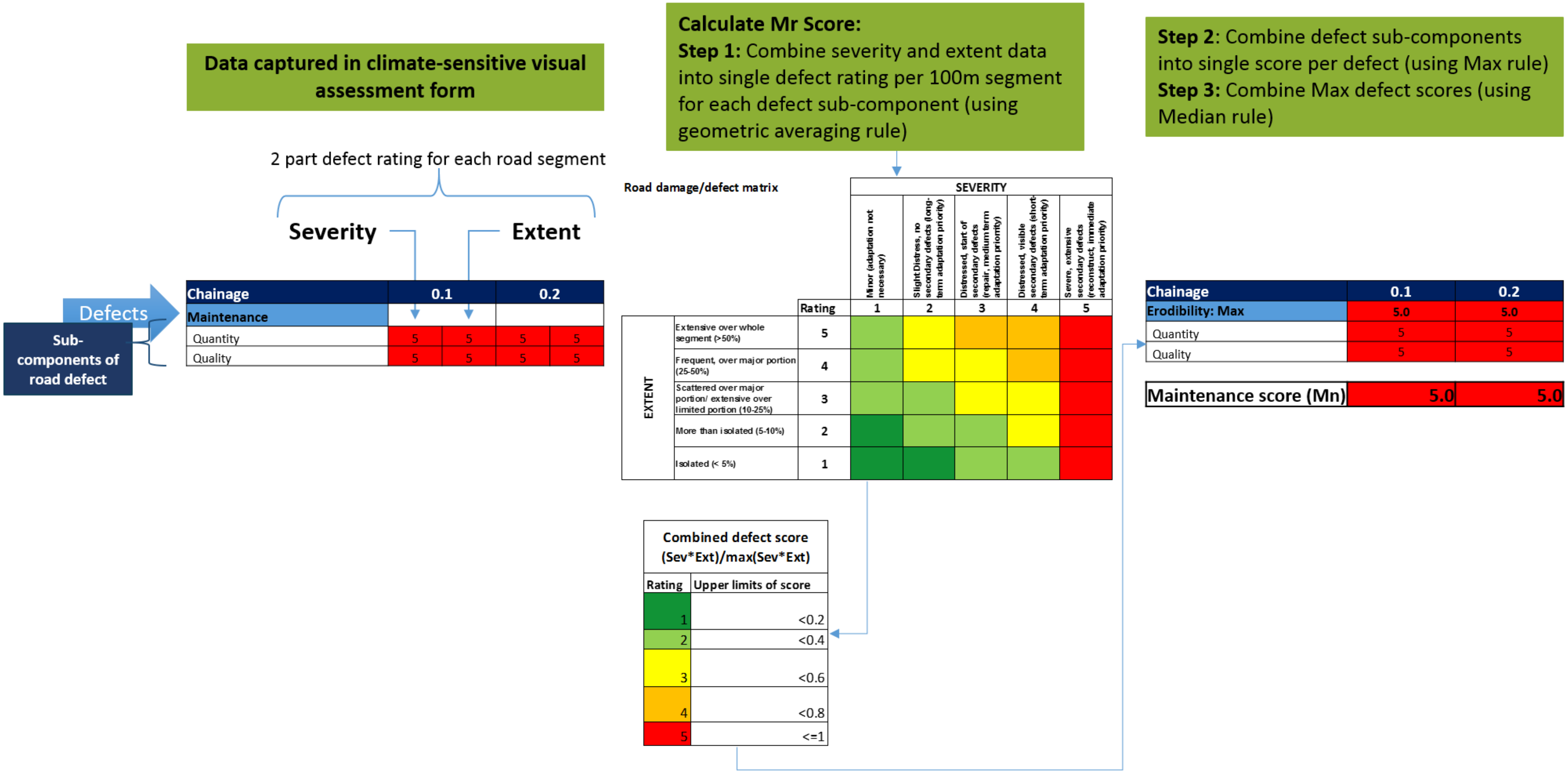
		Elements
Aspect	Maintenance	Quality
		Quantity (Frequency)

Maintenance is rated in terms of quality (not severity) and quantity. 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.

To calculate the Mn score, a similar process as explained under Step 3.1 is followed:

Aggregating maintenance element ratings
The first step in the calculation of the Mn score is to combine the severity and extent ratings for quality and quantity into a single rating for each element using geometric averaging. The combined rating is the uniform geometric mean (the square root of the product of severity and extent).

Calculate Mn score
The next step in the calculation of the Mn score to aggregate the combined element ratings into a single maintenance aspect rating. For example, the combined ratings for the elements of maintenance quality and quantity are aggregated to arrive at a single rating for the maintenance 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.



Data captured in climate-sensitive visual assessment form

Chainage	0.1		0.2	
Maintenance				
Quantity	5	5	5	5
Quality	5	5	5	5

Calculate Mr Score:
Step 1: Combine severity and extent data into single defect rating per 100m segment for each defect sub-component (using geometric averaging rule)

Road damage/defect matrix

			SEVERITY				
			Minor (adaptation not necessary)	Slight Distress, no secondary defects (long-term adaptation priority)	Distressed, start of secondary defects (repair, medium term adaptation priority)	Distressed, visible secondary defects (short-term adaptation priority)	Severe, extensive secondary defects (reconstruct, immediate adaptation priority)
		Rating	1	2	3	4	5
EXTENT	Extensive over whole segment (>50%)	5	🟩	🟨	🟧	🟧	🟥
	Frequent, over major portion (25-50%)	4	🟩	🟨	🟨	🟧	🟥
	Scattered over major portion/ extensive over limited portion (10-25%)	3	🟩	🟩	🟨	🟨	🟥
	More than isolated (5-10%)	2	🟩	🟩	🟩	🟨	🟥
	Isolated (< 5%)	1	🟩	🟩	🟩	🟩	🟥

Combined defect score (Sev*Ext)/max(Sev*Ext)	
Rating	Upper limits of score
1	<0.2
2	<0.4
3	<0.6
4	<0.8
5	<=1

Step 2: Combine defect sub-components into single score per defect (using Max rule)
Step 3: Combine Max defect scores (using Median rule)

Chainage	0.1	0.2
Erodibility: Max	5.0	5.0
Quantity	5	5
Quality	5	5

Maintenance score (Mn)	5.0	5.0

Figure 15 **Worked example calculating maintenance (Mn) score for two 100m road segments**

Step 3.3: Road criticality assessment (based on rural accessibility)

Road criticality pertains to the importance of a particular road and considers the public facilities reached by the road, the number of alternative routes available (including the condition of alternative routes and travel time/distance added) and the predominant vehicle types on the road. Land use/cover is considered as a contextual variable, but it is not explicitly included in the criticality assessment. 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 climatic events.

Aim:

The aim of this step is to conduct a road criticality assessment, the output of which is the calculation of a Road Criticality (Cr) Score.

Recommendations:

The following aspects are considered in the calculation of the Cr score:

- Number of alternative routes available
- Predominant vehicle types on this road
- Public facilities reached by this road

For each 100 m section, each of these three aspects is rated on a scale from 1 to 5, using a set of scoring rules as presented in Tables 11 to 13.

Number of alternative routes available

For the local vulnerability assessment, the availability of alternative routes is assessed. The availability of an alternative route is important, especially to prevent the loss of lives in emergency situations and to maintain connectivity during periods when a particular access road becomes impassable. Criteria for rating criticality in terms of the number of alternative routes available are shown in Tables 11 and 12. When there are no alternative routes, the road is classified as critical (Table 11), while in the case of a road with one or more alternative routes, criticality is determined based on the road condition of such alternative route and the additional travel distance added (Table 12).

Table 11 Criticality rating for no alternative routes

Number of alternative routes	Rating
0	5
>= 1	Refer to Table 12

Table 12 Criticality rating for the availability of alternative routes

Rating Matrix	Road condition of the alternative route		
Additional travel distance added	Good	Moderate	Poor
<= 15km	1	2	3
<= 25km	2	3	4
<= 50km	3	4	5
<= 75km	4	5	5
>= 100km	5	5	5

Predominant vehicle types on this road

Another aspect of criticality that needs to be assessed is the type of traffic that is common on a particular road by giving an indication of the dominant traffic type (largest vehicle) using the road. It is common to consider the predominant vehicle types on a road when assessing performance against serviceability standards. In this case, common vehicle type is considered from the perspective of rural access roads as enablers of access. Criteria for rating criticality in terms of the predominant vehicle types using a road are shown in Table 13. These criteria pertain to the type of goods being transported, their respective destinations, the particular class of vehicle typically used, as well as the expected impact such vehicles would have on roads.

Table 13 Criticality rating for the common vehicle types using the road

Common vehicle types	Rating	Reasoning: Importance of access and impact on road
Trucks/Buses (over 3 tonnes)	5	Transport of goods to intra-/inter-regional markets/ growth centres Heavy loads – greater impact on road condition
Light Utility Vehicles	4	Transport of goods to local market/s Moderate loads
Cars	3	Transport of people for work or other social reasons Moderate impact on the road if traffic is more than expected
Carts	2	Transport of goods within or between villages Less than moderate – heavier loads may be seasonal (harvest)
Bicycles/Motorcycles	1	Local travel Light load – least impact on road condition

Public facilities reached by this road

Rural areas should have connections to the larger region, namely other villages and markets/towns (Taylor, 2017). Another variable that is considered when evaluating criticality is therefore the access to public facilities and to markets that a road provides. The latter can be interpreted as places where goods can be traded or employment centres that facilitate improved living standards and nodes that strengthen the regional economy. Criteria for rating criticality in terms of the public facilities reached by this road are shown in Table 14. For the rating criteria, the order of the socio-economic functionality of the focal points was considered by integrating human development objectives with the size of the population that benefits from the services (CSIR, 2000; Monzur Md Sadeque *et al.*, 2017).

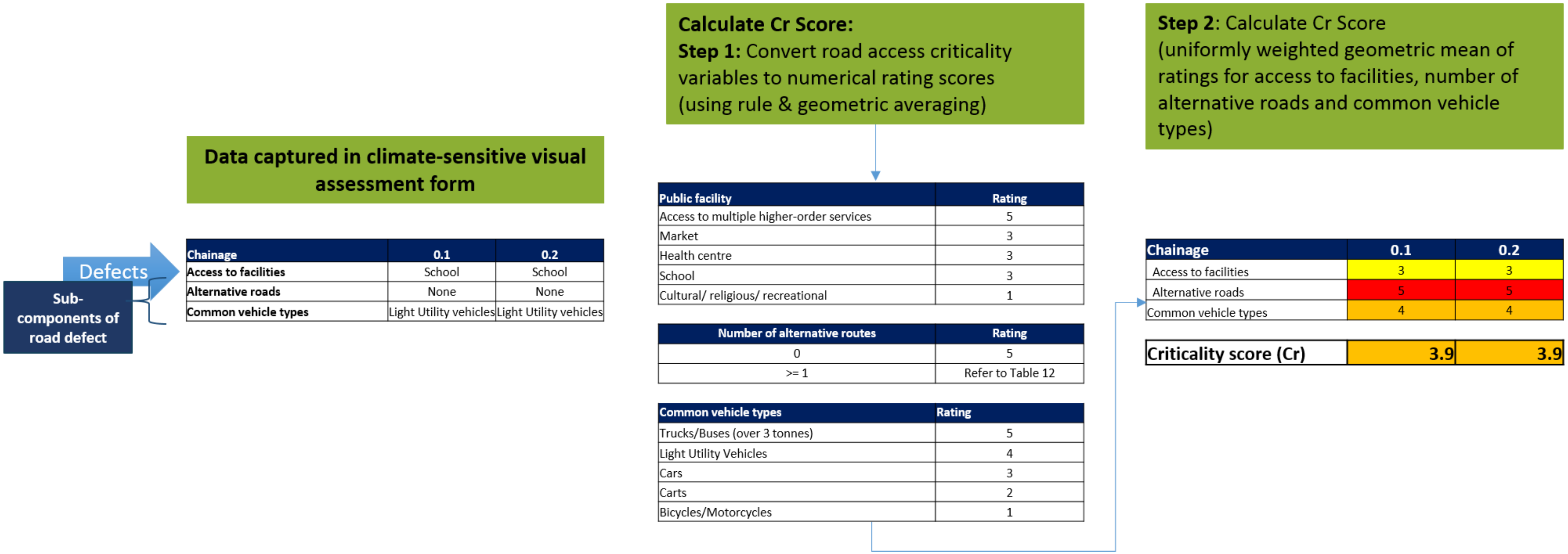
Table 14 Criticality rating for the public facilities reached by this road

Public facility	Rating	Criteria	Reasoning
Access to multiple higher-order services	5	Combination of cultural and higher-order facilities	Roads are critical to improving the livelihoods of rural communities
Market	3	Economic productivity and development	Stimulation of rural economic participation and growth through access to markets for trading goods, jobs and social welfare services
Health centre	3	Safety and improved quality of life	Reduced mortality and morbidity Disease prevention
School	3	Investment in improved socio-economic outcomes	Investment in the next generation's ability to be economically active Schools can also serve as emergency stations

Public facility	Rating	Criteria	Reasoning
Cultural/ religious/ recreational	1	Community development	Cultural, religious or recreational facilities, e.g. church or community hall

Calculate Road Criticality (Cr) Score

The Cr score is calculated as the uniformly weighted geometric mean of the ratings for these three aspects (number of alternative routes available, predominant vehicle types on this road and public facilities reached by this road), calculated for each 100 m assessment segment.



Data captured in climate-sensitive visual assessment form

Chainage	**0.1**	**0.2**
Access to facilities	School	School
Alternative roads	None	None
Common vehicle types	Light Utility vehicles	Light Utility vehicles

Calculate Cr Score:
Step 1: Convert road access criticality variables to numerical rating scores (using rule & geometric averaging)

Public facility	**Rating**
Access to multiple higher-order services	5
Market	3
Health centre	3
School	3
Cultural/ religious/ recreational	1

Number of alternative routes	**Rating**
0	5
>= 1	Refer to Table 12

Common vehicle types	**Rating**
Trucks/Buses (over 3 tonnes)	5
Light Utility Vehicles	4
Cars	3
Carts	2
Bicycles/Motorcycles	1

Step 2: Calculate Cr Score (uniformly weighted geometric mean of ratings for access to facilities, number of alternative roads and common vehicle types)

Chainage	**0.1**	**0.2**
Access to facilities	3	3
Alternative roads	5	5
Common vehicle types	4	4

Criticality score (Cr)	3.9	3.9

Figure 16 **Worked example calculating criticality (Cr) score for two 100m road segments**

Step 3.4: Calculate road vulnerability index

The outcome of the local climate vulnerability assessment is a multi-dimensional road vulnerability index (RVI). The RVI illustrated in Figure 17 integrates three composite indicators, namely an indicator of road condition deficiency to the impacts of climate (the Di score), an indicator of maintenance efficacy (the Mn score), and an indicator of the criticality of the road (the Cr score). Figures 18 – 20 practically illustrate how RVI and its three contributing components are calculated using Excel spreadsheet functionality. This can however also be done more efficiently in an object-orientated database such as a RAMS, should data need to be captured on a large scale, i.e. for substantial sections of the national road network as is recommended for the mainstreaming of climate adaptation in the rural roads sector.

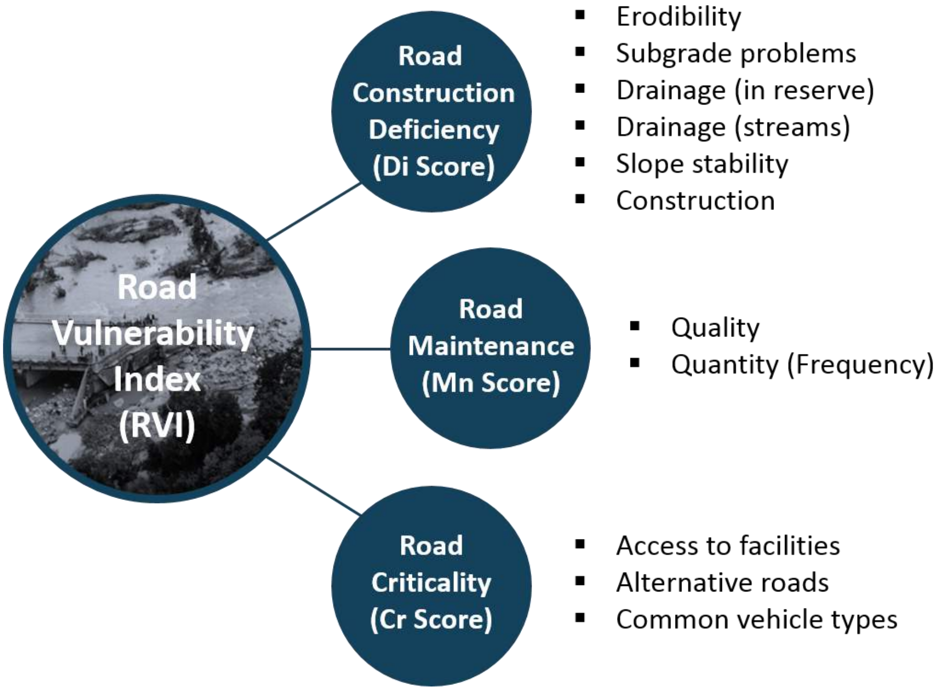


Figure 17 The rural road vulnerability index integrates three dimensions: road condition deficiency, maintenance and criticality

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.

Road Maintenance factor is an indicator of maintenance efficacy in terms of frequency (quantity) and quality of maintenance activities.

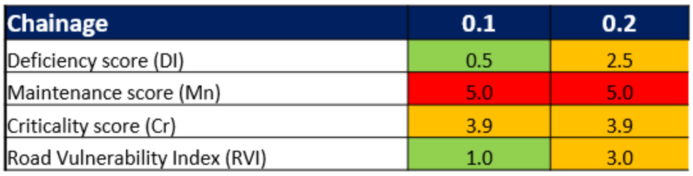
Road criticality pertains to the importance of that particular road for access to markets and public facilities. On a local scale, a narrative about the community’s use of a particular road is important to put into perspective the losses incurred by the community when access is interrupted due to climate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

For the **current situation, vulnerability** is calculated as follows:

- Calculate the Deficiency Score (Di) as the median of the erodibility, drainage, subgrade, slope stability and construction quality aspect scores. Recall that the aspect scores were calculated as maxima of the element values for that aspect.
- Calculate the Maintenance Score (Mn) as the maximum of the quantity and quality aspect scores.
- Calculate the Criticality Score (Cr) as the geometric average of ratings for the following variables: rating for the number of alternative routes available, rating for the predominant vehicle types using the road and the rating for the public facilities reached by the road.
- 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 aggregate deficiency (Di), maintenance (Mn) and criticality (Cr) scores as follows:

$$\mathbf{RVI = Di^a \times Mn^b \times Cr^c}$$

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



Chainage	0.1	0.2
Deficiency score (DI)	0.5	2.5
Maintenance score (Mn)	5.0	5.0
Criticality score (Cr)	3.9	3.9
Road Vulnerability Index (RVI)	1.0	3.0

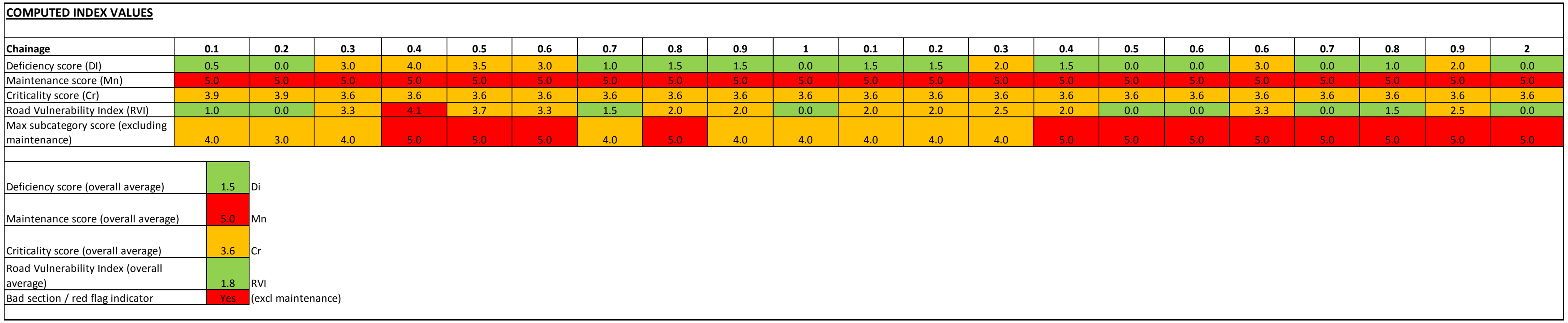
Figure 18 **Worked example calculating Road Vulnerability Index (RVI) for two 100m road segments**

ROAD RESILIENCE FIELD ASSESSMENT DATA AND ROAD CRITICALITY DATA

Road Number:	A002	**Date:**	**03/04/2019**	**Assessors:**	XY & ZA	**Weather:**	**Sunny & Hot**	**Topography**	**Rolling**						

Chainage	0.1		0.2		0.3		0.4		0.5		0.6		0.7		0.8		0.9		1		0.1		0.2		0.3		0.4		0.5		0.6		0.6		0.7		0.8		0.9		2	
Grade	Flat		Flat		Flat		Flat		Medium downhill		Medium downhill		Flat		Medium downhill		Medium downhill		Flat embankment		Flat embankment		Flat embankment		Flat embankment		Flat embankment		Bridge		Flat		Medium uphill		Medium uphill		Medium uphill		Medium uphill		Gentle uphill	
Access to facilities	School		School		School		School		School		School		School		School		School		School		School		School		School		School		School		School		School		School		School		School		School	
Alternative roads	None		None		None		None		None		None		None		None		None		None		None		None		None		None		None		None		None		None		None		None		None	
Common vehicle types	Light Utility vehicles		Light Utility vehicles		Motor Cars		Motor Cars		Motor Cars		Motor Cars		Motor Cars		Motor Cars		Motor Cars		Motor Cars		Motor Cars		Motor Cars		Motor Cars		Motor Cars		Motor Cars		Motor Cars		Motor Cars		Motor Cars		Motor Cars		Motor Cars		Motor Cars	
Land-cover / land-use	PU		PU		PU		PU		PU		PU		PU		PU		PU		PU		F		F		D		PU		PU		PU		PU		PU		PU		PU		PU	
	Peri-Urban/Urban		Peri-Urban/Urban		Peri-Urban/Urban		Peri-Urban/Urban		Peri-Urban/Urban		Peri-Urban/Urban		Peri-Urban/Urban		Peri-Urban/Urban		Peri-Urban/Urban		Peri-Urban/Urban		Forest/Dense vegetation		Forest/Dense vegetation		Degraded land		Peri-Urban/Urban		Peri-Urban/Urban		Peri-Urban/Urban		Peri-Urban/Urban		Peri-Urban/Urban		Peri-Urban/Urban		Peri-Urban/Urban		Peri-Urban/Urban	
GPS Location	1 33.21467S 29.01752W																												33.2145S 29.0199W													
Photo No.									335-338						339				240-342										343-345				346									
Erodibility																																										
Subgrade	4	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	5	2	5	2	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Road surface - unpaved	1	5	0	0	2	2	2	2	2	2	2	2	2	3	3	3	3	3	1	2	0	0	0	0	0	0	0	0	0	0	0	0	3	3	3	2	3	1	1	1	0	0
Side drains - unlined	1	3	1	4	1	4	1	4	0	0	0	0	0	0	3	4	3	4	0		0	0	0	0	0	0	0	0	0	0	0	0	5	3	5	4	5	3	5	3	5	3
Embankment slopes	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	3	3	3	4	3	0	0	3	3	0	0	0	0	0	0	0	0	0	0
Cut slopes	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	3	5	3	5	4
Subgrade problems																																										
Material type	0	0	0	0	0	0	0	0	5	5	5	5	0	0	0	0	0	0	0	0	0	0	0	0	4	4	4	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Moisture	0	0	0	0	3	5	3	5	4	5	4	5	0	0	0	0	0	0	0	0	3	5	3	5	4	5	4	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Drainage (in reserve)																																										
Road shape	3	5	2	5	3	5	3	5	3	5	3	5	3	5	3	5	3	5	4	5	4	5	4	5	4	5	5	5	5	5	5	5	3	5	3	5	3	5	3	5	3	5
Shoulders	2	5	2	5	3	5	3	5	3	5	3	5	3	5	3	5	4	5	4	5	4	5	4	5	4	5	5	5	5	5	5	5	3	5	3	5	3	5	3	5	3	5
Side slopes	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	2	2	2	2	2	2	2	2	2	2	2	0	0	0	0	0	0	0	0	0	0
Side drains	2	4	2	4	3	4	3	4	2	3	2	3	2	3	2	4	2	4	4	5	4	5	4	5	4	5	4	5	0		4	5	2	1	2	1	2	1	0	0	0	0
Mitre drains	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Drainage (streams)																																										
Structure	0	0	0	0	0	0	2	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	3	3	0	0	0	0	0	0	0	0
Approach fills	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Erosion of stream banks	0	0	0	0	0	0	3	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Protection works	0	0	0	0	0	0	5	2	4	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	3	0	0	0	0	0	0	0	0
Flood plain	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Slope stability																																										
Cut stability	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Fill stability	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	1	5	3	0	0
Construction																																										
Overall finish	0	0	0	0	3	5	3	5	3	5	3	5	3	5	3	5	3	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Erosion protection works	1	1	0	0	0	0	0	0	0	0	0	0	2	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	3	0	0	0	0	0	0	0	0
Maintenance																																										
Quantity	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
Quality	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
COMMENTS:																																										
							2 side drains								Road width decreases-ing				Potholes and ruts														Culvert with broken wing and headwalls									

Figure 19 Example of completed climate-sensitive visual assessment data capture sheet



COMPUTED INDEX VALUES

Chainage	**0.1**	**0.2**	**0.3**	**0.4**	**0.5**	**0.6**	**0.7**	**0.8**	**0.9**	**1**	**0.1**	**0.2**	**0.3**	**0.4**	**0.5**	**0.6**	**0.6**	**0.7**	**0.8**	**0.9**	**2**
Deficiency score (DI)	0.5	0.0	3.0	4.0	3.5	3.0	1.0	1.5	1.5	0.0	1.5	1.5	2.0	1.5	0.0	0.0	3.0	0.0	1.0	2.0	0.0
Maintenance score (Mn)	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
Criticality score (Cr)	3.9	3.9	3.6	3.6	3.6	3.6	3.6	3.6	3.6	3.6	3.6	3.6	3.6	3.6	3.6	3.6	3.6	3.6	3.6	3.6	3.6
Road Vulnerability Index (RVI)	1.0	0.0	3.3	4.1	3.7	3.3	1.5	2.0	2.0	0.0	2.0	2.0	2.5	2.0	0.0	0.0	3.3	0.0	1.5	2.5	0.0
Max subcategory score (excluding maintenance)	4.0	3.0	4.0	5.0	5.0	5.0	4.0	5.0	4.0	4.0	4.0	4.0	4.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0

Deficiency score (overall average)	1.5	Di
Maintenance score (overall average)	5.0	Mn
Criticality score (overall average)	3.6	Cr
Road Vulnerability Index (overall average)	1.8	RVI
Bad section / red flag indicator	Yes	(excl maintenance)

Figure 20 Computed index values for each 100m road segment, as well as single Road Vulnerability Index calculated (averages) for the entire road section

For a future vulnerability scenario, taking into account climate and population change, the RVI can be modified multiplicatively based on scenario modifications in the deficiency, maintenance and criticality scores. The scenario approach is preferable, as one can choose for example the low, median and high population growth to account for uncertainty in population projections and therefore derive criticality scores corresponding to the different growth trajectories. Similarly, in the case of climate change, there is a choice of using the output from an ensemble of climate simulation models and in that way incorporating the uncertainty associated with climate projections into the deficiency and maintenance indicators. It is recommended that scenarios for climate and population change be limited to three as this already results in nine permutations for the RVI.

For each permutation of climate and population changes re-assessment of road vulnerability is as follows:

- The deficiency factors are individually adjusted based on a grading framework as follows:
  - Increase in vulnerability (+1)
  - No increase in vulnerability (0)
  - Decrease in vulnerability (-1)
- For example, if as a result of climate change the return period for a design rainfall event is shortened where the road is located, then an increase in *vulnerability to flooding* is expected; hence the drainage score would need to be increased (+1).
- The vulnerability grading scheme also applies to possibilities considered regarding the implementation of maintenance procedures.
- Adjustment of the criticality score should be based on plans for new public facilities and emerging growth centres from the population projections.
  - Increasing criticality (+1) can be based on the combination of population growth and increases in higher-order social facilities.
  - No change in criticality can be associated with areas of low population growth.
  - Decrease in criticality (-1) would be characterised by areas of rapid population decline.
- The lower and upper limits in the scenario analysis – using both the vulnerability and criticality grading – are 0 and 5. This means that if in the current situation erodibility for a particular road segment is 5 and it is projected that the area will become more vulnerable to erosion due to climate change, the erodibility score would remain 5.
- Once adjustments pertaining to each permutation of climate and population change have been made, the aggregate deficiency, maintenance and criticality scores can be calculated and then geometrically averaged to get the vulnerability index. If there were nine permutations, there will be nine indices that can be mapped to assess difference and communicate with the stakeholders.

Phase 4: Embedment into the road asset management system (RAMS)

Aim:

The recommended way to incorporate climate change as a risk in a RAMS is to embed the data captured from the climate-sensitive visual assessment as well as from the local-level vulnerability assessments and indicators quantified during Phase 3 into the RAMS of road authorities. In this way, climate change can be considered as a risk when using data from the RAMS for planning.

The embedment phase consists of two steps. The output from Phase 3 is considered in Step 4.1 to decide which of these outputs to include in the RAMS, to prepare these data so that they are in the format that is required for import into the RAMS and to include these data in standard reporting practices once imported into the RAMS. Step 4.2 is concerned with communicating these additional climate-sensitive data to stakeholders (in addition to what is normally reported in the RAMS), so they may be used for climate adaptation decision making and planning.

Recommendations:

- An understanding of the RAMS database structure would be required during this phase.
- It would be essential for the person appointed to do the spatial data analysis to have close interaction with the RAMS champion(s) or persons managing the RAMS.
- Changes to the RAMS database structure would be required to accommodate climate change data. Alternatively, the climate change (future) assessments can be done in a GIS and only the resulting deficiency, criticality and vulnerability indices can be imported into the RAMS.

Step 4.1: Export data to the RAMS

Aim:

The aim of this step is to match the threat-specific factor scores and vulnerability indices, calculated in Phase 3 per road segment, to the correct roads in the RAMS where data (attributes) are stored per road link, from node to node. This would ensure that decision-makers at the network level will have insights into the overall degree of vulnerability of roads, including current structural defects, as well as into the function of different roads in terms of access and connectivity.

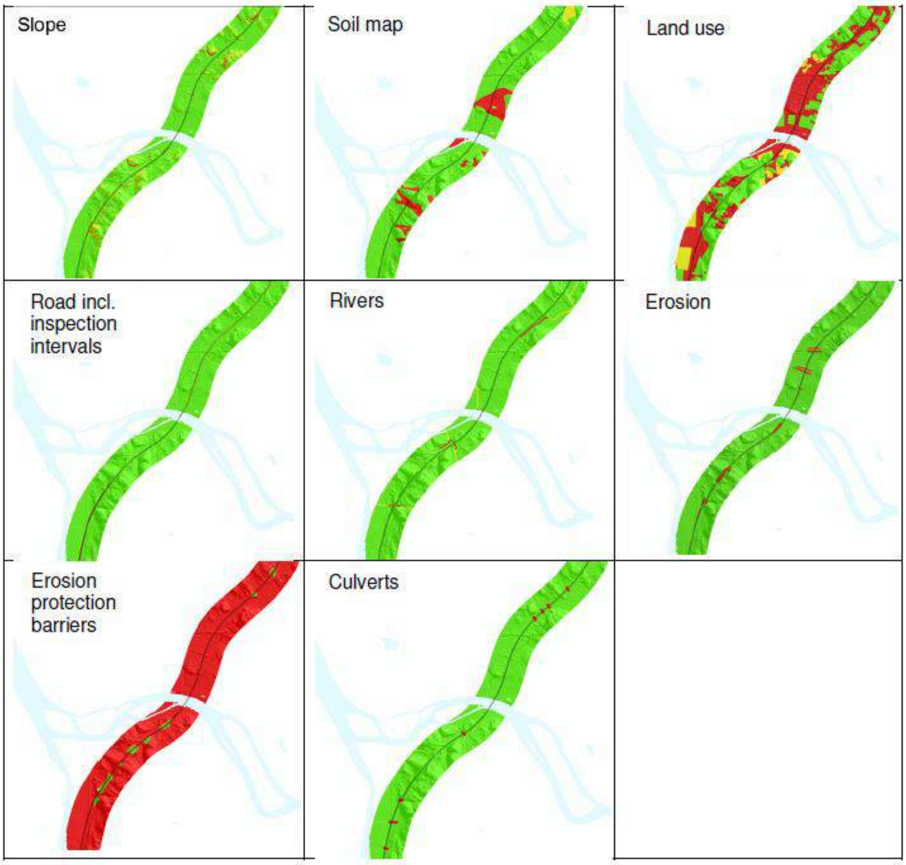
Recommendations:

- Establish a one-to-one link between the road data in the GIS and road links in the RAMS database.
- Allocate the deficiency factor scores, maintenance scores and road criticality scores to the road link in the RAMS database, using the one-to-one link.
- Link calculated hydrological data, such as run-off for different return periods, to the correct river bridges and major culverts by way of coordinates.
- Export the climate and population change indicators from the GIS in a format that can be imported into the RAMS (Road Asset Management System) and BMS (Bridge Management System) databases.

Step 4.2: Communicate with stakeholders

The purpose of undertaking a climate-sensitive vulnerability assessment is for the information generated from the exercise to inform the prioritisation of engineering and non-engineering adaptation options. The information and maps generated from the local vulnerability assessment are used to communicate about all the current and future challenges expected for a particular road network. Relevant stakeholders therefore have the opportunity to comment on the veracity of findings prior to committing to specific interventions. Maps such as the ones shown in Figure 21 are useful visual aids that give decision-makers clear insights on problematic locations.

Specific road vulnerability maps following climate hazards



Data source: Falemo *et al.* (2015)

Figure 21 An example of specific road vulnerability maps (following climate hazards) that can be generated from climate resilience indicators in the RAMS

The individual indices can be used to rank roads and structures in terms of priority for maintenance or adaptation. The benefit of embedding the climate vulnerability data into the RAMS is that it can be viewed interactively with information on locations of bridges and major culverts. Therefore, expected future run-offs for different return periods can be compared with the current capacity of such structures to identify and rank those structures that would need adaptation.

Phase 5: Climate adaptation

(Road adaptation according to prioritisation and climate-sensitive engineering designs)

The Road Vulnerability Index (RVI) calculated as an output in Phase 3 and imported into the RAMS in Phase 4 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 (Head, Verhaeghe & Maritz, 2019; Paige-Green, Verhaeghe & Head, 2019) would assist with identifying the required maintenance and adaptation activities. The way the assessment is applied would vary, depending on the circumstances for each study 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.

4.4 Concluding remarks on assessing the vulnerability of a road to climate hazards

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 vary the way in which 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 would be the availability of human resources and skills to perform the assessment. Any identified skills gaps should guide and inform strategic capacity development and training programmes. In conclusion, a list of indicators is provided, as well as the specific risks for which the indicators are recommended (see Table 15).

Table 15 Indicators suggested for assessing the vulnerability of a road to specific climate-related risks

Assessment components	Possible indicators	Climate-related risks			
		Road surface flooding	Erosion	Landslides	Pavement integrity loss
Road infrastructure	Road surface type	X	X		X
	Road surface level	X	X		
	Road width	X	X	X	X
	Road base material	X	X		X
	Geology of road base and embankment	X	X	X	X
	Distribution (or location) and hydraulic capacity of culverts/drums	X	X		X
	Distribution and height of bridges	X			
	Distribution and type of erosion protection works	X	X	X	
	Distribution of observed cracking along the road	X	X	X	X
	Maintenance frequency of road surface	X	X		X
	Maintenance frequency of drainage systems	X	X		X
	Number of alternative routes	X			X
	Distance to the nearest alternative route	X			X
Climate variability and change	Flood frequency and intensity	X	X	X	X
	Flood-prone areas within catchment	X	X	X	X
	Design flood estimate	X	X	X	X
	Design rainfall estimate	X	X	X	X
	Annual average rainfall intensity	X	X	X	X
	Average number of days per year with rainfall above 20 mm in 24 hours	X	X	X	X
	Annual average temperature		X		X
	Average number of days per year above 35°C		X		X
	Average number of days per year with excessive wind speeds		X		X
	Keetch-Byram drought index	X	X		X
	Expected change in annual average rainfall intensity	X	X	X	X

Assessment components	Possible indicators	Climate-related risks			
		Road surface flooding	Erosion	Landslides	Pavement integrity loss
	Expected change in average number of days per year with rainfall above 20mm in 24 hours	X	X	X	X
	Expected change in annual average temperature		X		X
	Expected change in number of days per year above 35°C		X		X
	Expected changes in average number of days per year with excessive wind speeds		X		X
	Expected changes in number of high fire danger days	X	X	X	X
	Expected changes in the Keetch-Byram drought index	X	X		X
Environmental conditions	Distribution of water bodies (including road ponds)	X		X	X
	Water catchment area/extent	X			X
	Length of longest watercourse in the catchment	X			
	Elevation	X	X	X	X
	Slope, aspect	X	X	X	X
	Land cover (vegetation)	X	X	X	X
	Proximity of tall trees to the road	X			
	Soil type	X	X	X	X
	Locations affected by landslides	X	X	X	X
	Distribution of observed soil erosion	X	X	X	X
Socio-economic conditions	Population distribution	X	X	X	X
	Location of markets	X	X	X	X
	Location of public facilities (schools, clinics, etc.)	X	X	X	X
	Land use	X	X	X	X

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