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

Climate Adaptation Options Report

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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. The majority of both bottom up and top down studies suggest that damages from climate change, relative to population and Gross Domestic Product, will be higher in Africa than in any other region in the world. In the past four decades' African countries have experienced more than a 1,400 recorded weather related disasters (meteorological, hydrological and climatological). These disasters have 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.

In order to help address this significant threat to Africa's development, the Africa Community Access Partnership, a research programme funded by UKAid, has commissioned a project, starting in April 2016, to produce regional guidance on the development of climate-resilient rural access in Africa through research and knowledge sharing within and between participating countries. The output will assist the development of a resilient, future-climate-proof road network that reaches fully into and between rural communities.

The study 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 rural access low volume roads. In addition, evidence of cost, economic and social benefit links to rural communities arising from more resilient rural access will be provided to support wider policy adoption across Africa.

In this report, engineering and non-engineering adaptation options are presented. The crucial importance of effective drainage is highlighted and also the critical importance of timely and appropriate maintenance.

Adaptation techniques for handling the expected changes in temperature and precipitation, windiness, seal-level rise and more frequent extreme events are identified and discussed. These are specifically related to unpaved roads, paved roads, subgrade materials, earthworks and drainage within and outside the road reserve as well as possible implications for construction activities. The importance of timely and good maintenance practices is also highlighted and guidance given.

Key words

Climate Variability; Climate Threat; Climate Impact; Climate Change; Vulnerability; Risk; Adaptation; Demonstration; Capacity Building; Rural roads: Low volume roads; Maintenance.

AFRICA COMMUNITY ACCESS PARTNERSHIP (AfCAP)

Safe and sustainable transport for rural communities

AfCAP is a research programme, funded by UK Aid, with the aim of promoting safe and sustainable transport for rural communities in Africa. The AfCAP partnership supports 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. AfCAP is brought together with the Asia Community Access Partnership (AsCAP) under the Research for Community Access Partnership (ReCAP), managed by Cardno Emerging Markets (UK) Ltd.

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Glossary (within the context of this document)

Adaptation	Autonomous or policy-driven adjustments in practices, processes or structures to take account of changing conditions.
Adaptive Capacity	The degree to which adjustments in practices, processes and structures can moderate or offset the potential for damage or take advantage of opportunities created by a given change [in climate].
Adaptation Needs	The circumstances requiring actions to ensure safety of populations and security of assets in response to climate impacts.
Adaptation Options	The array of strategies and measures that are available and appropriate for addressing adaptation needs. They include a wide range of actions that can be characterised as structural, institutional, or social.
Capacity Building	The ability of enhancing strengths and attributes of. And resources available to, an individual community, society, or organisation to response to change.
Climate Change	Change in the state of the climate that can be identified (e.g. 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. It refers to any change in climate over time, whether due to natural variability or as a result of human activity.
Climate Variability	Variations in the mean state and other statistics of the climate on all spatial and temporal scales beyond those of individual weather elements. Variability may be due to natural internal processes within the climate system (internal variability) or to variations in natural or anthropogenic external forcing (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 adverse human, material, economic, or environmental effects that require immediate emergency response to satisfy critical human needs and that may require external support for recovery.
Early Warning Systems	The set of capacities needed to generate and disseminate timely and meaningful warning information to enable individuals, communities, and organisations threatened by a hazard to prepare to act promptly and appropriately to reduce the possibility of harm or loss.
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.
Extreme Weather Events	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 not normally submerged. Floods include river (fluvial) floods, flash floods, urban floods, pluvial floods, sewer floods, coastal floods, and glacial lake outburst floods.

Hazard	The potential occurrence of a natural or human-induced physical event or trend or physical impact 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. In this report, the term hazard usually refers to climate-related physical events or trends or their physical impacts.
Impacts (Consequences, Outcomes)	Effects on natural and human systems. In this report, the term *impacts* is used primarily to refer to the effects on natural and human systems of extreme weather and climate events and of climate change. Impacts generally refer to effects on lives, livelihoods, health, ecosystems, economies, societies, cultures, services, and infrastructure due to the interaction of climate changes or hazardous climate events occurring within a specific time period and the vulnerability of an exposed society or system. Impacts are also referred to as consequences and outcomes. The impacts of climate change on geophysical systems, including floods, droughts, and sea level rise, are a subset of impacts called physical impacts.
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.
Mitigation	The lessening of the potential adverse impacts of physical hazards (including those that are human-induced) through actions that reduce hazard, exposure, and vulnerability.
Resilience	The capacity of social, economic, and environmental systems to cope with a hazardous event or trend or disturbance, responding or reorganizing in ways that maintain their essential function, identity, and structure, while also maintaining the capacity for adaptation, learning, and transformation.
Risk	The potential for consequences where something of value is at stake and where the outcome is uncertain, recognising the diversity of values. Risk is often represented as probability of occurrence of hazardous events or trends multiplied by the impacts if these events or trends occur. Risk results from the interaction of vulnerability, exposure, and hazard. In this report, the term 'risk' is used primarily to refer to the risks of climate impacts.
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.
Stressors	Events and trends, often not climate-related, that have an important effect on the system exposed and 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	Process which attempts to identify the root causes for a system's vulnerability [to climate variability and change).

Acronyms, Units and Currencies

$	United States Dollar
°C	Degrees Celsius
AASHTO	American Association of State Highway and Transportation Officials
ADB	Asian Development Bank
AfCAP	Africa Community Access Partnership
AfDB	African Develompent Bank
AsCAP	Asia Community Access Partnership
ASTM	American Society for Testing and Materials
BMS	Bridge Management System
BPC	Bipartisan Policy Center
BS	British Standards
CBR	California Bearing Ratio
CEC	Cation Exchange Capacity
CPT	Cone Penetration Testing
CSIR	Council for Scientific and Industrial Research, South Africa
DFID	Department for International Development, UK
EIA	Environmental Impact Assessment
ESP	Exchangeable Sodium Percentage
GDP	Gross Domestic Product
GFDRR	Global Facility for Disaster Reduction and Recovery
GIS	Geographic Information System
IPCC	Intergovernmental Panel on Climate Change
LVR	Low-Volume Roads
MESA	Million Equivalent Standard Axles
NCHRP	National Cooperative Highway Research Program
OECD	Organisation for Economic Co-operation and Development
OMC	Optimal Moisture Content
PG	Performance-Grading (bituminous binders)
PI	Plasticity Index
PMS	Pavement Management System
RAMS	Road Asset Management System
ReCAP	Research for Community Access Partnership
SADC	Southern African Development Community
SAR	Sodium Absorption Ratio
SATCC	Southern African Transport and Communication Commission
SMS	Slope Management System
SPT	Standard Penetration Testing
SSA	Sub-Saharan Africa
TRH	Technical Recommendations for Highways
TRL	Transportation Research Laboratory
UK	United Kingdom (of Great Britain and Northern Ireland)
UKAid	United Kingdom Aid (Department for International Development, UK)
UNFCCC	United Nations Framework Convention on Climate Change

Contents

1 Background and Objectives

1.1 Project background

1.1.1 Climate vulnerability

The African Development Bank (AFDB) states that Africa is one of the most vulnerable regions in the world to the impacts of climate change. The majority of both bottom up and top down studies suggest that damages from climate change, relative to population and Gross Domestic Product (GDP), will be higher in Africa than in any other region in the world (AFDB 2011). Its studies suggest adaptation costs in Africa in the region of $20-30 billion per annum are required over the next 10 to 20 years. There is a pressing need to mobilise resources to address the continent's current limitations to deal with climate events, as well as resources to deal with future climate change. Beyond this a series of more targeted adaptation investments are required and it is crucial that African decision-makers factor climate change into all long term strategic decisions.

In the past four decades (1975 to 2015), African countries have experienced more than a 1,400 recorded weather related disasters (meteorological, hydrological and climatological). These disasters have had significant impacts on countries' economies and in particular on rural communities and their livelihoods. The high social vulnerability and low adaptive capacity of these communities as well as their high exposure to natural hazards has 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 (CRED, 2016).

In many African countries, limited or non-existent funds for adaptation and mitigation are challenging these countries to identify the threats that are posed by climate change, develop adaptation approaches to the predicted changes, incorporate changes into mid-range and long-term development plans, and secure funding for the proposed and necessary adaptations. Existing studies have attempted to quantify the impact of climate change on infrastructure assets that will be affected by climate change in the coming decades.

1.1.2 Rural access

Sub-Saharan Africa (SSA) has one of the lowest rural road densities in the world, which is significantly stifling its potential for agricultural growth and development. In addition, less than 40 per cent of rural Africans live within two kilometres of an all-weather road, making social, medical and educational interventions timely, costly and unreliable. The majority of the road networks contributing to agricultural and social development in these rural areas can be classified as low volume.

Low-volume rural road networks in these countries vary from underdeveloped roads (tracks and un-engineered earth roads) to reasonable, high standard paved roads built to "conventional" standards. Irrespective of their quality, these roads are frequently rendered impassable as a result of periodic extreme weather events. Associated with these roads are water crossing structures, ranging from drifts/fords to culverts of varying sizes and larger bridges. High water velocities could damage these structures, rendering road links impassable. Flooding would lead to similar consequences. Whereas road pavements can usually be reinstated fairly quickly to restore rideability after extreme events, road closures caused by flooding can take several hours to weeks before water levels subside and accessibility can be restored. However, severe impairments of water crossing structures caused by destructive water velocities could take several weeks to months to reinstate, depending on the emergency response capability and adaptive capacity of the road authority.

The majority of the low volume rural road network in Africa is used for accessibility as opposed to mobility as shown in Figure 1.

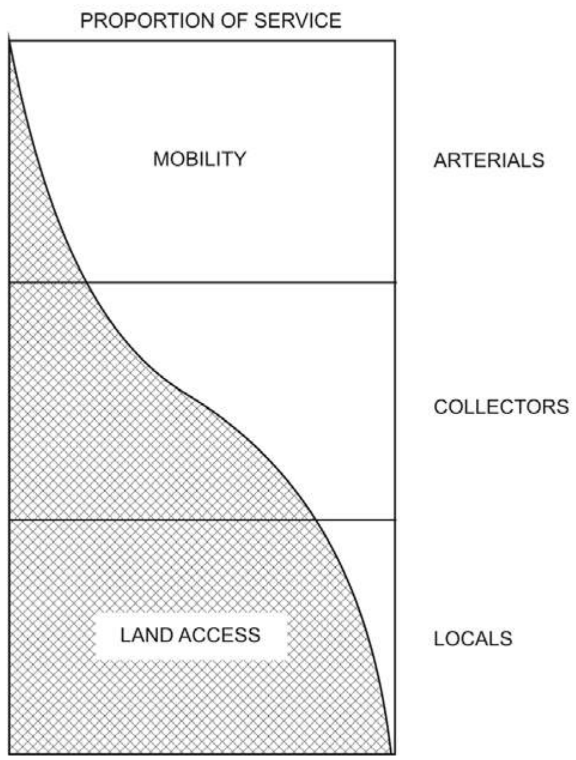


Figure 1: Use of different road types in terms of accessibility and mobility (AASHO, 1964)

It has been shown in southern Africa that for low volume road networks (< 1 million cumulative equivalent standard axles (MESA) over their service life), the environment (mainly climate) plays a much larger role in contributing to deterioration than the traffic does (Figure 2; SATCC, 2003). However, it should be noted that, rather than the cumulative effects of equivalent standard axles, one heavy, overloaded vehicle travelling on a low volume road that is flooded or has high moisture in the upper layers can cause deterioration and failure.

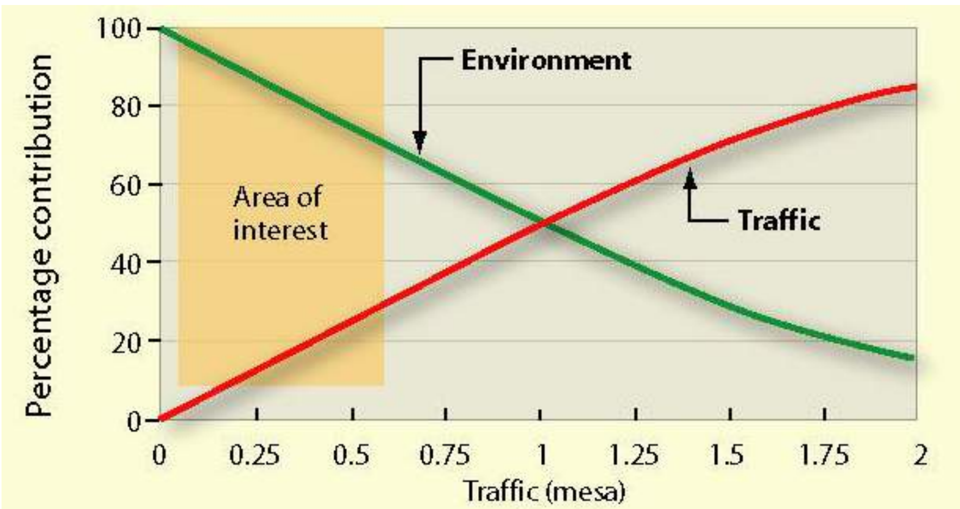


Figure 2: Relationship between road derioration and environment and traffic (SATCC, 2003)

With the expected changes in climatic conditions (le Roux et al, 2016) resulting from global climate change (greater frequency of extreme events, together with expected changes in precipitation and temperatures), the on-going and periodic deterioration of the existing low volume rural road networks in SSA can thus be expected to continue on a more frequent and increasing scale, somewhat more than for conventional higher trafficked roads. Instances of impassability while roads and structures are waiting to be repaired will increase, and communities and local economies are expected to be affected accordingly.

It is thus urgent that steps are taken to make rural roads, inclusive of drainage and bridge structures, more resilient to extreme weather events and to ensure all-weather passability on critical road links as far as possible. Resilience here is defined as the capacity to anticipate, prepare for, respond to, and recover from the impacts or consequences of significant hazard or multi-hazard threats with minimum damage to social well-being, the economy and the environment.

It is unlikely that all such occurrences can be avoided without significant cost implications. However, new road projects, inclusive of their drainage and bridge structures, as well as rehabilitation and upgrading projects, should ideally be planned and designed (within reasonable limitations) to incorporate greater climate resilience so as to minimise the potential for road closures.

All road development projects currently require an environmental impact assessment (EIA) to evaluate the impact of the proposed road on the environment. These vary from relatively rudimentary assessments to highly sophisticated, time consuming and costly exercises. However, it is becoming increasingly important that the converse effect of the environment on proposed (and existing) roads is evaluated equally.

A number of the climatic impacts are exacerbated by other factors. Vehicle overloading for instance results in rapid deterioration of the pavement structure, but when combined with higher pavement moisture contents, the deleterious influence is increased exponentially. Similarly, poor maintenance of drains affects the moisture content in the road. With higher rainfall, this effect is amplified.

This report concentrates on the future road scenarios in Mozambique, Ghana and Ethiopia, for which detailed climate projections have been developed within this overall project (le Roux et al, 2016). The general findings, however, cover a wide range of scenarios and should be applicable to similar scenarios that unfold in other sub-Saharan countries.

Many of the climate related problems are not within the provenance of one government institution, such as a roads authority. Cooperation with other government departments such as irrigation, water resources, flood control, environment, agriculture and emergency services may often be essential. The construction (and routine maintenance) of flood control structures and dams (usually by different departments), for instance, may be necessary to minimise damage to the road infrastructure (and local communities).

1.2 Scope and purpose of report

To contribute towards addressing this significant threat to Africa's development, the Africa Community Access Partnership (AfCAP), a research programme funded by UKAid, commissioned a project, which started in April 2016, to produce regional guidance on the development of climate-resilient rural access in Africa through research and knowledge sharing within and between partner countries. The output will assist in the development of a climate-resilient road network that reaches fully into and between rural communities.

As part of this programme, research is being conducted on understanding regional climate threats; identifying appropriate risk and vulnerability assessment methods; prioritising adaptation options; and optimising asset resilience in the context of rural access sufficiency. Evidence of economic and social benefit, or increased resilience of rural communities as a result of improved rural access, will be required to support wider policy adoption across Africa.

This report discusses the expected effects of different climate change attributes on low volume roads and highlights the process to be followed to ensure that as many roads as possible become more climate resilient and can retain their passability after both periodic and extreme climatic events or as a result of gradually changing climatic conditions.

The primary climatic attributes are firstly introduced and then the assessment and prioritisation of the current road network in terms of making roads and structures climate resilient are discussed. Suggested adaptation measures for each expected climate stressor and the relevant infrastructure component are then highlighted. The crucial importance of effective drainage is highlighted and also the critical importance of timely and appropriate maintenance.

Within the overall programme objectives, which are:

A: *to identify, characterise and demonstrate*[1] *appropriate engineering and non-engineering adaptation procedures that may be implemented to strengthen the long-term resilience of rural access, and*

B: *to build capacity and disseminate knowledge,*

the objectives of this report are thus to:

- Conceptualise climate vulnerability and adaptation strategies
- Set out a methodology for adaptation
- Provide options to create resilience
- Provide guidance for building adaptation strategies into roads Policy, Planning and Standards.

This report should be used in close conjunction with the *Climate Adaptation: Risk Management and Resilience Optimisation for Vulnerable Road Access in Africa - Climate Threats Report* (le Roux et al, 2016), objectives were:

- To present the status of current climate variability and projected future climate change in order to establish a baseline from which current and future stresses on rural accessibility can be assessed, from a community and a rural road infrastructure perspective; and
- To assess the impacts of climate variability and change on vulnerable rural access, primarily taking into consideration the direct impacts of climate change. The indirect impacts were also considered by highlighting the current status of rural accessibility, showing the way in which climate variability has impacted communities, and projecting how climate could affect communities in the future, given the climate change scenarios.

The *Climate Threats Report* (le Roux et al, 2016) presented current and projected rural population densities and reflected on observed impacts of African weather-related disasters. It then provided an overview of projected climate futures and their likely impacts and proposed a methodology to assess access risk and vulnerability. A Mozambique Case Study was used to illustrate the methodology.

[1] The physical implementation of the *demonstration programme* forms part of Phase 2 of the Programme, but the conceptual design of the demonstration programme is to be undertaken in Phase 1.

2 Climate Change Effects

2.1 General

Climate change, according to the Intergovernmental Panel on Climate Change (IPCC, 2007) and also for the purpose of this study, refers to a change in the state of the climate that can be identified (e.g. 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. It refers to any change in climate over time, whether due to natural variability or as a result of human activity. This usage differs from that in the United Nations Framework Convention on Climate Change (UNFCCC), where climate change refers to a change of climate that is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and that is in addition to natural climate variability observed over comparable time periods. The effects of climate change are putting large lengths of the world's road infrastructure at risk and thus need to be considered in both present road operation scenarios as well as decisions on future road infrastructure investments.

A number of climatic changes are anticipated but these are not consistent for all countries and will vary from one geographic location to another. The main countries covered in this project include Ethiopia, Ghana and Mozambique. These countries represent a geographic and climate spread representative of those in SSA; the findings and adaptation recommendations could therefore be expected to be applicable to countries affected by similar changes in climatic stressors.

The following primary climate changes are likely to occur to varying degrees in most parts of SSA:

- Increased temperatures (average, maximum and number of extremely hot days per year)
- Decreased precipitation and longer drier periods
- An increase in extreme weather events – violent storms, heavy precipitation, heat waves, etc.
- Rising of sea-level
- Migration of the tropical cyclone belt
- Increased wind speeds.

These will be accompanied by related secondary effects:

- Longer/shorter growing season
- Increase/reduction in soil moisture
- Changes in groundwater level
- Changes in vegetation density and type and rate of growth
- Flooding
- Changed frequency of extreme storm surges
- Changes in ecological equilibrium
- Changes in the optimum construction season (possibly timing and length) and conditions.

Together with these climatic changes and secondary effects, the impacts of for instance more severe flooding, increased wild-fire hazards, rising sea-levels and lowered groundwater tables on the road infrastructure need to be considered. Other associated influences such as water shortages under increased temperature environments as a result of higher evaporation, for instance, could also have an indirect impact on infrastructure provision.

It is anticipated that changes in other climatic parameters (e.g., relative humidity, barometric pressure, presence of fog) will have minimal impact on the engineering aspects of the low volume road infrastructure or else be incorporated into the above effects.

It has also been postulated (McGuire, 2016) that the incidence of seismic activity could increase as a result of global warming, with concomitant increases in destructive earthquakes and tsunamis.

Although these earthquakes are likely to occur on other continents as a result of unloading of the landmasses due to melting ice, the effects of resulting tsunami could affect the African continent.

This report will not only concentrate on the general effects that these climate changes and the resulting secondary effects could have on the sub-Saharan road infrastructure, but also address the existing resilience deficit of current road networks to current climate impacts. The dominant effects of each of these climate variables are summarised below, before details on possible adaptation measures are provided in the remainder of the report. The adaptation measures are not country specific as they are primarily related to the different events and not specifically to local conditions.

2.2 Temperature changes

A general increase in temperature with time is expected over the majority of SSA. For most pavement structures, this will have minimal influence, but secondary effects such as drying out of subgrades and surrounding soils, and increased wildfire hazards should not be forgotten. The impacts on bitumen are likely to be more significant and these will mostly be related to additional softening of bitumen during the expected increase in extremely hot days (> 32°C).

It is not anticipated that temperatures will decrease to any significant degree over most of SSA. It is thus unlikely that there will be a lowering of the snow-line elevation, a significant increase in frost occurrences, or an increase in freezing of water in pavements and earthworks.

2.3 Precipitation changes

In general, it is expected that the precipitation will decrease in most areas under discussion. This will generally have a favourable influence on most roads, which will tend to operate under higher negative pore water pressure (high soil suction) conditions and thus have significantly higher strength than normal. However, it is also anticipated that the reduced precipitation will be in the form of **less frequent but more severe** events. Provided that the pavement drainage is such that the water is removed from the pavement structure rapidly, the temporary increased precipitation associated with these events will have little effect on the road performance. **It will be essential, however, that drainage maintenance techniques are improved and implemented more frequently.**

It is well established that excessive water is one of the biggest cause of problems in road pavements and earthworks. Apart from its detrimental effect on many pavement materials, if the pavement becomes saturated with water, significant positive pore-water pressures develop under loading which lead to premature failure of the pavement layers. It is anticipated that in some areas, where (i) precipitation is likely to increase and/or extreme events are more likely, and (ii) the design and surrounding drainage systems of the pavement and earthworks do not sufficiently cater for effective/ rapid removal of this water, widespread pavement failures and earthwork instability can be expected.

2.4 More frequent extreme events

It is predicted that even though the precipitation may reduce in many areas, the precipitation that does fall is likely to be associated with fewer but more intense events. This will increase the potential for flooding, rapid stream flows, erosion and scour of stream-beds and structures, sedimentation and siltation, and could result in increased instances of slope instability. However, if these events have long time lapses between them allowing the road environments to dry out (say 4 to 6 weeks), the effects on slope stability will probably be minimal.

The factor that affects the duration of flooding in an area is the topography. Longer flooding and inundation periods occur in flatter terrains than in steeper terrains. In steep terrains shorter duration and higher velocities are normally experienced (with accompanying erosion and scouring), whereas in flat terrains the water "stands" for longer periods but the potential for scour and erosion is significantly reduced after the initial flood episodes.

2.5 Sea-level rise

A consequence of higher global temperatures will be the reduction of land-supported ice. Melting of these glaciers and ice-sheets will increase the volume of water in the oceans and lead to a rise in sea level. In addition, increased water temperatures will result in expansion of the water within other water bodies and sea water leading to the raising of the sea level. The impact of this will, obviously, only be noticed at existing coastlines, but the consequences are likely to be dramatic, with significantly more damage to low lying infrastructure and extensive coastal erosion and movement of beach sands resulting mainly from increased tidal variations, wind-generated waves and storm surges.

Sea level rise will result in coastal flooding being more extreme due to the higher ”base levels", increased salinity of coastal river waters with the related impacts on salt-sensitive structures and increased sedimentation in tidal areas.

2.6 Migration of the tropical cyclone belt

It is anticipated that the tropical cyclone belt that is currently centred on central Mozambique, will move northwards towards the Tanzanian border. This is likely to bring increased precipitation and winds, with associated flooding, to areas currently unaffected or affected to only minor extents, in some areas, while this will diminish in the more southern locales.

2.7 Increased wind speeds

Higher wind speeds result in quicker drying of road environments and soils, a larger and quicker loss of material from unprotected sites (unpaved roads and exposed earthworks) and a greater potential for wild fires. Other less significant (but requiring more maintenance) problems will also result from increased wind speeds such as movement of coastal and dune sands, damage to road furniture, road blockages due to uprooted trees, and increased wind stresses on bridges.

2.8 Climatic classification

Climatic zones and classifications are an important part of existing road design and management. Many design systems and catalogues make use of climatic zones (TRH 4, 1996, Gourley and Greening, 1999, etc.). Other tools such as deterioration models for unpaved roads (Paige-Green, 1989), models for the estimation of equilibrium moisture content in roads (Emery, 1992), landslide susceptibility maps (Leyland and Paige-Green, 2011), etc. include or are based on climatic factors related to classification systems.

The climatic classifications currently used mostly in road engineering are the Geiger-Köppen system, Thornthwaite's moisture Index and Weinert N-value.

2.8.1 Geiger-Köppen

This is a broad system (Figure 3) and is based on various parameters such as native vegetation combined with average annual and monthly temperatures and precipitation and the seasonality of precipitation. Climate change will obviously affect temperatures and precipitation, which will in turn affect vegetation, thus having a cumulative effect on the classification of climatic zones. This will need to be considered when using this classification system as part of roads design in future – it may be necessary to determine new values periodically.

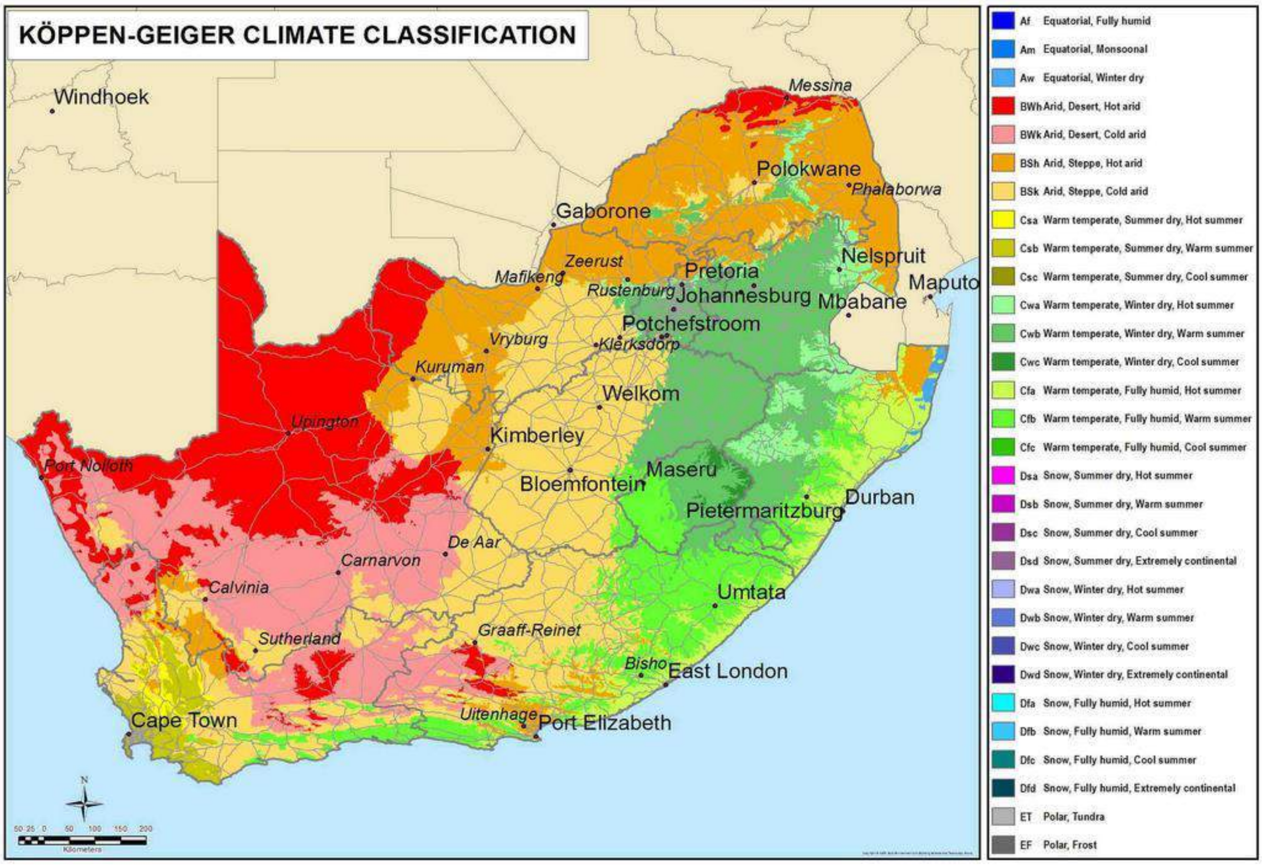


Figure 3: Example of Köppen-Geiger climate classification (South Africa)

2.8.2 Thornthwaite's Moisture Index

Thornthwaite's moisture index was originally developed for agricultural use and is based on a model including the potential evapotranspiration and precipitation.

By comparing the precipitation and potential evapotranspiration month-by-month at any station, it is possible to calculate the water surplus (i.e., precipitation exceeds potential evapotranspiration) and water deficiency (i.e., potential evapotranspiration exceeds precipitation). The water need is the potential evapotranspiration. It should be noted that Thornthwaite assumed a soil water storage capacity equivalent to about 10 cm of rainfall.

Manipulation of these parameters gives indices of annual humidity (I_h) and aridity (I_a) as follows:

$$I_h = \frac{100s}{n}$$

$$I_a = \frac{100d}{n}$$

where ***s*** is water surplus, ***d*** is water deficiency and ***n*** is water need.

Water surplus and water deficiency generally occur during different seasons in most places and must therefore both be used in a moisture index, the former having a positive effect and the latter a negative effect. Taking into account the effect of the soil water storage (i.e., a surplus in one season minimises the effect of a deficit in the following dry season, the index of aridity has only 60 per cent of the weight of the index of humidity), the moisture index is calculated as follows:

$$I_m = I_h - 0.6I_a$$

or

$$I_m = \frac{100\Sigma s - 60\Sigma d}{\Sigma n}$$

Thornthwaite's moisture index for South Africa is shown in Figure 4.

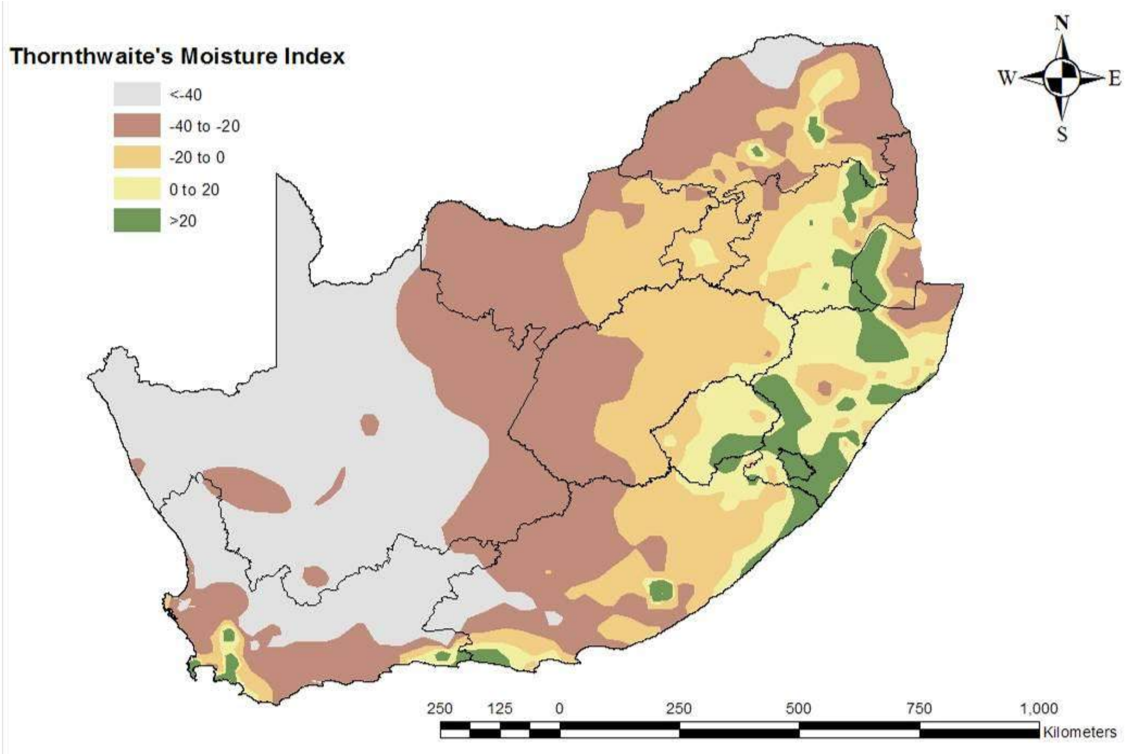


Figure 4: Map of Thornthwaite's moisture index for South Africa

Thornthwaite's Moisture Index has been adopted for use in many applications in pavement engineering, from design to management of maintenance as well as in numerous prediction models, from pavement deterioration to the estimation of subgrade moisture content and the prediction of subgrade expansiveness.

2.8.3 Weinert N-value

Weinert developed the N-value concept to identify weathering zones for different rock types. Similarly, to Thornthwaite's moisture index, it is calculated as:

$$N = 12E_j/P_a$$

Where,

E_j is the evaporation from a shallow freewater surface in the hottest month (January for South Africa) and

P_a is the annual precipitation.

The evaporation can be directly measured or calculated from the humidity (wet bulb depression in any month) the latitude and the wind speed.

The Weinert N-value (an example of the South African map is shown in Figure 5) was found to represent wet, moderate and dry zones at values of 2, 5 and 10. This has subsequently been incorporated to differentiate between roads designed in the three climatic zones and is used in various road design methods and for pavement performance modelling.

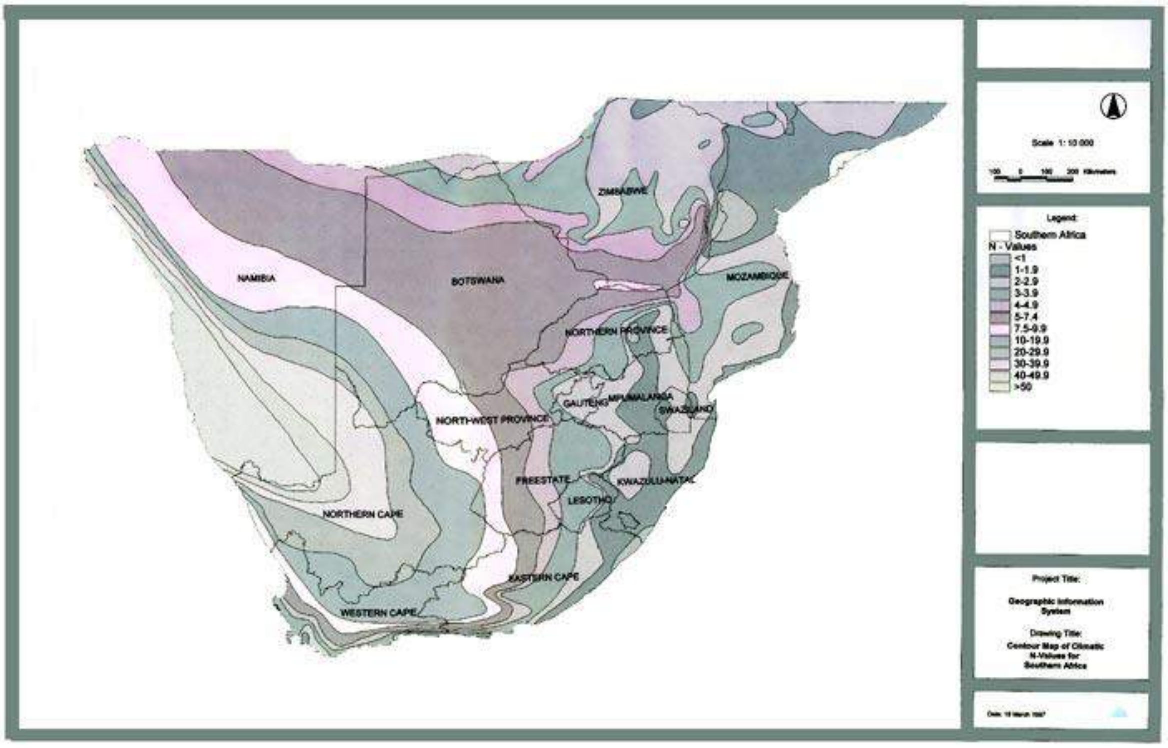


Figure 5: Example of Weinert N-value map for southern Africa

2.8.4 Landslide susceptibility maps

These are maps that have been developed as a preliminary indicator of high risk areas for instability. One of the critical input parameters is a climatic factor, which in the case of Figure 6 is the water surplus factor, where the precipitation exceeds the runoff and infiltration.

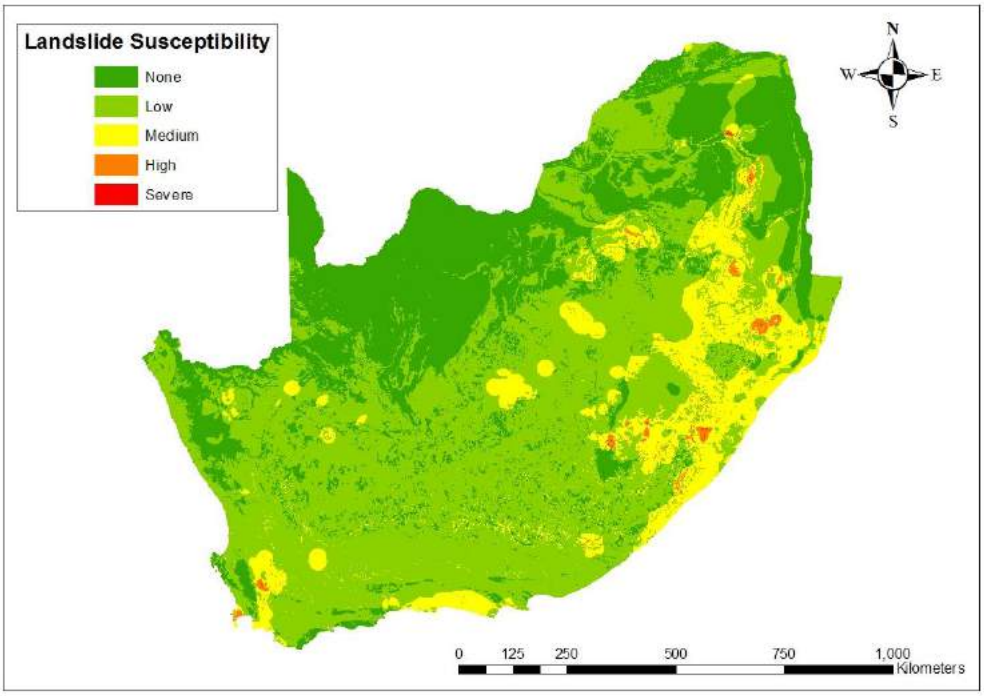


Figure 6: Example of a typical landslide susceptibility map for South Africa

In Section 2.8, climatic classification methods and mapping techniques were illustrated using South Africa as an example (Figures 3 to 6). Ideally such maps should be developed for the whole SSA region reflecting the current status quo as well as projected changes in the classification by 2050 and 2100.

3 Inventory of Road Elements

The following list, adapted from NCHRP #20-83 and NCHRP 750 (2014a), is set out as an *aide memoire* of the elements to be considered when addressing climate change effects:

Road segments:

Subsurface conditions (subgrade):

- Directly influences design of foundations and support structures for the infrastructure itself
- Has to accommodate the various stresses acted upon the material/soil, inclusive of geostatic, horizontal and shear stresses
- Design of foundations reflect the soil conditions, water table, dead weight of the structure and forces that add to the dynamic loads
- Degree of saturation and expected soil behaviour under saturated conditions, which are important factors for subsurface design.

Materials specifications:

- Materials are selected for their performance under design loads and environmental conditions
- Pavements affect facility performance at a considerably large spatial scale and their performance can change dramatically given changing conditions, such as heavier vehicles, higher traffic volumes, or subgrade soils dynamics (saturation, erosion, etc.)
- Steel, concrete and timber bridges must each handle the dead weight and dynamic loads they will be subject to, and thus the strength and resiliency of the bridge materials become of paramount importance
- Strength and protection of materials used in the design might have to be enhanced to account for expected changes.

Cross sections and standard dimensions:

- Cross sections for a road would show the depth of subgrade, materials and thickness, width of lanes and shoulders, slopes of the paved surface, expected design of the area outside the paved surface, and other appurtenances that might be found in a uniform section of road
- Slope of the paved surface will be determined by the physical forces from vehicles and also by the need to remove water from the paved surface
- Cross sections also need to be provided for locations of culverts, special drainage needs, bridges and other structures close to the side of the road
- Road owners usually have design manuals with standards for lane and shoulder widths, transverse slopes, radii for road curvature, dimensions of barriers, culverts, drainage grates, signing, etc. based on historical conditions which may now be inappropriate for current climate.

Drainage and erosion:

- Standard designs for drainage systems, open channels, pipes and culverts should reflect the expected runoff or water flow within the catchment area that will occur given assumed magnitude of storms (i.e. return periods)

- Runoff from impermeable surfaces such as bridge decks or road surfaces must be handled in such a way that water flows are redirected away from the facility itself, but do not harm the surrounding environment
- Consequences of exceedances and construction costs versus failure risk should be factored in the design of the drainage systems.

Structures:

- Current approach to bridge design is to consider the inherent uncertainty in expected loads and resistance factors that the bridge will be exposed to, and thus probabilistic methods are used to incorporate such uncertainty
- Waterway crossings should be studied with respect to the following factors:
    - Increases in flood water surface elevation caused by the bridge
    - Changes in flood flow patterns and velocities in the channel and on the floodplain
    - Location of hydraulic controls affecting flow under the structure or long-term stream stability
    - Clearances between the flood water elevations and low sections of the superstructure to allow passage of debris
    - Need for protection of bridge foundations and stream channel bed and banks
    - Evaluations of capital costs and flood hazards associated with the candidate bridge alternatives through risk assessment or risk analysis procedures
- Most bridges in Africa fail as a result of scour. Bridge owners should re-evaluate return base flood and super-flood events.

Construction practices and activities

- Need of having to utilise different construction materials could affect construction practices
- Lengthening or shortening of the construction season may influence the road authority's construction programme
- May require improved training of construction workers having to work more often in inclement weather

Corridor perspectives:

Direct climate impacts, such as road closures due to flooding, collapse of structures and slope failures, could affect the efficacy of the transport corridor and, by implication, accessibility of communities to markets and to essential service points such as health care and educational facilities.

Potential impacts of changing environmental conditions on a typical road segment would accumulate over a corridor and throughout the network where similar circumstances exist (e.g., subsurface affected because of changes in soil moisture).

Erosion, drainage and runoff impacts:

- Changes in precipitation, both overall levels and rainfall intensities, are considered one of the major factors likely to be experienced in future, impacting on:
    - Culverts and road-related drainage systems
    - Increased runoff and erosion impacting on surrounding land uses and ecological resources
    - Nearby water bodies, such as streams and rivers
- New means will be required for handling erosion and runoff, primarily by reducing volumes or diverting flows away from sensitive areas.

Right-of-way maintenance:

- Changes in climate may require changes in right-of-way maintenance operations
  - Changes in growing season (and thus more or less maintenance), invasive species infestation, flooding caused by backed up drainage systems
  - Road closures as a consequence of fallen trees, etc.
- Restoration of access after collapse of road link and/or structures (e.g., as a consequence of floods) by provision of temporary by-passes
- “Emergencies” may become more “routine” maintenance practices.

Network perspective

Alternative routes and corresponding system operations strategies:

- Extreme weather events causing corresponding disruption to the road network
- Responses to such events will require strategic and coordinated response plans to deal not only with the immediate aftermath, but also to help speed up the recovery process
- Travel information systems should be developed and deployed as part of an overall “adaptive management” strategy.

Intermodal connections:

- Strategies to protect road access should be combined with strategies to protect transportation access.

Location engineering (where to place the facility to begin with):

- The important question with respect to transportation facility location studies is how areas that might be susceptible to climate change effects, such as coastal or low-lying areas might be evaluated for suitability.

Building and protecting assets:

- The need to be cognisant of changing local environmental conditions and their potential impact on the road manager’s assets
- Assets should be rendered climate resistant (e.g. protection from inundation) so that they can be operationalised during or shortly after extreme events to conduct emergency repairs.

4 Overview of Adaptation Methodology

This Section presents an outline of potential adaptation strategies and methodologies that could be deployed. These would have to be customised for the particular needs and priorities of road authorities.

4.1 Adaptation strategies

Adaptation can be defined as:

> *Actions taken by infrastructure stakeholders to avoid, withstand or take advantage of current and projected climate changes and impacts. Adaptation decreases a system's vulnerability, and increases its resilience to impacts.*

An adaptation strategy is put in place to enable a Roads Authority to systematically develop and implement its responses to the challenges of climate variability and change in support of the delivery of its objectives. It provides a platform for decision makers to examine their individual Departments' outputs, including standards, specifications and maintenance for the development of resilience of the road network. It provides a systematic process to identify the activities that will be affected by a varying and changing climate, determine associated risks (and opportunities), and identify preferred options to address and manage them.

Adaptation strategies are put in place to:

- Decrease the vulnerability of transport infrastructure to changing climate conditions
- Increase the resilience of infrastructure
- Support planning for placement of new infrastructure in areas which are projected to have a lower risk of potentially harmful environmental changes
- Support the identification of new construction materials, new construction methods, flexible design standards, and different approaches to design to ensure infrastructure can withstand the projected changes in climate).

Adaptation strategies aim to reduce the **impacts** of specific types of climate effects by identifying and prioritising adaptation options, which could include:

- Protecting existing assets or relocating assets away from vulnerable areas to preserve functionality
- Retrofitting vulnerable facilities
- Improving overall catchment/storm-water drainage
- Constructing new facilities
- Do little or nothing and divert funds/efforts to facilities with greater priority.

Alternatively, a strategy aims to reduce or mitigate the **consequences** of the impacts to infrastructure for impacts that have already occurred , with the purpose of, for instance:

- Preserving human life
- Reinstatement of former accessibility
- Minimising economic impact
- Replacing damaged infrastructure as quickly as possible
- Changing maintenance regimes.

4.2 Methodology overview

Each of the climate factors has direct implications for the condition of infrastructure as well as for its operations and maintenance. Once the significance of these implications is assessed, road managers may select from a range of adaptation strategies to respond to these impacts (Figure 7). These adaptation responses will, in turn, affect the condition and resilience of the infrastructure, as well as the operations and maintenance requirements addressed by the adaptation actions. In addition, climate factors will have impacts on the ecological conditions in which the infrastructure is built and maintained; effects on the planning, design, and construction phases of the highway system; and impacts on the effectiveness of ecological mitigation measures.

Through an adaptive approach, asset managers can evaluate the effectiveness of adaptation strategies on system performance, and then tailor future adaptation actions to further improve performance and enhance the resilience of the road network. By taking pro-active measures, the most vulnerable infrastructure can be protected with reduced the risk of system failure and the consequent impact on human life and economic activity.

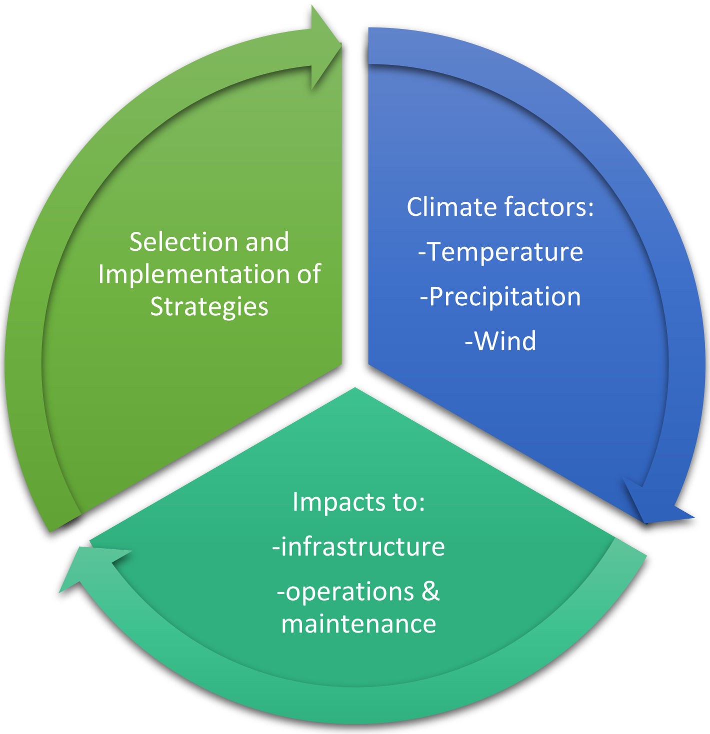
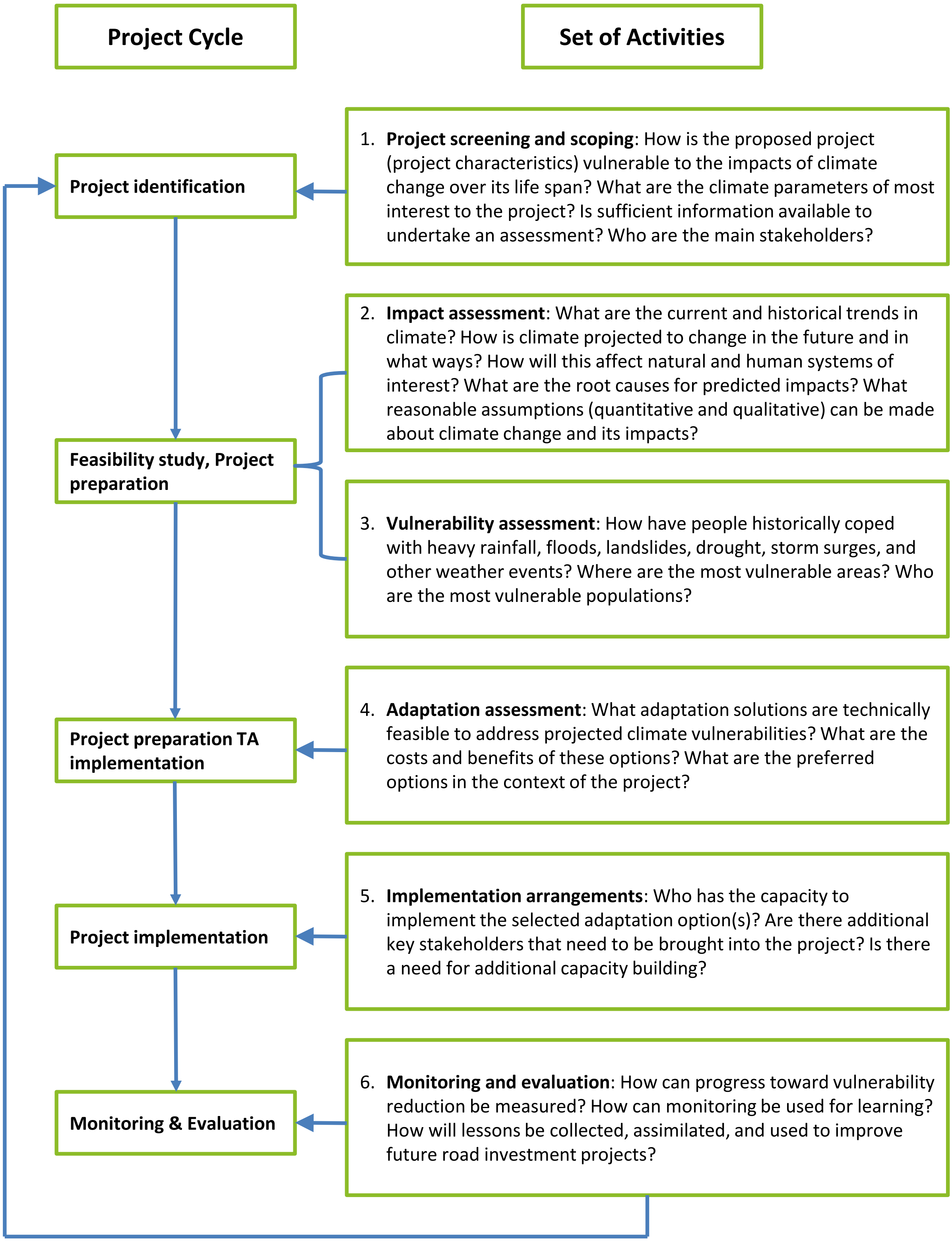


Figure 7: Climate drivers that impact highway infrastructure and operations, resulting in need for adaptation strategies

4.3 Methodological approach

The following methodological approach for assessing adaptation to climate change uses a modified approach of the *ADB Guidelines for Climate Proofing Investment in the Transport Sector Road Infrastructure Projects* (ADB, 2011) and is divided into six different sets of activities. The process begins with a rapid screening as to whether a project may be at risk from climate change, and ends with defining implementation arrangements and monitoring frameworks. The core activities fall under the categories of impact assessment, vulnerability assessment, or adaptation assessment through to implementation and monitoring/evaluation, as illustrated in Figure 8. The activities are then broken down into 20 steps, as described hereunder.



TA = Technical Assistance

Figure 8: Adaptation activity stages (ADB, 2011)

4.3.1 Project screening and scoping

Project **screening** is carried out to determine a project's risk level as a result of climate change, and to prioritise projects.

Project **scoping** is used to identify how climate impacts affect the overall project objectives and to set the boundaries within which the assessment of adaptation options will be undertaken.

Steps comprise:

STEP 1: Screen Project Exposure

Risk screening tools have been developed by a number of organisations to rapidly assess the risk posed to a planned project, or caused by a planned project, as a result of climate change and natural hazard (e.g. DFID, 2009).

STEP 2: Establish the Adaptation Objective

A project's needs for adaptation should be considered as follows:

a. The risk that climate change poses to the project objective and outcomes:
    - reduced road safety and security due to, for instance, increased landslides and increased wave heights
    - reduced access and mobility of rural communities to markets due to road closures
    - unsustainable and costly rehabilitation works when drainage provision is insufficient for peak rainfall/flooding events
    - increased maintenance costs due to increases in, for instance, landslides or failure of embankments.

b. The risks the project may pose to increasing the vulnerability of the surrounding area and population:
    - reduced environmental buffers against floods and droughts due to increased access into ecologically sensitive areas
    - additional strain on already limited water resources for human activity/consumption due to increased population along roads (i.e. roads often attract new human settlements along the route)
    - increased flooding in surrounding areas due to reduction in permeable surfaces (e.g., caused by newly paved roads)

Objectives should be chosen to minimise these potential effects. Establishing how climate change may affect the project objective and outcomes will help ensure that the right data is collected, the necessary expertise is used and that the most appropriate national or local partners are involved.

STEP 3: Survey Existing Information and Knowledge

Identifying existing available information helps to avoid duplication and saves time and money. Each country has a climate change focal point under the United Nations Framework Convention on Climate Change (UNFCCC). Several African countries have also prepared national adaptation programs of action to identify their most urgent adaptation needs.

All available data covering climate change and patterns should be identified and analysed for their usefulness. The same would apply to the inventory of Infrastructure assets and their condition.

STEP 4: Identify and Engage Stakeholders

Relevant stakeholders could include: road and transport authorities; other government departments and institutes dealing with meteorology, water resources, flood control, environment, agriculture and emergency services; and if available climate change focal points and disaster risk reduction focal points. A number of institutions and research organisations may be conducting work relevant to the project. Further, specific engagement of local communities, nongovernment organisations, and small to large businesses operating in the sector will be important for conducting a vulnerability assessment and for engagement in selecting the most effective adaptation strategies.

STEP 5: Identify Methodology and Data Needs

Identification of all relevant climate parameters relevant to the project, and collection and collation of data. The climate parameters could include:

- sea level and wave action (for coastal roads)
- precipitation intensity and slope (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 assessments).

Identifying the method(s) for the assessment and prioritisation of options, such as cost-benefit analyses or multi-criteria analyses, will also determine and ensure that the relevant data are collected during project preparation.

STEP 6: Identify the Required Expertise

In addition to team leader and engineering support, and depending on the nature of the project, it may be necessary to consult a hydrologist, economist, climate specialist and/or social scientist.

4.3.2 Impact assessment

For any given project, the decision of what types of climate scenarios and projections to develop is based on a number of factors, including the need to account for a wide range of uncertainty, time frames, budget sizes, and data availability. In an increasing number of cases, climate change scenarios have already been produced and can be adapted for use by the project. In all cases, understanding the history of climate (temperature, rainfall, storm surges, and extreme weather events) is always a necessary first step.

STEP 7: Construct Climate Change Scenarios

Climate projections are based on simulations by climate models and can be useful in determining how climate variables such as temperature and precipitation may change in the future. Section 3.2, *Projected Climate Change over Africa*, in the Climate Threats Report (le Roux et al, 2016) sets out the main changes in climate for the African continent and for specific AfCAP supported countries.

STEP 8: Estimate Future Biophysical Impacts

Once climate change scenarios have been constructed, an attempt should be made to quantify the key relationships between observed and projected changes in climate parameters—such as average temperature, average precipitation, temperature and precipitation extremes, sea level rise, and storm surges—and impacts on the transport sector. Biophysical models constitute one way to analyse the physical interactions between climate and an exposure unit such as a watershed or a road. Here are some examples of how different biophysical models can be used:

- **Dose-response models:** These models can elicit the effects of changes in average precipitation and temperature on the maintenance costs, construction costs, and service life of road infrastructure.
- **Hydrologic models (rainfall-runoff models):** These models translate changes in precipitation and temperature into changes in runoff and water levels. They can be useful to determine changes in future extremes (floods and droughts).
- **Hydraulic and/or hydrodynamic models**: These models can be used to predict future inundated areas based on precipitation and the deployment of protective infrastructure. They can also predict the flood extent of an estimated sea level rise.

The results of these impact assessments will have significant implications for the cost of the project so caveats and uncertainties associated with the methods should be carefully assessed.

STEP 9: Assign Probabilities to Identified Impacts

Section 4 of the *Climate Threats Report* (le Roux et al, 2016) sets out a semi-quantitative, indicator-based assessment method for quantification and prioritisation of risks. A geospatial climate-related road infrastructure risk and vulnerability assessment can provide key geographic information to inform adaptation decisions for rural access. This may be targeted firstly at a regional district scale for each country and secondly at a local scale within districts. The district-level assessment may be more relevant 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 threats. Its core focus is on the methodology for the district scale assessment, which is aimed at providing a rough high-level indication of where changes in climate patterns might affect rural roads, for the purpose of identifying the highest risk areas/districts in each country.

The Intergovernmental Panel on Climate Change, IPPC (2007) uses a likelihood scale based on a probabilistic assessment of some well-defined outcome that may have occurred in the past or may occur in the future (Table 1). The use of return periods and of changes in return periods aims to attach probabilities or changes in probabilities to extreme weather events.

Table 1: Definition of likelihood of occurrence (IPPC, 2007)

Terminology	Likelihood of the Occurrence
Virtually certain	> 99% probability of occurrence
Very likely	> 90% probability of occurrence
Likely	> 66% probability of occurrence
About as likely as not	33 to 66% probability of occurrence
Unlikely	< 33% probability of occurrence
Very unlikely	< 10% probability of occurrence
Exceptionally unlikely	< 1% probability of occurrence

4.3.3 Vulnerability assessment

STEP 10: Identify vulnerabilities of the Planned Project and Area

Vulnerability refers to the degree to which a system is susceptible to, and unable to cope with, adverse effects of climate change. Vulnerability is a function of the character, magnitude, and rate of climate change and variation to which a system is exposed; its sensitivity; and its adaptive capacity. The specific nature and degree of the vulnerability are very much site specific and must be assessed at the specific location of the project site.

Vulnerability and adaptive capacity are also a result of the interaction between socio-ecological factors and processes such as income level, settlement patterns, infrastructure, ecosystem and human health, gender, political participation, and individual behaviour (OECD, 2009).

Section 4.2 of the Climate Threats Report (le Roux et al, 2016) sets out four phases for the road risk and vulnerability assessment:

Phase 1: Data Preparation
Phase 2: Evaluation of asset vulnerability
Phase 3: Evaluation of asset criticality
Phase 4: Identification of adaptation options

These are further described in more detail in the following Steps:

STEP 11: Identify biophysical drivers of vulnerabilities

Some biophysical drivers of vulnerability include poor land management, deforestation, slash-and-burn agriculture and monoculture cropping. Some ecosystems, such as mountain ecosystems, are inherently more sensitive to change (i.e. slope instability and geophysical instabilities, for instance), while low-lying coastal areas and desert margins are more exposed to climate changes and risks.

Using Geographic Information Systems (GIS), it is useful to map areas that are particularly vulnerable to a combination of local conditions and climate variability. This assessment can be conducted in the context of initial environmental and social assessments for a road project. The mapping can point out areas that are vulnerable because of their geographic as well as socioeconomic characteristics, such as:

- areas that are sensitive due to topography (e.g., steep slopes), soil composition, physical instabilities, or elevation (e.g., height above sea level);
- areas in the watershed that are exposed to climate-related hazards, including floods, landslides and droughts.

Maps of the above areas can be overlaid with areas reflecting climate change projections. For example:

- future flood hazard maps can be developed using existing flood risk maps, historical rainfall maps, and projected rainfall change maps;
- future drought hazard maps can be developed using projected rainfall and temperature change maps for the years 2020 and 2050;
- maps of sensitive areas due to topography can be overlaid with climate hazard maps to determine the levels of exposure of sensitive areas to climate hazards.

From this type of assessment, it is then possible to develop a significant understanding of the areas and populations most exposed and most vulnerable to climate variability and change. For example:

- **land use and land cover maps** can be overlaid with vulnerability maps to determine which of the key land use and land cover (i.e., natural forests, cultivated areas, residential areas, others) are vulnerable to climate change;
- **maps of population distribution and vegetation use** (e.g., agricultural production) can be overlaid with vulnerability maps to determine which program and project areas in the area are vulnerable to climate change.

STEP 12: Identify socioeconomic drivers of vulnerabilities

Biophysical vulnerability maps can be extended to examine overlaps with population area as well as projected populations based on future growth scenarios. It is also useful to identify those socioeconomic factors that influence coping capacities. Common indicators of adaptive capacity include human development indices, population density, low levels of economic diversification, and dependence on agriculture for livelihoods. Education levels and literacy rates have also been associated with a population's ability to respond to changes.

In Africa, socioeconomic conditions are often rapidly changing and population is rapidly growing. For example, an area with low population may become highly populated over the lifetime of a project (with improvements in accessibility potentially being a contributing factor). These changes in vulnerability need to be explicitly accounted for in the assessment, including the costs and benefits of the adaptation options identified during the vulnerability assessment.

Community participation in identifying vulnerabilities and adaptation strategies promotes good governance and ensures that measures are relevant and sustainable.

Where there can be co-benefits between climate change adaptation and other economic or social objectives, there will be increased motivation for early action. Affected stakeholders can often identify risks, benefits, and lessons from past experiences that can be factored into the design of the adaptation strategy.

4.3.4 Adaptation assessment

STEP 13: Identify all potential adaptation options

Based on an understanding of expected and current climate change impacts and vulnerabilities, the project team can identify a wide range of adaptation options (cf. Section 5).

It is also important to recognise that in some cases, the best adaptation option(s) may be beyond the scope of an existing project or beyond the remit of the road authority. For example, realigning roads away from floodplains may be the most appropriate option in some situations, but may be difficult to address at the project stage. Others may including protecting the road infrastructure at the expense of accessibility during flooding (i.e. locate infrastructure at ground level instead of on embankments; the latter standing a greater risk of getting damaged during flooding). Similarly, watershed reforestation may be the most appropriate option in some situations. These should be taken up as part of an upstream planning process and can be flagged for such higher-level discussions.

STEP 14: Conduct consultations

Identification of adaptation options will necessarily involve inputs from a number of stakeholders. Conducting roundtable consultations provides useful input for the process of identifying and appraising the whole range of adaptation options.

STEP 15: Conduct economic analysis

The goal of the economic analysis of adaptation options is to provide decision makers with information pertaining to the expected costs and benefits of each technically feasible option and to rank these options according to the net total benefit (measured in present value terms) that each delivers.

The specific feature of climate change pertains to the uncertainty associated with its various impacts. Given the significant uncertainty associated with the predicted impacts of climate change, conducting a cost-benefit analysis of adaptation options requires paying particular attention to the treatment of risk and uncertainty.

This process is described in the ADB Guidelines, including the *methodological approach to cost-benefit analysis of adaptation options*, *Cost-benefit analysis of adaptation: Accounting for risk and uncertainty and Decision Rule* (ADB, 2011).

STEP 16: Prioritise and select adaptation option(s)

The adaptation assessment results in a prioritised list of adaptation options for implementation, which are selected from among several possibilities. Their prioritisation can be based on an assessment of their technical feasibility, their benefits and costs, their social acceptability, and the opportunities they may offer for synergies with national priorities. While the use and outcome of a cost-benefit analysis is often given more weight in the prioritisation process, it is important to recognise that other factors and criteria may also influence decision making.

The expertise required is multidisciplinary and as such is one of the more challenging aspects of adaptation planning. Options must be scientific, socially beneficial, and economically viable. Roundtable discussions involving different stakeholders can work well and can include, for example, the project engineers, environmental specialists, social safeguards experts, nongovernment organisations, implementing entities, and national climate change representatives.

4.3.5 Implementation arrangements

STEP 17: Establish arrangements for implementation

A lead organisation should be selected to implement the adaptation measures. While this organisation may be the main executing agency responsible for the road sector project (such as a ministry of transport or department of rural roads), other ministries, organisations, and institutes may be needed, given the cross cutting nature of the adaptation activities. As flooding is often a key impact on roads, a national disaster preparedness committee may also have a role to play.

When the project partners are selected, the scope of the project is likely to be limited by each partner's lines of responsibility. For instance, while the ideal adaptation approach may include engineering and environmental measures, the latter is likely to fall outside the roles and functions of a ministry of roads/transport. This adds further reasons for addressing adaptation at the earliest stages of policy and strategy development.

STEP 18: Identify needs for technical support and capacity building

Capacity and awareness required to manage climate variability/change and adaptation are currently limited. Provisions for training and capacity building will be needed for executing agencies, partner institutes, local communities, project management units, and contractors. An institutional assessment of existing capacity and gaps should inform this plan.

4.3.6 Monitoring and evaluation

Establishing monitoring and evaluation frameworks ensures accountability (and that lessons are learned) to inform future adaptation efforts.

STEP 19: Design a monitoring and evaluation plan

There is little experience worldwide in understanding how effective the different options to reduce vulnerability to climate change actually are, making monitoring and evaluation all the more important to develop improved knowledge. There are a number of challenges in doing so, including the long-term nature of actual climate change, the need to acquire appropriate baseline data and metrics for measuring vulnerability and isolating vulnerability to climate change from other sources of pressure.

The development of outcome level and output level indicators to assess the impacts of adaptation investments is ongoing. ADB (2011) identifies three levels of results monitoring: impacts, outcomes, and outputs.

Table 2 provides some examples of indicators at each level. Given the challenges related to measuring for impact, which may occur beyond the project life, output level indicators may be the most robust.

Table 2: Typical indicators of results monitoring (after: ADB, 2011)

Indicator Type	Indicator
Impacts (long-term effect)	Increased robustness of infrastructure design and long-term investment development Increased resilience of vulnerable natural and managed systems, such as flood management
Outcomes (process indicators)	Percent reduction in road closures due to structural failure, landslides or flooding Percent reduction in flooding where drainage capacity has been increased Improved decision making and sector planning based on climate change considerations Improved rural access
Outputs	Transport sector planning and documents include adaptation strategies Design and specification documents have resilience measures built in Maintenance programmes routinely cover preventative measures Length of road constructed to withstand climate change impacts Area of environmental protection measures

STEP 20: Feedback into policy-making and knowledge management processes

An adequate adaptation strategy is likely to be composed of a number of activities including *engineering measures*, such as incorporating design changes, and *non-engineering measures*, such as ecosystem resilience measures and early warning systems for disasters. Lessons from adaptation measures undertaken at a project level should inform policy makers about appropriate approaches at the sector and/or national levels.

4.4 Prioritisation of adaptation needs

Whichever climate adaptation measures are implemented, they are almost inevitably going to increase the cost of the provision of the majority of new roads or involve costs for the retro-fitting of such measures to existing infrastructure. A World Bank study (World Bank, 2009) found that the cost of adapting to climate change, given the baseline level of infrastructure provision, is no more than 1 to 2 per cent of the total cost of providing that infrastructure. However, this climate resilience may decrease costs over a longer period by preventing damage to, and interruptions of the infrastructure and improving social conditions. In general, the cost of adaptation is small in relation to other factors that could influence the future costs of the infrastructure.

Adaptation will initially require prioritisation of the needs. The process of prioritisation will need significant input from both road authorities and communities where different needs and importances may prevail and typically would require decisions of a strategic nature. The following will need to be considered in this process:

- Potential loss of life
- Availability of alternative routes
- Cost and consequences of closure
- Environmental/sustainability issues (i.e. pollution, aesthetics, etc.)
- Cost of repair
- Available funds
- Accessibility requirements.

Generally, safety (loss of life) considerations will take precedence over the others. However, other than landslides, the safety implications of road failures are generally minimal. It should be borne in mind that it is still more important to ensure that the primary and secondary road networks are maintained in good condition before concentrating on the tertiary or low-volume access road network.

It is important that all roads are carefully and correctly classified in terms of their required levels of serviceability as a part of the prioritisation process. This serviceability level will be a function of numerous factors, but mostly whether the road is purely an access road or whether it is also used for mobility (Figure 1). Various levels of serviceability, for instance, based on whether the road is primarily access or is also used for mobility and the expected needs of the communities affected can be identified (adapted from TRH 20 (DOT, 1990)). Such a classification can be directly related to the required prioritisation as shown in Table 3 for accessibility and in Table *4* for mobility.

Table 3: Guidelines for Levels of Serviceability for accessibility

Level of Serviceability	Required standards for accessibility		
	Comfortable driving speed (km/h)	Impassability	Duration of impassability
5	15	Frequently	Not more than 5 days
4	20	< 5 days/yr	Not more than 2 days
3	35	Never	None
2	50	Never	None
1	60	Never	None

Table 4: Guidelines for Levels of Serviceability for mobility

Level of Serviceability	Required standards for mobility		
	Max Roughness (IRI units in m/km)	Impassability	Duration of impassability
5	12	Not more than 4 days/yr	Not more than 1 day
4	9	Never	None
3	8	Never	None
2	7	Never	None
1	6	Never	None

Decisions on the classification of the level of serviceability should be based on a multi-criteria analysis and need to include issues such as social, traffic, connectivity and economic considerations. These analyses should be done at a strategic level. This will be based on the inventory of roads developed as part of the Road Asset Management System (RAMS) for any country as well as the existing condition, in order to identify any preliminary improvements. Assessors carrying out the visual condition assessments will need to be aware of the possible climate changes, which may vary from country to country, and make specific visual assessments of potential road and structure vulnerabilities based on the specific stressors identified for their individual countries or even regions within a country. The following should be considered in this assessment:

- The degree of exposure of the road infrastructure to different climatic hazards;
- The sensitivity of the infrastructure to such changes in climate, and;
- The adaptations necessary to mitigate the potential for damage (inclusive of adaptive capacity).

These actions that can be taken to reduce vulnerability to changing climatic conditions include avoiding, absorbing, and/or taking advantage of climate variability and impacts. Avoiding high risk areas is probably not possible for most existing roads but could be considered for new infrastructure. In most cases, the implementation of adaptation measures to existing vulnerable assets is the only option.

It is postulated that, in many cases, older engineered roads in a country's road network would be less affected by *gradual* changes in precipitation and temperature conditions. This is because these roads would more than likely have been upgraded or rehabilitated taking into account historical data on climate variability. However, the increase in extreme events that is expected to occur in the shorter term needs to be catered for on existing roads (and networks). The design of new roads and bridges needs to consider longer-term changes in local climatic conditions. However, this must be done with a degree of circumspection as it is neither practical nor economical to apply blanket solutions to entire road networks. A typical example of this would be during the design of a new road with numerous cuts and fills – it would be unwise, for instance, to increase the design Factor of Safety from the traditional 1.5 to say 1.7 on all cuts and fills – each one must be considered individually.

One of the biggest problems with installing resilience of the infrastructure is predicting the timing and quantum of climatic changes in relation to the design/service lives of the roads. An earth road may only have a design life of 5 or 6 years before significant upgrading is necessary. A large bridge on the other hand will be expected to provide good service for between 50 and 100 years, depending on its type. Whilst earth roads are likely to be highly vulnerable in places to climate impacts, the economic implications of these impacts would in most cases be negligible compared with these on structures such as bridges.

A number of sub-Saharan countries with coastlines have various small islands off their coasts. In addition, much of the economic activity and habitation of the countries is centred along the coastal areas, which are highly vulnerable to sea-level change. Particular attention will need to be paid to these areas.

No indication of costs is included in this report as these will be very project and country specific. Each proposed project will need to be assessed in terms of the costs of adaptation versus the cost of doing nothing, taking into account all of the engineering, social and environmental costs and the discounted overall life-cycle costs to allow fair comparisons. The overall economic impacts are, however, expected to be massive. As an example, the World Bank (2010) has estimated that climate change has the potential to result in a $ 3.1 billion impact to roads in Ethiopia (through to 2100) when the effects of temperature, precipitation and flooding increases are taken into consideration. They also indicate that these costs could be reduced by 54 per cent if adaptation policies are adopted through policy changes by the government. However, even with these adaptations, the potential cost to Ethiopian roads from climate change could be as high as $ 1.4 billion (World Bank, 2010).

Numerous adaptation options are available and can respond to various degrees of risk. These include:

- Avoid the risk (often impracticable);
- Remove or reduce the risk to a level that minimises the consequences and that can be handled using existing resources – this would make use of appropriate technological solutions;
- Implementation of appropriate adaptation measures.

4.5 Adaptation options in the roads sector

The types of actions that can be taken to reduce vulnerability include avoiding, withstanding, and/or taking advantage of climate variability and impacts. Avoiding areas projected to have a higher risk of potentially significant climate impacts is an important factor in planning decisions. If such locations cannot be avoided, steps need to be taken to ensure that the road infrastructure can withstand the projected changes. For example, the potential for increased flooding might be a reason to increase bridge elevations beyond what historic data might suggest. It should, however, be noted that most of the problems experienced are related to existing infrastructure that cannot be as easily relocated.

Secondly, the result of adaptive action either decreases a system's vulnerability to changed conditions or increases its resilience to negative impacts. For example, increasing temperatures could cause pavements on the highway system to fail sooner than anticipated. Using different materials or different approaches that recognise this vulnerability can lead to pavements that will survive expected higher temperatures better.

With respect to resilience, operational improvements could be made to enhance detour routes around flood-prone areas. Another example of resiliency is well-designed emergency response plans, which can increase resilience by quickly providing information and travel alternatives when roads are closed and by facilitating rapid restoration of damaged structures. By increasing system resilience, even though a particular facility might be disrupted, the road network as a whole still functions.

Adaptation options can generally be divided into engineering and non-engineering:

Engineering (structural) options:

The following are the primary engineering options (cf. Section 5):

- ***Subsurface conditions*** - the stability of any type of infrastructure depends on the materials on which it is built (subgrade). An important factor pertains to the degree of soil saturation, fluctuations in moisture content and the expected behaviour of the soil under saturated conditions. The type, strength, or protection of subsurface conditions and materials may have to be modified to control and prevent soil saturation from damaging the overlying infrastructure.

- ***Material specifications*** - materials of appropriate quality must be used in both unpaved and paved roads and unsuitable materials may have to be replaced or enhanced to preserve the expected lifetime of the road or structure.

- ***Cross section and standard dimensions*** - Standards may need to be revised, for example, to increase the crossfall of pavements in areas where one can expect a need to remove more water from the road. Similarly, standards (or guidelines) pertaining to road elevations or the vertical clearance of bridges may have to be revised upward.

- ***Drainage and erosion*** - upgraded standard designs pertaining to drainage systems, open channels, pipes, culverts and surfacing options (e.g. for steep hill road sections) are needed to reflect changes in future expected runoff or water flow and consequential potential for damage caused by erosion.
- ***Protective engineering structures*** - can be used to address rivers in spate, rising sea levels and storm surges. These may include drifts, dykes, seawalls, rocky aprons and breakwater systems.
- ***Maintenance*** – It is essential that all aspects of maintenance related to roads, drains and structures are diligently and timeously addressed. Most problems will be precluded by good maintenance.

Non-Engineering Options:

The following are the primary non-engineering options (cf. Section 6):

- ***Modify goals and policies*** - Incorporate climate change considerations into government goals and policies; these could be general statements concerning adequate attention of potential issues, or targeted statements at specific types of vulnerabilities (e.g., sea-level rise).
- ***Alignment, master planning and land use planning*** – to avoid or mitigate recognised vulnerabilities for access and economic development.
- ***Improved network management to anticipate and mitigate impacts*** - establishment and implementation of adaptation plans to provide primary and alternative access routings, from a transportation perspective, to mitigate impacts.
- ***Maintenance planning and early warning*** – for affected infrastructure that is already in place, increasing emergency and maintenance contingency budgets will enable better supervision and monitoring of the most vulnerable areas.
- ***Environmental management*** - environmental buffers moderate damage from floods, droughts, and landslides.

Do nothing or do minimal

In many cases there is just not enough budget to deal with all affected areas, roads and structures, or that the consequences of climate change are too severe to justify comprehensive physical adaptation. In these circumstances, a planned programme of dialogue with affected communities, well dispersed information and contingency programmes are necessary to minimise the adverse effects of these decisions.

5 Engineering Adaptation Options

5.1 Hazards, exposure and vulnerability

During the design of new infrastructure, climatic impacts should be determined as part of the Environmental Impact Assessment or Strategic Environmental Assessment and can thus be taken into account in the design, which can incorporate the necessary adaptation measures.

For existing roads, however, during the routine visual assessment of roads for input into Pavement Management Systems (PMS), it will be essential to include an assessment of the vulnerability of the road and associated structures (bridges, culverts, embankments, slopes, etc.) to variability and changes in the climate. Potential vulnerabilities and their mitigation will need to be identified. Guidelines for this will need to be included in the visual assessment manuals for the Asset Management System to assist assessors with these decisions. These should be developed in conjunction with the regional Asset Management Project currently being carried out under the AfCAP umbrella.

Unlike the prioritisation process, the vulnerability assessment would be a more tactical operation. The climate sensitivity of all components of the road infrastructure needs to be identified in terms of two primary parameters during routine road condition assessments. These are the potential for:

- *Damage (i.e. physical harm that impairs the value, usefulness or normal function of an asset)* – this can normally be repaired rapidly by local works teams
- *Collapse (i.e. structural failure initiated when the material is stressed beyond its strength limit)* – this is usually costly to repair and involves significant construction and repair works, often by specialised teams requiring a tendering process and can lead to road closures for an extended period of time.

In order to minimise the cost of acquiring data on the climate vulnerability of assets, it is essential that vulnerability assessments be carried out simultaneously with routine road condition assessments and that all necessary data elements are captured. However, the lack of effective asset management in many SSA countries will impact on the availability of historical asset condition data that would inform and support climate vulnerability studies and the identification and prioritisation of adaptation options. In order to achieve the latter, data will need to be collected directly for each road in the network.

In the Climate Threats Report (le Roux et al, 2016), risk is defined as a function of hazards, rural access road exposure and vulnerability in terms of rural community access. 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 of low volume road facilities, the associated structures and road environment as well as rural communities in places that could be adversely affected (within the hazard footprint);
- **Vulnerability**: Propensity to be adversely affected, considering the dependence of rural communities on these low volume access roads.

Adaptive capacity is the ability of the infrastructure to accommodate changes in climate with minimum disruption or minimum additional cost. This could be gauged by assessing the response to the following questions:

- What is the ability of the infrastructure, as it currently stands, to withstand the anticipated climate impacts?
- What are the regulatory, physical, managerial or competing-use barriers that could impede the ability of the infrastructure to accommodate climate impacts?
- Does the current state of repair of the infrastructure limit its ability to accommodate climate impacts?
- Are the changes in climate likely to exceed the infrastructure's capacity for adaptation faster than the infrastructure can be adapted?
- What steps currently underway are necessary to address climate variability that may impact the infrastructure?

The assessment of vulnerability of infrastructure to even current climate variability is challenging because of the range of factors, in addition to climate, which contribute to vulnerability. The assessment of road network vulnerability to changing climate is even more challenging because of the dynamic nature of vulnerability.

Thus, training of assessors to identify potential vulnerabilities in the road infrastructure will also be required – it is probably not cost-effective to include special assessors specifically to identify and record potential vulnerabilities. The routine assessment will thus need to include the field identification of potential vulnerabilities as well as an estimate of the associated risk, both requiring special training and skills to ensure useful results.

Using a structured programme, the identification of vulnerabilities can be relatively easily learned and can be based on an assessment form, identifying specific areas to be assessed and including an attribute and a potential severity in terms of consequences. An example of such a form is included in Appendix A. Current and future vulnerabilities should be identified if there are any suspected differences.

For prioritisation purposes, the hazard and the consequences need to be converted to some form of risk. The most promising and convenient means of doing this successfully in SSA is probably using a likelihood/consequence estimate of the risk (FHWA, 2012) or an impact/criticality assessment (WSDOT, 2011). These options are discussed in Appendix B, with recommendations on keeping them as simple as possible such that consistent and comparable results are obtained from a wide range of assessors.

In general, the vulnerabilities can be classified as those that are "ground-related" and those that are "topographically related". The ground-related vulnerabilities are related to parameters that describe landforms, hydrology and material properties and can be quantified, while the topographic vulnerabilities are more related to the concentration and surface flow of water as related to slope lengths, angles, surface characteristics, etc. It is important to note that with respect to slope instability, it is not a one-off storm that usually creates instability, but more the antecedent conditions and recent past precipitation events as discussed in Section 5.3.2.5.

Life-cycle cost analyses should include a factor for climate resilience of the facility, although assumptions will mostly have to be made regarding the benefits – little precedent is available to assist with estimating these benefits. Any climate resilient road or structure is likely to cost more than conventional structures to construct. However, the total life-cycle cost is generally expected to be less for such structures, unless no extreme events occur and the additional resilience was not called upon and becomes redundant (effectively becoming an insurance policy). This is, however, probably an unlikely scenario during the life cycle of most infrastructure facilities.

5.2 Consequences and mitigation

Road infrastructure should always be designed taking local environmental conditions into account (climate, topography, traffic, etc.). Historical records of climate are generally used to determine temperatures and precipitation trends. This existing data is probably generally inadequate now with the accelerating climate change trends being observed, although some preliminary trends may be usefully based on the weather records over the past 5 or 10 years. However, for general design purposes, it is probably better to make use of the high resolution predictions that are becoming increasingly and more readily available.

Modern, high volume roads are designed to last from 30 years (pavement structures, excluding the surfacing) to 100 years (major structures), or longer (i.e. long-life pavements). Similarly, low volume engineered earth roads are expected to last between 5 and 6 years, and the wearing course of gravel roads between 6 and 10 years, whilst their drainage structures and bridges are expected to last between 50 and 100 years. Hence, changes in climate will need to be factored in and considered in the design of all new roads and major rehabilitation projects so as to equal or improve on the typical life expectancies referred to above.

The consequences of climate change are wide and varied and need to be assessed case by case. Mitigation, however, should preferably be done pro-actively, but there will always be instances of extreme conditions that were not planned for. In general, pro-active mitigation is essentially the application of good engineering practice, including design, construction and maintenance. Normal engineering principles applied properly, for example would provide for correct pipe diameters for culverts based on the current expected water flows, as well as specific return periods. Adjustments to the return periods (factored for expected changes in water flow rates) based on climate predictions, however, will generally need to be made, or where these are not available, longer return periods can be used.

Various climate change parameters or “stressors” such as average temperature, temperature ranges, average and seasonal precipitation, lower humidities, higher wind speeds and extreme weather events, etc. could all contribute to the need for more resilient engineering solutions. Changes in precipitation intensities and duration are probably more likely to have major influences on the road infrastructure than the actual changes in precipitation.

Climatic effects on roads are mostly taken into account using some form of moisture mapping, such as the Weinert N-value or Thornthwaite’s Moisture Index, the latter becoming more popular recently. Both of these indices are based mainly on temperature, rainfall and evaporation (or evapotranspiration) and updated maps or data specific to individual sites, indicating the change of these with time will need to be developed for the SSA region.

The potential hazards related to the different expected climatic stressors for the various low volume road facilities and associated structures and their likely consequences are summarised in the tables below, with detailed guidelines related to the preventive and adaptation measures being provided for each facility and suggested remedies in Section 5, and summarised in Section 5.10).

Increased precipitation is predicted for some areas – water is widely known as the worst enemy of roads and the presence of additional water is highly likely to result in numerous premature road failures and is probably one of the most probable climate threats. The consequences of increased precipitation are summarised in Table 5.

Table 5: Hazards related to increased precipitation

FACILITY	CONSEQUENCE - POSSIBLE PROBLEMS AND DAMAGE
Unpaved roads	Flooding (excessive surface water) Softening of material Impassability Erosion of surface Loss of shape Blockage of drains
Paved roads	Loss of strength of layer materials, especially in the upper base layer Damage to thin surfacings Damage to pavement edges Blockage of drains and culverts Erosion of unpaved shoulders
Earthworks	Increased slope instability Saturation and weakening of soils Erosion of surface and drains Undercutting Excessive vegetation growth Siltation and blocking of drains
Subgrade soils	Expansion and cracking Collapse and settlement Softening of support More movement of saline materials Deformation of rigid structures Erosion
Drainage (water from within road reserve)	Accumulation of water adjacent to road Erosion of road surface and drains Softening of materials beneath road
Drainage (water from outside road reserve)	Erosion of embankments and abutments of culverts and bridges Silting/sedimentation of culverts and bridges Scour of bridge foundations Overtopping of bridges and damage or destruction Damage to bridges by debris
Construction	Excessive moisture in materials – construction delays Reduced working periods and increased delays Water damage to partially completed works
Maintenance	Additional maintenance necessary More bush clearing Additional damage to drains Need to retain good shape of unpaved road surfaces Improved unpaved shoulder maintenance Pothole patching and crack sealing of paved roads

Decreased precipitation will generally result in improved road support conditions (drier strengths mobilising soil suction) and less drainage problems. However, the reduction in precipitation is expected to be associated with less frequent but more intense storms, that could lead to stronger, more erosive runoff and stream flows with increased erosion and siltation. It is also likely that there would be more rapid damage to road structures as a result of water not being removed from the road surface and side-drains as quickly and efficiently as necessary. The likely consequences are summarised in Table 6.

Table 6: Hazards related to decreased precipitation (but more extreme events)

FACILITY	CONSEQUENCE - POSSIBLE PROBLEMS AND DAMAGE
Unpaved roads	Increased wear and loss of gravel from drier surface Increased dust emissions over longer periods Increased development of loose material and roughness (corrugations) More rapid deterioration of gravel due to loss of cohesive fines
Paved roads	Damage to thin surfacings and asphalt More rapid binder deterioration
Earthworks	Drying out and cracking Rapid ingress of moisture into tension cracks in slopes (slope failures from shrinkage and tension cracks) Increased erosion from more intense storms Damage to vegetation by more wild-fires More difficult to establish erosion protection through bio-engineering
Subgrade soils	Drying out of materials Shrinkage and cracking (volumetric movements)
Drainage (water from within road reserve)	Drying out of drains – more susceptible to erosion when rain does come Higher risk of burning of roadside vegetation and loss of root stabilization Less vegetation to bind soil
Drainage (water from outside road reserve)	More erosion More silting and sedimentation Overtopping of bridges Damage to bridges and culverts from debris
Construction	Insufficient water for construction Quicker loss of compaction water due to evaporation
Maintenance	More unpaved road surface maintenance More maintenance to drain damage Increased surface erosion repairs

A general increase in temperature is predicted for most of SSA. The potential consequences of this are summarised in Table 7.

Table 7: Hazards related to increased temperatures

FACILITY	CONSEQUENCE - POSSIBLE PROBLEMS AND DAMAGE
Unpaved roads	More rapid drying out of road Increased cracking Increased development of roughness (corrugation) Quicker generation of loose material
Paved roads	More rapid ageing of bituminous binders Softening of bitumen in asphalt and more rapid deformation when hot Expansion and buckling of concrete roads and structures
Earthworks	More rapid drying out and cracking Loss of vegetation (or change of species) on side slopes (insufficient water) More wildfires causing loss of root binding
Subgrade soils	Minimal effects Some shrinkage of soils
Drainage (water from within road reserve)	More rapid drying out, cracking and erosion Loss of vegetation (or change of species) on side slopes More wildfires causing loss of root binding
Drainage (water from outside road reserve)	Greater expansion/contraction of bridge elements
Construction	Quicker reactions when cement stabilising Quicker drying of concrete
Maintenance	Ensuring vegetation is kept cut to minimise wild-fires Regular maintenance of bridge movement components (bearings and construction joints)

It is predicted that, in general, temperatures will rise but there could be localised areas where temperatures could drop slightly. It is, however, highly unlikely that these temperature decreases would result in an increase in freezing of water in the roads, which in SSA is essentially currently restricted to localised areas at extremely high altitudes. A summary of potential consequences is provided in Table 8.

Table 8: Hazards related to decreased temperatures

FACILITY	CONSEQUENCE - POSSIBLE PROBLEMS AND DAMAGE
Unpaved roads	No effects except at extreme altitudes – freezing of water in road surface
Paved roads	Reduced windows for construction of bituminous surfacings Less rapid ageing of bituminous binders More brittle fracture of bitumen when cold
Earthworks	Possible freezing of soils at high altitudes
Subgrade soils	Minimal effect
Drainage (water from within road reserve)	Minimal effect
Drainage (water from outside road reserve)	Minimal effect
Construction	Reduced working periods for certain operations (paving, stabilization)
Maintenance	Increased maintenance of bituminous surfacings (crack sealing and pothole repair)

The potential for higher wind speeds appears to be relatively high. These could affect a number of infrastructure properties, but would mostly increase the risk for wild-fires, with specific consequences. Much of the wind problem is expected to be associated with increased numbers of tropical cyclones in coastal areas, although increased wind conditions can be expected inland as well. A summary of potential hazards is provided in Table 9.

Table 9: Hazards related to increased windiness (and consequent wild-fires)

FACILITY	CONSEQUENCE - POSSIBLE PROBLEMS AND DAMAGE
Unpaved roads	More rapid drying out Increased deterioration rates due to fines loss Increased accumulation of sand
Paved roads	Increased accumulation of sand Possible damage to bituminous surfacings caused by fire
Earthworks	Loss of vegetation due to burning Higher erosion rates on side slopes
Subgrade soils	No effect
Drainage (water from within road reserve)	Loss of vegetation due to burning More erosion of drains
Drainage (water from outside road reserve)	Greater wind-load on bridges Loss of vegetation due to burning More erosion of drains More debris in flood waters due to fire damage Fire damage to bridges (wooden mainly but also concrete)
Construction	More dust Quicker evaporation of construction water
Maintenance	Increased unpaved road maintenance to minimise corrugations resulting from dust loss Regular clearing of river debris and catchment vegetation

As well as actual damage to the road infrastructure, non-engineering issues such as poor visibility for road users resulting from smoke on the roads could lead to unsafe conditions and damage to roads and road furniture resulting from increased accidents. These are discussed in a separate section.

The effects of sea-level rise and storm surges is limited to very localised areas and may only have a small impact on the road network, but should be considered in those areas of coastal roads where the population may be affected (Table 10).

Table 10: Hazards related to sea-level rise and storm-surges

FACILITY	CONSEQUENCE - POSSIBLE PROBLEMS AND DAMAGE
Unpaved roads	Flooding and storm damage Increased subgrade moisture contents Erosion and siltation
Paved roads	Damage to road surfacings by salts and water impact Deposition of debris Increased subgrade moisture contents and reduced support
Earthworks	Increased moisture contents with sea-level rise Fluctuating moisture levels with surges Reduced soil strengths
Subgrade soils	Increased moisture contents
Drainage (water from within road reserve)	Accumulation of water adjacent to road Erosion Softening of materials
Drainage (water from outside road reserve)	Scour of foundations Deposition of debris Increased salt damage to concrete and steel
Construction	Wetter conditions Saline waters
Maintenance	Increased maintenance in coastal and low-lying areas

As discussed previously, rainfall is expected to generally decrease, but it could increase in some areas. This would result in changes in ground-water level, with corresponding changes in the soil properties. However, over most of SSA, existing ground water levels are deep, other than in coastal areas and near large dams and drainage structures, and fluctuations in ground water level will have minimal impact on roads. Possible hazards related to groundwater level changes are summarised in Table 11.

Table 11: Hazards related to changes in ground-water level

FACILITY	CONSEQUENCE - POSSIBLE PROBLEMS AND DAMAGE
Unpaved roads	Wetter or drier subgrades
Paved roads	Wetter or drier subgrades More saline conditions affecting pavement structures
Earthworks	Slope instability (localised)
Subgrade soils	Volumetric movements possible
Drainage (water from within road reserve)	Localised seepage and springs
Construction	Difficult working conditions
Maintenance	No marked changes

It should be noted that many of the predicted changes in climate (particularly temperature) are actually quite small in terms of even the day to day variations in these properties currently experienced, although they may prevail over much longer periods. Other than precipitation changes, which are likely to have a significant effect on water control, the effects of other stressors are likely to be minimal, but must certainly be considered in pavement and earthwork design. Other issues such as changes in water availability, land-use and local vegetation species resulting from climate change may have equal or greater impacts on some of the issues identified above. These should be viewed in the context of many road construction activities (e.g. re-gravelling, resealing, overlaying, etc.) only having expected design lives of between perhaps 5 and 10 years.

A simple analysis tool (spread-sheet based) has been developed and is available on CD ROM (NCHRP, 2014a). This identifies a wide range of climatic stressors, various impacts and adaptations for their minimisation using a decision based process.

It is interesting to note that maintenance activities appear in the tables above time and time again. Good maintenance is a part of good engineering and can go a long way in reducing climate change vulnerabilities. A specific section on maintenance is thus included in this report (cf. Section 5.8).

Another tool has been developed for many African countries (still incomplete in many respects) that identifies at a regional/district level, various vulnerability characteristics. The Global Facility for Disaster Reduction and Recovery (GFDRR, 2016) has created the online tool (***ThinkHazard!***), which enables non-experts to consider natural hazard information in project design. This tool should be assessed for its usefulness at country level.

Once vulnerabilities are identified and adaptations for each of these are proposed, adaptation plans should be developed and prepared for implementation. These should then be monitored and evaluated after implementation to ensure that they are actually adequate and most appropriate.

The importance of good design cannot be overemphasised. Although many possible adaptations are identified and described in this document, conventional design criteria for rural access roads should not be forgotten. This is particularly relevant to geometric design, which is not covered in detail in this report. Issues such as vertical and horizontal alignment are, except for roads being designed anew, normally controlled by the existing track or road alignments with minor adjustments for safety reasons. Horizontal geometry generally follows the existing track with perhaps some reduction in curvature at sharp bends, and where land expropriation problems are not an issue in most cases.

5.3 Increasing resilience of roads

This section deals with adaptations required for roads in terms of the different road attributes.

It is interesting to note that in Ghana, it has been concluded that the engineering solutions needed to make a climate-resilient road can to a very large extent be found in the existing design manuals, "from solutions to hydraulic-related problems, such as scour and sedimentation, to problem soils and sub-grade problems as well as slope stability and surface drainage solutions" (COWI, 2010). The problem identified is a *lack of appropriate and timely maintenance*. While it is agreed that current designs are probably sufficient if implemented properly and with *adequate drainage* facilities for extreme events for critical infrastructure, there are a number of adaptations or specific design decisions that can increase the resilience of roads to climate change. These are detailed in the remainder of this section.

5.3.1 Unpaved roads

Unpaved roads consist of earth roads or gravel roads. Earth roads may be either constructed using the in situ material that has been moved and shaped (engineered earth roads) or the in situ material that has been developed into a "road" by vehicles moving along it (un-engineered earth roads – typically constructed at natural ground level). Gravel roads, on the other hand, are constructed of well-compacted, selected gravel, resilient to erosion and weakening by water and are, by their nature, generally classified as all-weather roads. It should be noted that all unpaved roads, including gravel roads, can be impacted by erosion on steep gradients in mountainous or hilly terrain.

The main climate impacts on unpaved roads are related to the presence of excessive water on the road surface and within the pavement structure, which is one of the scenarios predicted for many parts of SSA (increased precipitation or extreme events). The impact is also strongly related to the duration and intensity of the precipitation. Increased temperatures will result in drying out and shrinkage (and cracking) of the road structures where excessively plastic materials are used.

In order to ensure adequate climate resilience, however, the unpaved roads must not only be designed and constructed adequately, but must be maintained to ensure that the road surface sheds water rapidly and effectively, without excessive erosion.

The resilience to extreme weather events of the different types of unpaved roads is very different and each of these is dealt with separately below.

5.3.1.1 Un-engineered earth roads

Description

In the case of un-engineered earth roads, the quality of the material on which the vehicles move (driving surface) is purely a function of the in situ material, which seldom complies with the specifications for good wearing course gravel. This material has normally only been subjected to traffic compaction (usually minimal) and has no constructed shape or drainage (Figure 9). Un-engineered earth roads are thus highly susceptible to a range of problems:

- They have little mechanical strength as a result of their minimal compaction - densities are thus low, making them more permeable, weaker and more prone to deformation (shearing and rutting) under traffic when wet
- They are usually at or below natural ground level and precipitation will not be removed from the road surface or surrounding environment unless they are on a grade
- Traffic initially wears away the organic binders (roots and grass) and then starts developing a track below natural ground level that becomes a flow path for precipitation
- The low strengths and densities increase their potential for being lost by water and wind erosion.

Figure 9: Typical un-engineered earth road showing damage caused by water retention

Adaptation

There is nothing that can be done to un-engineered earth roads in terms of adaptation for changes in precipitation, temperature or extreme events. Even increased maintenance will only lower the road surface below the natural ground level exacerbating any problems.

For a more resilient road, un-engineered earth roads thus must be improved by shaping and raising to at least engineered earth road standard, but preferably to a properly designed gravel road standard, inclusive of the provision of adequate side and cross drainage as well as river crossings. Only if the natural in situ material classifies as a suitable gravel wearing course should it be upgraded to an engineered earth road.

The main impact of climate change on un-engineered earth roads will be in terms of increased precipitation, with temperature changes, increased windiness and groundwater level fluctuation having minimal impact, unless impacted by local floods.

5.3.1.2 Engineered earth roads

Description

Engineered earth roads are still constructed from the in situ materials but these materials are typically moved during the forming of side drains on to the road surface to raise the road above the natural ground level and provide better cross-sectional shape. This results in better drainage of the road surface and enhanced performance (Figure 10). However, the degree of compaction applied to engineered road surfaces is normally minimal, if any, and there is usually no quality control testing carried out. In addition, the materials comprising the wearing course seldom comply with the necessary specifications for good wearing course gravels. Their performance is thus only marginally better than un-engineered earth roads when subjected to either high traffic counts or inclement weather conditions.

Figure 10: Typical engineered earth road showing shaped structure and side drains

Adaptation

As is the case for un-engineered earth roads, unless the in situ material actually complies with the necessary gravel wearing course specifications, there is little that can be done to engineered earth roads in terms of adaptation for changes in precipitation, temperature or extreme events, unless the road surface is raised well above the natural ground level, and adequate side and cross drainage as well as river crossings are provided. If the material complies with the specification, then properly controlled construction must be carried out, carefully ensuring that all oversize material is removed and that the specified degree of compaction is achieved. In addition, the shape of the road (i.e. cross-fall and crown) must be carefully controlled. Overall, if the in-situ material properties do not comply with the specification for wearing course gravels, the road must be upgraded to an imported gravel road standard to ensure climate resilience.

The main impact of climate change on engineered earth roads will be in terms of increased precipitation, with temperature changes, increased windiness and groundwater level fluctuation having minimal impact, unless impacted by local floods.

5.3.1.3 Gravel roads

Description

Gravel roads are properly engineered roads without any bituminous, concrete, block or other protective surfacing. The engineering component of gravel roads, however, differs significantly from one road authority to another. A gravel road should consist of a properly shaped structure, raised above the natural ground level to an extent that allows suitable cross-drainage structures. In addition to this, appropriate side drains should be constructed and a wearing course gravel complying with certain criteria should be placed on top of the pavement structure, with or without an underlying “subbase” depending on the quality of the supporting layers. The wearing course must then be generally constructed and specifically compacted to an appropriate density, to optimise the benefits of the good quality gravel. Without any of these inputs, the selected material, no matter how good it is, will be rapidly lost under traffic and climatic effects.

Shoulders are considered as part of the gravel pavement and these too should be designed and constructed to ensure that the road sheds all rain water rapidly and effectively, without significant softening, erosion or scouring.

Depending on the traffic and climate, and assuming that periodic maintenance is carried out, the wearing course would normally be expected to last for between 6 and about 10 years, by which time it will have worn away (traffic and weather wear) and would need to be replaced. Poor construction (mostly insufficient compaction and poor material selection) will usually result in the material not lasting even the minimum 6 years expected.

Apart from the obvious problems related to extreme precipitation events and erosion of unpaved roads, the impact of less rainfall on unpaved roads will be notable. Unpaved roads deteriorate quicker in the dry season, when the moisture in the wearing course dries out and the effective cohesion due to soil suction is lost. This results in greater dust emissions, the loss of the cohesiveness (in the dust) and the greater propensity to form corrugations.

Adaptations

A properly designed and constructed gravel road with appropriate wearing course materials should be able to withstand even the most severe climatic effects, with the possible exception of gravel roads on steep gradients where they could be impacted by erosion. Excessive water is really the only climatic attribute likely to have a significant effect on the performance of gravel roads. This water could arise from local precipitation or rainfall somewhere distant that flows down nearby rivers causing flooding, as occurs in the Limpopo and Zambezi valleys in Mozambique. The optimum solution in these areas is to place the road outside the normal flood limits, but this is usually impracticable.

In order to obtain the best durability and performance (and hence the best climate resilience), the material should comply with performance-related specifications as far as possible. Material deficient in plasticity, grading or strength will not perform satisfactorily, without increased maintenance, and will not be climate resilient.

Typical specifications for good gravel wearing course materials are summarised in Figure 11 for material test results using ASTM/AASHTO based test methods and in Figure 12 for results based on BS test methods.

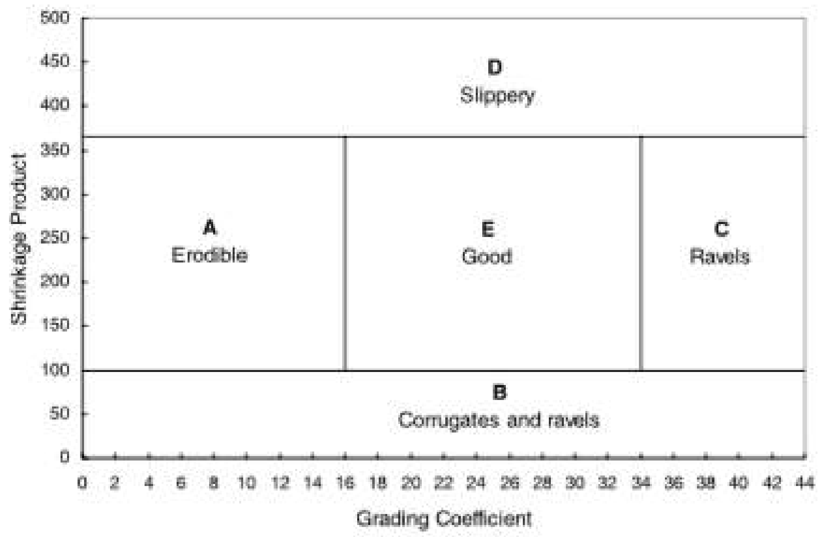


Figure 11: Specification for wearing course gravels using ASTM/AASHTO based test methods

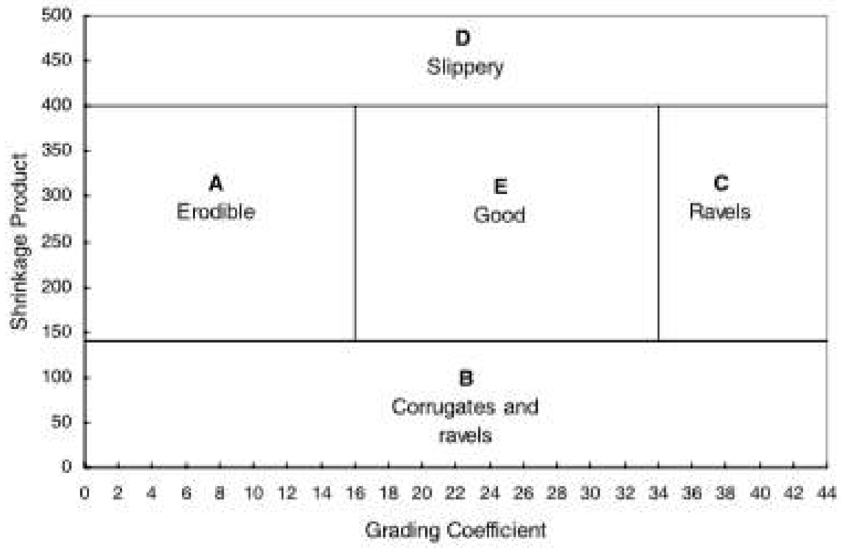


Figure 12: Specification for wearing course gravels using BS based test methods

In areas that are expected to have higher precipitation or those where more frequent extreme events are to be expected, it will be important to ensure that the minimum Shrinkage Products in Figure 11 and Figure 12 are maintained and that the Grading Coefficients in the two figures remain between the respective lower and upper limits shown, i.e. 16 and 34 for ASTM testing and 14 and 30 for the BS test methods. Materials with properties outside these limits will be particularly prone to erosion and damage under heavy precipitation.

It will be equally important that the roads are constructed properly. Construction requirements are primarily that excessive oversize material is removed (this interferes with compaction and results in roads more prone to erosion) and that the wearing course material (and shoulders) is compacted to a minimum of 98% heavy compaction effort.

It is also essential that good maintenance is regularly applied to the road. This must ensure that deep depressions (ruts or potholes) are not permitted to form in the wearing course, the shoulders are properly shaped to ensure that water runs off the wearing course into the side drains and that no windrows are left after blading impeding removal of water from the wearing course surface.

Periodic maintenance should also be adapted to improve the resilience of the road network. During regravelling or ripping and reshaping, the material properties should be modified where necessary (typically by stone removal and/or blending of additional materials and the construction quality can be improved where it is found to be deficient.

The generation of dust from unpaved roads is almost inevitable from most materials that have a significant silt and fine sand content. In areas where the dry/drought season becomes longer, it may be necessary to apply dust palliatives to selected sections of the road, such as those passing schools or clinics or where geometrics and sight distance are poor. Chemicals such as lignosulphonates and magnesium/calcium chlorides are usually cost-effective in these cases. The loss of dust also reduces the plasticity of the materials resulting in quicker formation of corrugations, which need to be maintained more regularly. Generally, corrugations form quicker than other defects and dragging with tyre drags is a cost effective means of maintaining these roads.

There will be areas where even properly engineered and constructed gravel roads are subject to on-going damage due to flooding, which may require costly and frequent maintenance. In these areas, consideration should be given to localised lengths of paved or even concrete roads.

5.3.2 Paved roads

Low volume paved roads usually consist of a series of layers of material with properties that improve towards the top of the pavement. On top of the base course is a wearing course that can consist of various materials, typically a thin bituminous surfacing (spray seal). However, thin asphalts, concrete, interlocking bocks, cobble-stones or various other weather-resistant surfacings could be used.

Paved roads may be sub-divided into those surfaced with a bituminous surfacing (asphalt or spray seals) and those with non-bituminous surfacings (concrete, block paving, cobble stones, paving slabs, etc.). Their respective performances under wet and hot conditions can differ and they will thus be dealt with separately in terms of their adaptation measures.

As in the case of unpaved roads, there may be areas where conventional paved roads with thin surfacings are not effective and, again, consideration should be given to retaining them in an unpaved condition (the environmentally-optimised design concept) with the planned capacity to apply more frequent maintenance when necessary, e.g. after severe flooding.

5.3.2.1 Thin bituminous surfacings

Description

The bitumen is the most important part of thin flexible pavement surfacings (seals) in terms of waterproofing the pavement structure, and deterioration of this will result in degradation and eventual failure of the surfacing. Bituminous binders deteriorate through the loss of volatiles and oxidation, which are enhanced by high temperatures and increased ultra-violet radiation. This deterioration of the bitumen results in hardening and drying of the bitumen and ultimately cracking of the seal and the ingress of water into the pavement if the cracks are not timeously maintained.

Conversely, one of the problems with high water pressures beneath an intact or uncracked road surface is that under the imposed hydraulic pressure, the impermeable surfacing can lead to high uplift pressures beneath it resulting in lifting and disintegration of the surfacing (Figure 13).

Figure 13: Loss of surfacing caused by high uplift pressures during flooding[2]

Extreme water conditions will inundate the structural layers beneath the surfacing leading to weakening of these materials and structural failure of the road.

Typical thin bituminous surfacings on roads generally need to be rejuvenated or resealed every 7 to 10 or 12 years, depending on the nature of the bituminous surfacing. The necessary adaptations to the bitumen type and seal design for climate change can thus be incrementally introduced over time during such periodic maintenance interventions.

Adaptation

The main adaptations in terms of bituminous surfacings will be to make use of bitumens that are modified and introduced with time in order to provide better resistance to climatic deterioration. The use of multiple seals also provides better protection of the bitumen deeper in the seal and will thus be slightly more resistant to cracking and deterioration over time.

Increases in moisture content in the subgrade will result in higher pavement deflections under heavy loading, which in turn will cause more rapid cracking of aged binders that have stiffened up. The periodic and managed application of binder rejuvenators or dilute emulsion fog spays will maintain the bitumen in a more ductile condition and avoid such cracking to a major extent. On the other hand, reductions in moisture content in the subgrade will lead to lower deflections and less potential for fatigue cracking. However, if the subgrade dries out with significant shrinkage, cracking of the overlying pavement structure could occur. Good drainage of the road environment is essential to minimise such moisture fluctuations (see Section 5.5).

In areas with the potential for increased rainfall, it will be important to avoid pavement designs that produce a “bath-tub” effect, i.e. where the pavement structure is more permeable than the surrounding layers resulting in accumulation of water in the structural layers of the pavement and the development of high pore-water pressures under traffic loading.

It is known that the materials within and beneath the pavement structure reach an equilibrium moisture content in the central areas of the pavement, outside the “zone of seasonal moisture movement”. The actual moisture contents at equilibrium are generally between about 55 and 85% of Optimum Moisture Content (OMC) in the structural layers and about OMC in the subgrade. Prediction models for these values make use of the subgrade material properties and the climate, in terms of Thornthwaite’s moisture index (I_m). Should climate change result in significantly less precipitation and higher evapo-transpiration these figures may change slightly, but it is highly

[2] Photograph: Department of Transport and Main Roads, Queensland, Australia

unlikely that the materials in the equilibrium moisture zone will dry out to the extent that shrinkage leading to cracking will occur.

However, in the zone of seasonal moisture movement, the variation may be significantly higher leading to shrinkage and cracking. One way of avoiding this is to move the zone of seasonal moisture variation away from the pavement carriageway, by sealing the shoulders with an impermeable surfacing. The sealing of shoulders with a different type of seal (e.g. double seal on the carriageway and single seal on the shoulder) is often used for delineation of the carriageway and safety reasons. Improper sealing of the shoulders could lead to cracking and ravelling of the shoulder seal (Figure 14), which in turn could cause greater seasonal moisture variation within the pavement carriageway, potentially resulting in shrinkage and cracking.

Figure 14: Deterioration of single chip seal shoulder compared with double chip seal on carriage way

In areas where drainage of the pavement environment is difficult and the formation has inadequate height, periodic flooding is likely to result in the moisture contents within the structural layers increasing to more than OMC (up to about 125% in the saturated condition) and the structural properties of these layers decreasing significantly. It may be necessary in some instances to close the road or impose load restriction measures after periods of intense/extreme rain or flood events. Such restrictions are usually difficult to control and enforce and should be avoided as far as possible.

As pavement technologies develop and are implemented, some of the more innovative developments such as “Water Retentive Pavements” which have a sub-layer consisting of water retentive materials that absorb moisture and then evaporate it through capillary action when the pavement heats up or “Heat-shield Pavements” which reflect near-infrared radiation by the application of special coating materials on their surfaces may actually benefit from changes in climate.

5.3.2.2 Asphalt surfacings

Description

Although it is not very common, some low volume roads may be paved using asphaltic concrete. Asphalt is a thermally dependent visco-elastoplastic material and as such is affected strongly by high and low temperatures. It is also costly compared with traditional spray seals. Significant reductions in temperature will make asphalt stiffer and more prone to cracking under heavy loads while significant increases in temperature will result in softer asphalt that is more prone to rutting and deformation under traffic. Bearing in mind that asphalt is not used frequently on low-volume roads and the number of heavy vehicles is usually small, this is unlikely to be a major problem in most rural areas.

In addition, as the life of a new asphalt surfacing layer is typically 10 to 15 years, adjustments in their design can be made at regular intervals during their service lives. Designing for different temperature conditions in the future is unlikely to have an effect on the cost of resurfacing as there are only small difference in the costs of different bitumen types, necessary to adapt the design for differing temperatures.

It should be noted that there are currently wide seasonal and daily variations in temperature within roads, and the expected changes are probably going to be minimal with respect to these variations. Temperatures at depths of 20 and 200 mm in the road as well as the ambient air temperature (Figure 15) have been monitored in a variety of road types over a period of nearly two years. The range of air temperatures was between -6 and about 50°C while the upper road temperature varied between 4 and 60°C and at a depth of 200 mm between 9 and 48°C. The question of whether a 3 or 5°C temperature change would have a notable impact on such a road then arises.

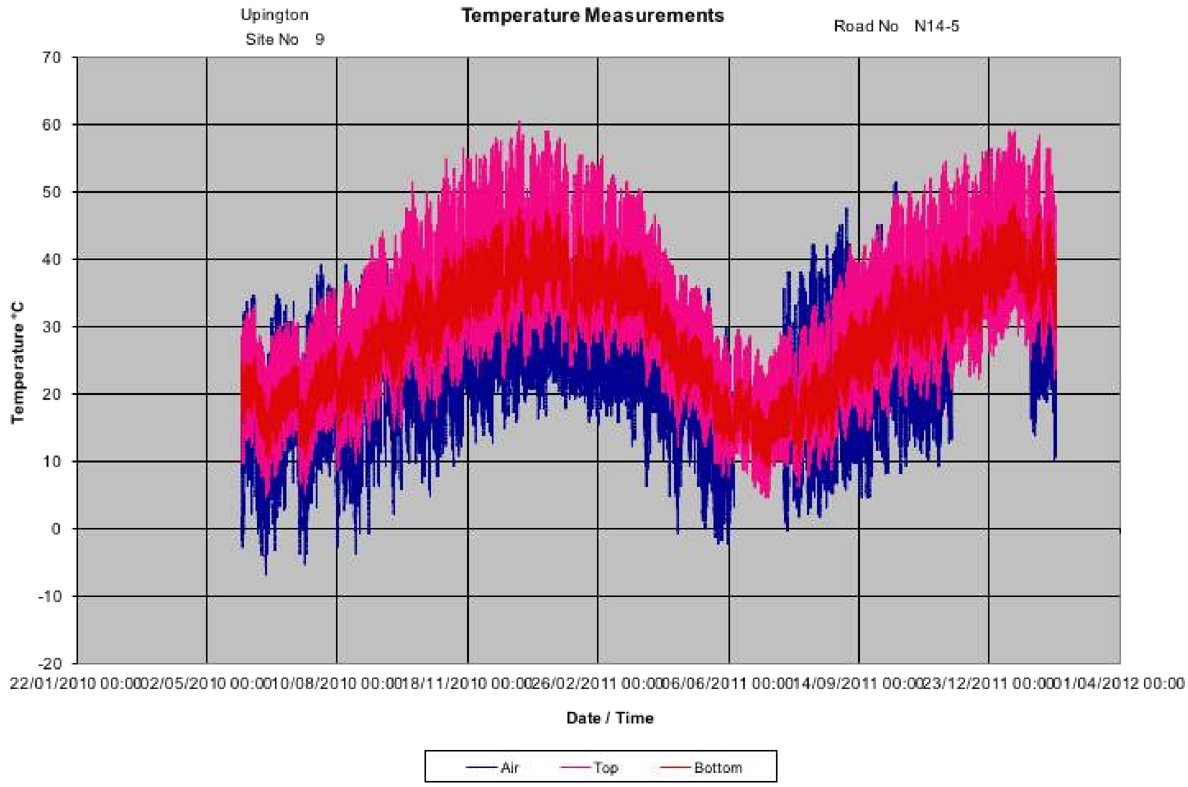


Figure 15: Variations in air and road temperatures with time

Typically for asphalt designs, the design criteria include the average and standard deviation of the yearly 7-day average maximum air temperature and the yearly 1-day minimum air temperature. These are converted to the yearly 7-day average maximum and the yearly 1-day minimum pavement temperatures using standard data. What is most likely to change in future is the number of extremely hot days per year (taken as those days hotter than 32°C) which are likely to double or even triple in many areas.

As there is an international move towards classifying bitumen binders according to the performance-grading (PG) specification, which is essentially temperature based, problems with regard to temperature variations will be reduced. The PG classification uses a minimum and maximum temperature range for each binder, e.g., a PG 76-28 bitumen would perform in the range between minus 28°C and plus 76°C. The low temperatures will seldom be encountered in SSA (i.e. with the lowest minimum being about -10°C and the upper temperatures being about 80°C specified, these are generally higher than those normally encountered on most low volume roads in SSA.

Adaptation

Asphalt is normally designed to perform best within a specified temperature range – this includes the expected minima and maxima.

In areas where higher temperatures or longer periods of extreme temperatures (> 32°C) are expected, bitumen binders with slightly higher softening points should be used, or modified binders. This can be an ongoing and it is likely that the properties of binders will evolve with their modification by suppliers as temperatures increase over time. As each road is resealed or overlaid during planned periodic maintenance or structural enhancement interventions, this modification can be included and there is no real need for proactive intervention. Where temperatures are expected to decrease, bitumens with slightly lower softening points may be more desirable to promote their durability and minimise excessive cracking due to higher stiffnesses.

5.3.2.3 Concrete surfacings

Description

Roads with a concrete upper layer are probably the most resilient of all "paved" roads towards weather effects, but their use is rather limited in the provision of low volume roads to restricted problem areas, such as very steep gradients, climbing curved areas and built-up areas without proper (waste) water removal . Concrete is a high strength engineered material that is designed specifically for the situation it will be used in and is resistant to erosion and deformation. Various types of concrete roads can be implemented, including jointed andcontinuously reinforced concrete and roller-compacted concrete. However, problem related to excessive thermal expansion when movements at both ends of the block are constrained can result in buckling and uplift, especially in the case of thin-layer continuously reinforced concrete (Figure 16).

Figure 16: Lifting of thin continuously reinforced concrete road resulting from thermal expansion

Although the concrete pavement may be resilient to any climatic effects, the potential for underlying layers and edge supports to be eroded remains high under extreme events and thus could lead to "undermining" and collapse of the concrete pavement. Water is usually only likely to enter and affect concrete roads from the shoulders, unsealed expansion cracks and unrepaired potholes and cracking.

Adaptation

In order to avoid buckling of concrete roads it will be necessary to ensure that expansion joints are included in the concrete, even in continuously reinforced layers. These joints will need to be sufficiently wide to accommodate any potential increased expansion and will have to be fully sealed with a rubberised joint sealing compound to exclude the entry of water. The joint sealing compounds will need to be regularly checked and repaired should they indicate signs of detachment or drying out.

It is of utmost importance that the shoulders alongside concrete roads are kept well shaped by regular maintenance, at or slightly below the concrete surfacing height and able to efficiently move water away from the concrete slab into the side drains. Any accumulation of water on the shoulder adjacent to the slab will seep into the underlying layers potentially leading to weakening and edge-break of the slab.

5.3.2.4 Other non-bituminous surfacings

Description

Many different types of surfacings consisting of discrete elements (e.g. interlocking blocks, cobble-stones, hand-packed stone, etc.) may be used for low volume roads, especially when labour-based construction techniques are expedient. Nearly all of these include openings between the individual blocks that will allow water to penetrate through the “surfacing” into the underlying support layers. Trafficking of the roads in this condition will inevitably result in deformation of the blocks and failure of the road (Figure 17). The main benefit of this type of construction, however, is that the blocks can be manually removed, the support layers can be strengthened (e.g. with the addition of stronger material or aggregate or even localised chemical stabilisation where appropriate) and the blocks can be replaced.

Figure 17: Damage to hand-packed stone road after flooding

Adaptation

It is recommended that surfacing consisting of discrete elements are not used in areas that are likely to be subjected to flooding or overtopping by rivers. They can be used in the approach areas but concrete pavements are typically the best alternative in the actual areas likely to be flooded. Where discrete element surfacings are used for specific reasons, it is better than they are laid on a strong, well compacted subgrade (CBR > 30%) and a climate-resilient subbase. Grouting between the individual elements can be done by using a cement paste for the full depth of the element, but this practice could reduce the load bearing flexibility of the pavement system (i.e. layer could behave as a weak rigid pavement).

5.3.2.5 Earthworks

The main earthwork types considered in this report are cuttings and embankments (fills) – conventional formations necessary to raise the road above natural ground level are covered in Sections 5.3.1, 5.3.2 and 5.5. Cuttings are considered as any excavation through in situ soil or rock such that an unsupported slope remains after completion of the excavation. This may occur on one side of the road only (side cutting) or on both sides (box cutting).

Embankments on the other hand are designed and constructed from imported material placed so as to raise the level of the road above the natural ground and expected water levels. They may be constructed on the side of a hill, through a valley, on flat ground to raise the level of the road for drainage purposes or as approaches or abutments to bridges. They can also be associated with inland riverine or coastal estuarine or marine environments.

Other than closures of rural roads as a result of flood damage, the most common cause of rural road closures is probably slope failures/landslides, either including part of the road or placing material on the road from above (Figure 18), blocking and damaging the road. Closures due to slope instability can be costly and time-consuming to repair.

Figure 18: Road closure due to slope failure. Note deviation on the left created to by-pass the failure

Recent investigations in Nepal[3] have shown that poor road construction, together with high rainfall has led to a marked increase in the number of landslides in various areas. Local residents (Himalaya Times, 2016) have indicated that the “haphazard use of heavy equipment for road construction has brought problems; elsewhere; national and community forests are being destroyed for road construction projects”. It should be borne in mind that uncontrolled excavation at the toes of high slopes and the lack of appropriate surface and sub-surface drainage will inevitably lead to slope instability as discussed in the following sections (Section 5.3.2.6 and Sections 5.7 and 5.8).

It is not the intention of this report to describe in depth the requirements of instability investigations and analyses, but to provide some indicators that will assist the assessors and new designers in determining when specialist geotechnical input is necessary for any slopes. There are also many

[3] http://blogs.agu.org/landslideblog/2016/07/29/2016-monsoon-1/

comprehensive texts available that discuss potential slope instability investigation techniques and countermeasures (Turner and Schuster, 1996; PIARC, 1997).

It is also advisable to include, as part of the Asset Management System of all road authorities, a basic Slope Management System (SMS) that identifies the potential for failure and consequences of failure of all slopes within their jurisdiction. High risk slopes on the rural road network can then be prioritised for attention, or at least regular surveillance. This is normally carried out at strategic level for the road network, while actual surveillance activities would be carried out at a tactical or operational level.

It is important to recognise that no economic design is a guarantee against failure and that the likelihood of failure is seldom zero – the risk is only reduced to acceptable engineering standards. It is thus important to estimate the potential of failure and the potential consequences in terms of loss of life, accessibility and overall economic costs.

5.3.2.6 Cuttings

Description

One of the main causes of failures of cuttings (instability) is an increase in water level within the cutting, leading to a decrease in strength due to excess pore water pressures. Most natural slopes are in a state of equilibrium with the prevailing environment/climate (i.e. they have a factor of safety of close to unity under the existing worst moisture (and seismic, where appropriate) condition) and any disturbance, particularly at the toe of the slope, during construction will lead to a reduction in this safety factor and a potential for failure when the moisture condition in the slope worsens.

Experience has shown that the antecedent rainfall is probably equally important as new precipitation in initiating slope instability. Even high rainfall after dry periods seldom leads to large-scale instability, whereas moderate rainfall after extended wet periods is far more likely to cause major instability (Fourie, 1996).

Different techniques are required for the stability assessment of new road developments and for existing ones and these are discussed separately.

New roads

- During the design of new roads, an assessment of potential slope instability problems is (or should be) made. This involves a review of the topography, geology, soil and rock properties and weathering, surface and groundwater drainage and inspection of existing slopes and past instability history in the area. Cuttings that are likely to have any significant consequence should they fail need to be designed by geotechnical experts. This would involve an assessment of the potential for failure (either limit equilibrium or probabilistic) requiring inputs such as the likely mode of failure, shear strength and density properties of the soils and rocks involved and likely groundwater and seepage conditions.
- For low volume rural roads, it is, however, often more cost-effective to handle instability during construction rather than to spend large sums of money on the preliminary investigation and prevention of instability. This, of course, does have implications in terms of contractual arrangements and potential claims.

Existing roads

- An assessment of the stability of existing slopes is necessary to identify those with any significant potential to fail. Standard evaluation procedures such as misshapen trees, deformation of fences, bulging of soils, seepage of water, the presence of tension cracks, etc. (as highlighted in Appendix A) should provide an early indication of potential problems that need further assessment.

- One major issue with slopes is the sudden removal of dense vegetation, including trees, from above and behind the slope. Many instances of slope failure have resulted from increased ground-water height in the slope after the removal of trees, which have literally been able to "evaporate" large volumes of water from the ground prior to their removal. In addition, as the roots of the vegetation die off and decompose, their binding/reinforcement effect on the soil will be lost, effectively reducing the shear strength of the soil.
- Increases in the potential for wildfires will also affect the slopes. Apart from the effect of the increased impact of raindrops on the exposed soil after burning, which will lead to easier loosening and removal of soil by water, the binding effect on the soil of roots of plants that are lost in the fire will be lost, adding to an increased erosion potential.

Adaptation

The adaptation measures for cuts and embankments are very similar. The main differences are that embankments are constructed in a controlled manner from materials with known properties, while cuttings retain the nature of the existing geology/soil with variable properties, geological structures and water regimes.

There are generally local and international best practices that need to be applied during design, construction and remediation of cuts and fills and that can help to minimise the occurrence of slope instability. These cuts and fills are best investigated and designed by geotechnical specialists experienced in the area.

Many slope stabilization techniques are available for increasing the stability of slopes but these are mostly expensive and require sophisticated designs, certainly for higher slopes. For low volume roads, it is more typical to minimise excavations, and use lower cost slope protection techniques, such as cut-off drains and small retaining structures (gabion baskets, etc.) to improve stability. On the rare occasion where larger excavations or excavations that remove the toe of high slopes are required for low volume roads, a full geotechnical investigation should be carried out to ensure the most cost-effective and stable design. Detailed methods for this are discussed in such documents as Turner and Schuster (1996).

Areas likely to be prone to instability would normally have a lower class of road in terms of its geometric standards, which would be both cheaper to build and less costly to repair and maintain when slope failures do occur – this should go hand-in-hand with the priority of the road but preferably have less strict horizontal and vertical standards in order to minimise earthworks and lower design speeds. However, new alignments in mountainous areas are likely to prove particularly troublesome and will require geotechnical specialist inputs.

It is possible to install relatively simple early warning systems for potential instability of slopes and embankments – piezometers, extensometers, inclinometers, etc., are all relatively simple, but may be prone to vandalism and theft unless adequate community involvement is included in their installation, monitoring and upkeep. However, if a Slope Management System (SMS) is implemented, usually as part of the overall Asset Management System, potentially unstable slopes can be prioritised for remedial action and stabilization as part of the climate resilience plan. Either integrated in or developed independent of an SMS, one should also consider the implementation of slope failure incident maps.

In terms of direct climate change effects, under scenarios of higher rainfall, properly designed and graded surface cut-off drains behind the crest of slopes is essential to control excessive water. Temperature changes may affect the rock integrity – bigger volumetric changes under higher and more variable temperatures and thus opening of fractures/discontinuities. In most cases, increased aridity will result in improved stability conditions.

The role of water in slope stability has recently been clearly shown in areas of California, currently experiencing one of the worst droughts in living memory (in 2016). Significant decreases in landslides and slope instability have been reported in the past drought period.

5.3.2.7 Embankments

Description

The primary types of embankment related to rural access roads are those constructed to raise the road above normal formation level, particularly in flood-prone areas and at approaches to bridges or stream crossing structures.

Embankments deteriorate or fail in one or more of three ways. They can either deform due to differential settlement (consolidation) of the underlying materials; they can fail in shear leading to collapse of part of the embankment; or, and perhaps more commonly in the context of rural access roads, by erosion and undercutting of the embankment and road structure during flooding.

Settlement of the embankment under rural roads (usually the result of consolidation of soft, wet subgrade materials beneath the embankment induced by the mass of the embankment materials) is seldom a significant problem, only leading to deformation of the road surface, which can be relatively easily and cheaply repaired. Similar to cuttings, stability failures usually result from a decrease in strength due to excessive pore water pressures, and normal design precautions should be followed on these cases.

Embankments placed on colluvial (hillwash) materials, even on relatively gentle hillslopes, need particular care in their design. Water often flows through the colluvial materials lying on bedrock due to permeability gradients. To compound matters, colluvium is often poorly consolidated and has high void ratios and low shear strengths. An embankment on colluvial material thus has a strong potential to slide down the hillslope.

Major problems occur, however, when embankments are overtopped during flooding. Localised turbulent flow can result in severe erosion and eventually collapse of the embankment and road (Figure 19 and Figure 20).

Figure 19: Undercutting and collapse of pavement due to erosion of embankment

Figure 20: Complete loss of embankment and road due to turbulent flow conditions during overtopping and weak subbase

Complete loss of embankments, as in the example shown in Figure 20, will have significant implications from a financial perspective (reinstatement costs) and an economic perspective (impairment of mobility and access), whilst potentially also affecting road user safety if early warning systems are not implemented timeously.

Adaptation

When assessing embankments for adaptation measures, it is important to identify the potential water paths and approach angles (water approaching perpendicularly is easier to control than water approaching at a more acute angle), whether the water will flow over the embankment and the impact of the water on the embankment materials. In areas where erosion of the embankment is likely, the installation of rip-rap protection is necessary or flatter side-slopes can in many cases prevent damage. However, if the local materials are liable to be easily eroded, the rip rap should be grouted and measures (Figure 21) taken to ensure that the water cannot enter the embankment from above and (especially) behind the erosion protection.

Figure 21: Grouted stone embankment protection of erodible material

Damage of the pavement is best avoided by constructing a “capillary cut-off” beneath the structural layers in the pavement above the expected maximum flood level such that water flows through this layer and does not affect the overlying layers – it also avoids the capillary suction of water into the structural layers. This should consist of a permeable layer (100 to 150 mm thick) of coarse sand or gravel at least 150 mm above the expected highest water level and not more than 600 mm below the pavement structural layers.

It has been highlighted that a protection technique that was successful at one site may not necessarily be the optimum solution at other sites (NCHRP 496, 2016). The following technical issues need to be addressed for each situation: hydrologic and hydraulic factors, geological and geotechnical factors. Issues such as legal and funding aspects and acceptable risk often, however, play a major role in the design decisions.

As embankments associated with drainage structures are subjected to the same conditions as the actual drainage structures, the same hydrologic data must be used to give an estimate of the expected maximum water height, any potential overtopping height if overtopping is likely and the water flow velocities.

The associated geological considerations include the subsurface conditions, topography, water flow paths and channel dimensions, the susceptibility to erosion and deposition of the river surroundings and the basin characteristics. Key geotechnical characteristics include the erodibility of the embankment materials, their properties (strength and permeability) and structure (culverts and bridges) and pavement-related considerations.

To avoid damage to embankments the best choice among numerous design options must be made. These include:

- Identifying and quantifying the expected design flood
- Designing for overtopping, particularly in terms of erosion on the down-stream side of the embankment
- Counteracting seepage through the embankment
- Counteracting seepage under the embankment
- Avoiding the erosion effects of wave action where this is likely
- Taking into account softening of the soils by saturation
- Countering lateral sliding of the embankment
- The provision of adequate and well-spaced culverts (cf. Section 5.5)
- Design of moisture resilient pavements on the embankment
- Ensuring embankment stability during rapid drawdown conditions
- Flattening side slopes to reduce flow velocities
- The elimination of low points in the pavement such that turbulent conditions do not occur
- The elimination of trees and termite mounds that will cause localised turbulence
- High degrees of compaction in embankments and the elimination of cavities caused by termites
- Application of more cohesive materials on and grassing of embankment slopes.

New embankments:

For the construction of a new embankment in a potentially problematic area, the selection of the optimum road location is essential. A comprehensive understanding of site characteristics and constraints, such as geology and soils, geotechnical characteristics, stream hydraulic characteristics, upstream and downstream conditions, construction activities, and storm-water management facilities is needed. This should include the assessment of vulnerability factors for fill slope failure, such as distance from the edge of the slope for a range of failure volumes, to estimate the influence zone for fill slope failure. By identifying and quantifying these issues, an appropriate design can be adopted. Such designs could include relocating the embankment, stabilizing the stream or designing for possible failure modes.

Existing embankments:

In case of an old problematic site, it is essential to understand the key issue leading to recurring or aggravated damage. Possible issues include an increase in the severity of flooding events and the effects of stream instability caused by changes in upstream or downstream conditions (including man-made activities).

In many cases, the use of embankments should be avoided. It is better to allow the water to run over the road at natural ground water level than to interfere with the flow of the water. The potential for erosion of sandy material may be increased, but this can be overcome using mass concrete walls on the downstream side of the road and retaining the road as an unpaved one (Figure 22). This will usually eliminate the erosive effects of flood waters and unpaved wearing courses can be easily maintained after the waters subside to restore the riding quality should the need arise.

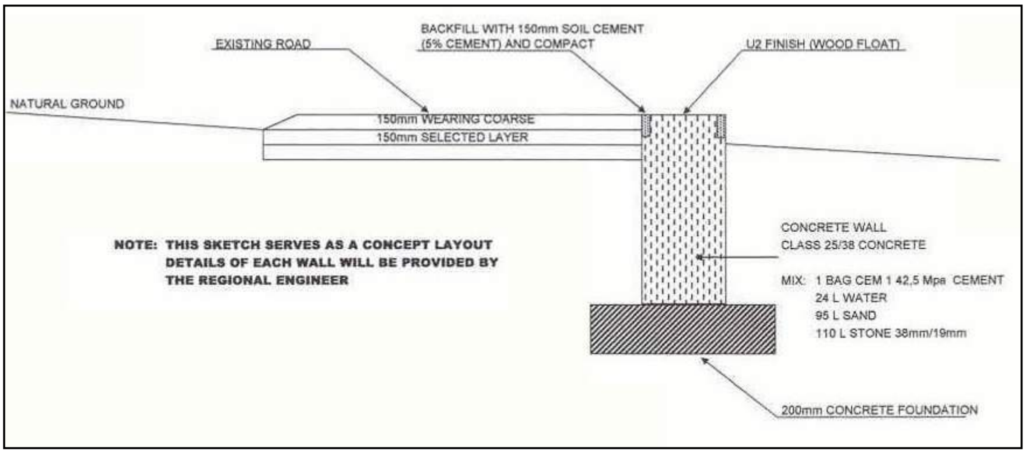


Figure 22: Mass concrete wall to minimise flood damage in valleys in erodible materials

An alternative to this is to use concrete drifts. These can be fairly complex structures to minimise erosion (Figure 23) or simple structures, possibly combined with the mass concrete walls as shown in Figure 22. It is, however, preferential that they are at the natural ground level to minimise sedimentation on the structure and erosion downstream of the structure.

Figure 23: Complex concrete ford with water velocity controllers and stilling pond

5.3.2.8 Erosion

Description

Additional information on erosion to that discussed earlier is included under earthworks here as it is mostly related to impacts on the surface of cuts, embankments and drainage structures, more than actually undercutting embankments due to turbulent water conditions discussed previously. Sloping soil surfaces over which water flows will erode as a function of the velocity of the water flowing on the surface and the erosion resistance (cohesion) of the soil surface.

Some form of vegetation should be used on all roadway slopes that will accept plant growth. Slopes should also be designed as far as possible to encourage vegetation, usually at batters less than 1V:1.5H. The vegetation helps to reinforce the soil, prevents excess erosion and reduces water runoff velocities and friction.

Eroded material typically gets deposited as soon as the runoff velocity reduces and is usually deposited on the road or in the side or cross drains. These all require more frequent cleaning (maintenance).

Foot and vehicle tracks leading off the road and down slopes result in a loss of grass growth, which soon causes erosion and material loss when rain falls on such areas (Figure 24).

Figure 24: Erosion cause by access of vehicles and pedestrians off road

A major factor affecting soil erodibility, after the material properties, is the effect of fire. Fire damage causes rain to fall directly onto the soil (no vegetation protection on burnt land), leading to loosening of the unprotected soil particles by the impact of raindrops. These loose particles are then more easily washed away (eroded) in water/runoff flowing over the soil (Figure 25). The steeper the grade, the faster the water will flow down the surface and the more serious the loss of material will be. The potential for wild-fires leading to these problems will be significantly increased by stronger winds and drier conditions.

Figure 25: Loss of unprotected soil in center of photograph. Burnt area on left is exposed to rain impact and erosion compared with vegetated area on right.

In summary, the following protection techniques are commonly used to minimise surface erosion:

- Bioengineering (cf. Appendix C)
- Riprap and geotextiles
- Gabions
- Articulated concrete blocks

- Concrete lining
- Paving
- Geocells

The location and extent of the protection must be designed dependent on the anticipated flow mechanisms.

5.4 Subgrade soils

The impact of poor or problem subgrades on roads can be equally or even more important than climate in many cases. However, the combined impact of climate and the subgrade is critical to the performance of road pavements.

It is easier, cheaper, and more feasible to deal with future subgrade problems during the initial construction than as a reconstruction option later. There is no option for routine subgrade maintenance as it is covered by the upper layers of road material and once constructed cannot be easily accessed for repair or modification.

Raising the road helps promote positive drainage away from the road surface and avoiding moisture build-up in the subgrade materials. The danger is that a dam effect for water that would otherwise move downstream is created and increased flooding in other areas can result. If the roadway is raised, then the design needs to incorporate more culverts or free draining rockfills underneath the road section that gives the water free movement. The use of embankments for trapping water in small dams adjacent to the road has been implemented in some areas, but this needs careful design to ensure that the water does not have a deleterious effect on the embankment or pavement structure.

The presence of capillary cut-offs as discussed under embankments should not be underestimated to assist in overall drainage and drying of embankments.

Various problem subgrade materials are likely to occur and these need to be addressed differently. The following sections highlight the different problem soils and offer suggestions as to their impact in future climatic scenarios and means of minimising potential problems. Problematic subgrade soils, if not timeously identified and appropriate countermeasures taken, can have a significant effect on both pavements and embankments and potentially can be severely affected by climatic changes. All of these potential problems are moisture related and mostly lead to cracking of bituminous seals, increasing the likelihood of water entering the pavement structure.

It is important to delineate the subgrade conditions as these will dictate the pavement structure required to carry the design traffic over its design life. Different procedures are required for new roads and roads that are being upgraded from gravel to paved standard. The objective is to understand the underlying materials and to identify any possible problem soils timeously.

5.4.1 Expansive Clays

Causes

Expansive clays are widespread internationally and of major economic significance. Typical damage to roads includes longitudinal unevenness and bumpiness, differential movement near culverts and longitudinal cracking. The presence of trees alongside the road often results in localised moisture extraction by their roots with the development of sporadic subsidence and arcuate cracking. Expansive clay damage to roads usually affects their serviceability more than their structural integrity, provided cracking and surface distress are timeously and effectively repaired. Damage is generally restricted to areas that have significant seasonal rainfall or poor surface water drainage.

Expansive soils are those containing smectite (montmorillonite) clays, which are mostly derived from the chemical weathering of basic rock forming minerals. Probably the worst expansive clays occur on deeply weathered gabbros, basalts and dolerites in tropical and sub-tropical areas. Expansive clays are also commonly found in transported soils derived locally or from some distance from weathered basic igneous rocks. Smectites can also form from the alteration under alkaline conditions of other silicate minerals low in potassium, as long as calcium and magnesium are present and leaching is impeded. Although the expansive potential of a soil can be related to many factors, it is primarily controlled by the quantity of smectite minerals.

Volume changes in expansive soils are confined to the upper few meters of a soil deposit where seasonal moisture content varies due to drying and wetting cycles. The zone within which volume changes are most likely to occur is defined as the active zone. The active zone can be evaluated by plotting the in situ moisture content with depth for samples taken during the wet and dry seasons. The depth at which the moisture content shows no seasonal variation is the limit of the active zone. This is also referred to as the lower depth of seasonal moisture change. However, with the anticipated changes in precipitation and temperatures, the length and characteristics of the dry season are expected to change, resulting in greater moisture movements in this critical depth zone. These are expected to cause more extensive expansive clay damage to roads.

Recognition of expansive clays

The simplest way of identifying the presence of expansive soils is through field observations where the surface expression of cracking in dark grey, black or sometimes red soils is evident as shown in Figure 26. However, the presence of a thick non-expansive transported or topsoil cover can sometimes mask these cracks and excavation of a test pit, in which cracking and slickensiding of the material will be observed is necessary. The identification of smectite in subgrade soils is best done using X-ray diffraction.

Figure 26: Typical evidence of the presence of expansive clay soils

By their nature, smectite clays will tend to be more plastic than other clay minerals and a measure of the plasticity index, or better still the activity (ratio of plasticity index to clay fraction) is a good indication of the presence of smectites. This is one of the earliest methods of indicating potentially expansive soils using Figure 27 based on the clay fraction of the soil (minus 2 µm) and the standard Plasticity Index (PI). It should be noted that the estimates for the degree of swell using this technique do not take into account the initial moisture content of the material, assuming that they move from a state of dryness normally used in the laboratory to wet. It is known that an equilibrium moisture content develops under a road structure and the moisture fluctuation in this zone is minimal. However, from beneath the outer wheel track of roads with unsealed shoulders to the edge of the fill, significant and variable moisture fluctuations occur. It is unlikely that the initial moisture content in these zones is, however, particularly dry.

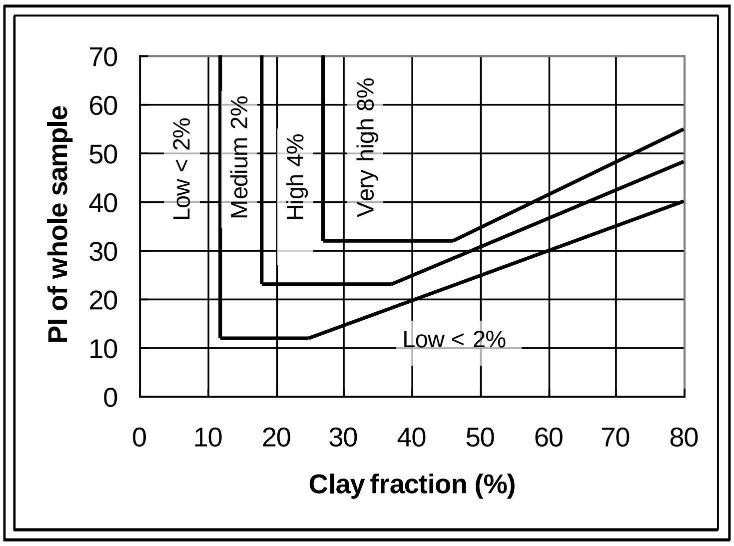


Figure 27: Identification of expansive clay soils and estimate of expansion (Van der Merwe, 1976)

An indication of potentially expansive soils can also be obtained from land type soil maps where materials identified as "vertic" soils will always have expansive characteristics, while soils with a high base status (or "eutrophic") and clay content should be investigated more thoroughly, as they have the potential to be expansive.

Simple field identification tests for clay content, requiring no equipment, include the thread test, ribbon test or the glass jar sedimentation test.

Adaptations

Although the estimation of potential heave is imperative for structures on expansive clay, it is not as critical for subgrades under roads. It is more important to identify the possible existence of the problem and the potential for differential heave along the road and take the necessary precautions. These will generally be based on the expected degree of swell determined from Figure 27.

If the calculated potential heave exceeds 25 to 50 mm (product of potential heave and thickness of expansive layer) countermeasures should be installed. If there is likely to be significant differential movement as a result of variable material properties or thicknesses, changing loading conditions or localised drainage differences, the countermeasures will need to take this into account to avoid localised sections of road with poor riding quality. However, reductions in riding quality are acceptable on lightly trafficked roads (< 100 000 ESAs).

Where culverts or small bridge structures are involved, it is usually necessary to quantify the potential movement more accurately. This is best done using oedometer testing of specimens cut from block samples. Correct orientation of the block samples is imperative as expansive clays tend to be highly anisotropic with significantly lower swells in the horizontal direction. This testing needs to be carried out in conjunction with good estimates of the potential changes in in situ moisture content from season to season.

Solutions that can be considered for low volume roads over expansive clays include:

- Flattening of embankment side slopes (between 1V: 4H and 1V:6H)
- Remove expansive soil and replace with inert material (between 0.6 and 1 m depending on depth of clay)

- Retain the road over the clay as an unpaved section and keep maintained
- Pre-wetting prior to construction of the fill or formation (to OMC)
- Placing of uncompacted pioneer layers of sand, gravel or rockfill over the clay and wetting up, either naturally by precipitation or by irrigation (100 to 500 mm depending on clay thickness and potential swell)
- Lime stabilization of the clay to change its properties (expensive – up to 6% lime may be required)
- Blending of fine sand with the clay to change its activity (blend ratio to be determined by laboratory experimentation)
- Sealing of shoulders (not less than 1 m wide)
- Compaction of thin layers of lower plasticity clay over the expansive clay to isolate the underlying active clays from significant moisture changes
- Use of waterproofing membranes and/or vertical moisture barriers, which are generally geosynthetics (only limited success has been achieved using these methods.

In many cases, for low volume roads, it may be better to retain the road as a gravel road over the expansive clay sections and apply the necessary maintenance.

One of the most important considerations is to try and minimise the zone of seasonal moisture movement beneath the road (Figure 28) and increase the zone of moisture equilibrium. A combination of slope flattening, material replacement, sealed shoulders and lined side drains as shown in Figure 29 is usually the most cost-effective means of achieving this, but the design of counter-measures needs to be specific to any situation.

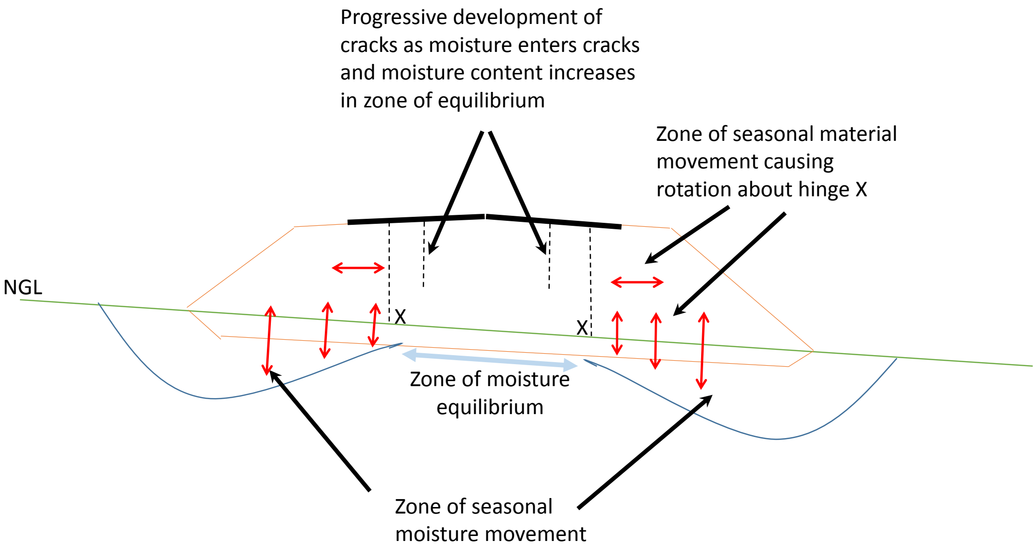


Figure 28: Typical moisture movement regime under roads on expansive clays

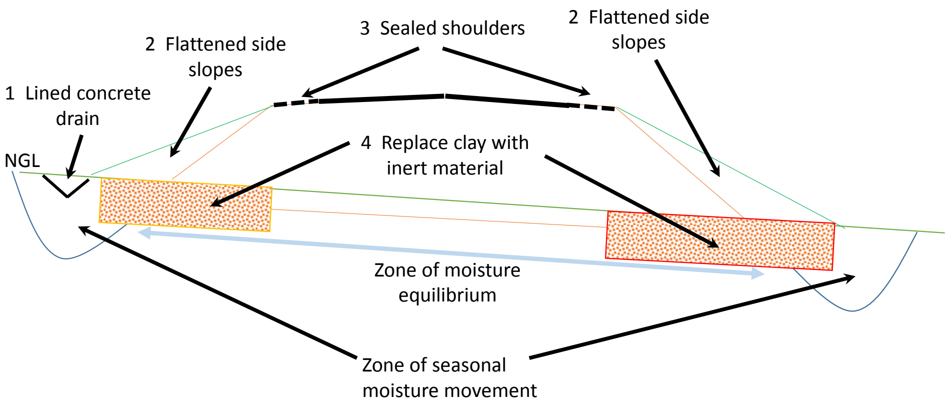


Figure 29: Some countermeasures used to increase zone of moisture equilibrium

Expansive clays are often thick and laterally widespread and this makes the implementation of countermeasures costly. The most successful technique for counteracting subgrades susceptible to high movement is to remove the expansive clay beneath the road structure and replace it with a raft of inert material. This would typically involve the excavation and removal of between 600 and 1 500 mm (or even deeper in some cases) of material over the entire footprint of the road prism (or at least beneath shoulders and side slopes) combined with drainage structures that remove all water from adjacent to the fill slopes and culverts. Removal of material results in the reduction of the swell potential as well as slightly increasing the load on the expansive subgrade with a usually denser, better compacted material. Unfortunately, this is often impracticable or uneconomic for low volume roads, unless the problem is localised. More frequently, expansive materials cover a wide area and the importation of substitute material involves the haulage of large quantities of inert material over long distances. The recommended and probably most economical solution specifically for low volume roads showing high to very high potential swell is to partially remove the clay from the subgrade and replace it with a less active material, increase the fill height using inactive material to provide a greater load on the clay, seal the shoulders of the road and flatten the fill slopes using the material removed from the subgrade and side drains. This has the effect of moving the zone of seasonal moisture fluctuation away from the pavement structure and inducing movements and cracking in the more flexible fill slopes rather than in the stiffer pavement structure.

Particular attention should be paid to culverts. The clay beneath them must be replaced with an inert material, all joints must be carefully sealed to avoid leakage and inlets and outlets well graded to avoid ponding of water. It is essential, however, that a proper understanding of the potential moisture movements in and around the road is obtained and this is related to the swell potentials of the various pavement materials (fill, shoulders, subgrade, etc.).

It is also good practice to remove and control the re-establishment of “water loving” trees. The roots of such trees seek water beneath the pavement and remove it from the clay, causing significant depressions in the road during the dry season, which may or may not recover in the wet season. This is usually associated with arcuate and/or longitudinal cracking.

Changes in subgrade moisture due to climate change effects (increased or decreased precipitation, higher temperatures, increased windiness and wild-fires) will have a significant impact on ground surface movements and associated structures. Increased cracking of pavement structures is likely and the necessary countermeasures against such changes will need to be implemented.

5.4.2 Dispersive/erodible/slaking materials

Causes

Dispersive, erodible and slaking materials are similar in their field appearance (highly eroded, gullied and channelled exposures), but differ significantly in the mechanisms of their actions. Fortunately for road builders, only the (probably less common) dispersive soils present problems of any consequence. Figure 30 shows a typical dispersive soil with definite evidence of piping.

Figure 30: Dispersive soil showing formation of "pipes"

Dispersive soils are those soils that, when placed in water, have repulsive forces between the clay particles that exceed the attractive forces. This results in the colloidal fraction going into suspension and in still water staying in suspension (Figure 31). In moving water, the dispersed particles are carried away. This obviously has serious implications in earth dam engineering, but is of less consequence in road engineering except when used in fills. Dispersive soils often develop in low-lying areas with gently rolling topography and relatively flat slopes. Their environment of formation is also usually characterised by an annual rainfall of less than 850 mm.

Figure 31: Dispersive soil in water (crumb test) showing suspension that does not settle out

Erodible soils will not necessarily disintegrate or go into dispersion in water. They tend to lose material as a result of the frictional drag of water flowing over the material that exceeds the cohesive forces holding the material together.

Slaking soils disintegrate in water to silt, sand and gravel sized particles, without going into dispersion. The cause of this process is probably a combination of swelling of clay particles, the generation of high pore air pressures as water is drawn into the voids in the material and softening of any incipient cementation.

Slaking and erodible soils when occurring as subgrades or even when used in fills are unlikely to cause significant problems unless water flows through the fill or subgrade. Problems are thus mostly associated with poor culvert and drainage design. The inclusion of dispersive soils in the subgrade or fill on the other hand has been seen to lead to significant failures through piping, tunnelling and the formation of cavities in the structure. It is therefore important to identify dispersive soils timeously.

Recognition

The testing and recognition of dispersive soils requires various soil engineering and pedological laboratory tests. These include:

- Determination of the Exchangeable Sodium Percentage (ESP)
- Cation Exchange Capacity (CEC)
- Crumb test[4]
- Double hydrometer test, and
- Sodium Absorption Ratio (SAR) and the pH.

The crumb test on undisturbed lumps of material (placed in pure water) is usually the simplest first indication, but is not always definitive. Dispersive soils tend to produce a colloidal suspension or cloudiness over the crumb/lump during the test, without the material necessarily disintegrating fully. Disintegration of the crumb in slaking soils is very rapid and forms a heap of silt, sand and gravel. Erodible soils do not necessarily always disintegrate in the crumb test as they require a frictional force of moving water to loosen the surface material, without any of the loose material remaining in suspension.

It is not very important (or even really possible) to quantify the actual potential loss of dispersive material from subgrades and fills as the process is time related and given enough time, all of the colloidal material could theoretically be dispersed and removed, leading to piping, internal erosion and eventually loss of material on a large scale. It is, however, important to identify the presence of dispersive soils, and their differentiation from erodible and slaking materials, so that the necessary precautions can be taken if they affect the constructed pavement. With expected increased drying out of soils during extended drought periods followed by intensive storms, damage of roads including dispersive soils can be expected to be significant.

Adaptations

The countermeasures for avoiding dispersive soil damage in the road environment are relatively simple:

- Avoid its use in fills as far as possible
- Remove and replace it in the subgrade
- Manage water flows and drainage in the area well

As the presence of sodium as an exchange cation in the clays is the major problem, treatment with lime or gypsum will allow the calcium ions to replace the sodium ions and reduce the problem. The use of gypsum is recommended over lime as lime may lead to soil stabilization with its associated cracking, allowing water to move through the cracks.

[4] The Emerson crumb test (2002) has been found to be applicable for low volume roads. Rain water can be used for the test in the absence of distilled water. The test has been found to be reliable for the prediction of dispersive behaviour of soils with the pinhole test.

It is also important that the material is compacted at 2 to 3 per cent above optimum moisture content to as high a density as possible.

To avoid problems with slaking and erodible soils, the drainage must be well controlled. Covering of the soils with non-erodible materials and careful bio-engineering, assisted by geosynthetics where necessary, is usually effective. Once erosion has occurred, the channels and gullies should be back-filled with less erodible material and the water flows redirected.

5.4.3 Saline soils

Causes

Unlike dispersive soils that are affected by the presence of excessive cations of sodium attached to clays, saline materials are affected by the combination of specific cations and anions in the form of soluble salts, independent of clays. These can be a major problem on road projects where migration of soluble salts to beneath bituminous surfacings (Figure 32) leads to weakening of the upper base and blistering and disintegration of the surfacings. Soluble salts, particularly sulphates, and their acids can also have a serious detrimental effect on the stability/durability of chemically stabilized materials and concrete.

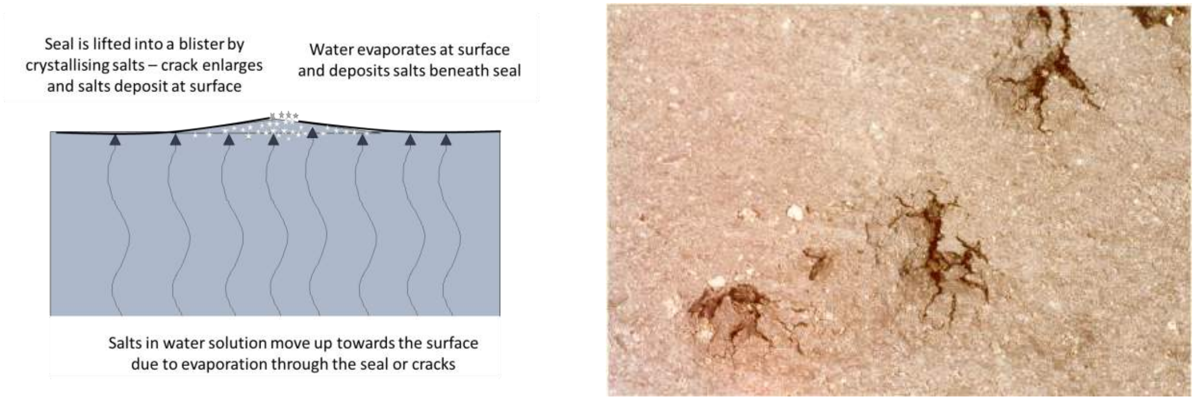


Figure 32: Mechanism of soluble salt damage to bituminous surfacings

Soluble salt damage to roads has been reported primarily from arid, semi-arid and warm dry areas. Salts can originate from the in situ natural soils beneath the structures as well as from imported material for the pavement layers or from saline construction water. Only the presence of soluble salts in subgrade materials is considered in this report as the materials for other layers can be controlled provided the problem is identified timeously.

Subgrade materials in areas where the land surface shows some depression resulting in seasonal accumulation of water are particularly prone to the accumulation of salts leached from the surrounding areas. In other flat areas, capillary rise of groundwater and precipitation in saline soils can result in the upward migration of salts to or near the soil surface. With the expected climate change, increasing aridity and changes in sea-level are expected to increase soluble salt problems if the necessary precautions are not taken.

Recognition

In some cases, the visible presence of crystallised salt deposits at the soil surface is a certain indication of the need for additional investigation for possible salt problems. This is often associated with the presence of animals licking the soil surface. In most other cases, the presence of salt is best confirmed by using laboratory test methods.

In the conventional road engineering context, the identification of possible soluble salt problems is based on the pH and conductivity of the materials. It should be noted that the results of the electrical conductivity and pH tests can vary significantly depending on the pre-treatment, the moisture content at which the measurements are made and particularly on the material size fraction tested.

Limits for the use of saline materials are generally based on work in specific countries and their applicability to other areas is unknown. In general, an electrical conductivity on the passing 6.7 mm fraction in excess of 0.15 Sm^{-1} (or an electrical resistance of less than 200 Ω on the minus 2 mm fraction) should raise concern and indicate the need for further investigation. Similarly, soluble salt contents in excess of 0.5 per cent should be a cause for possible concern and lead to additional investigations.

Adaptations

The following measures should be considered:

- As soluble salt problems arise from the accumulation and crystallization of the salts under the road surfacing and in the upper base layer, minimisation of salts in the pavement layers and subgrade should be attempted.
- If the surfacing is sufficiently impermeable (coefficient of permeability, k in nanometre/ second)/ surfacing thickness, T in mm or $k/T < 30$ $(\mu sec)^{-1}$) to avoid water vapour passing through it, crystallisation will not occur beneath the surfacing.
- Construction should proceed as fast as possible to minimise the migration of salts through the layers. Only impermeable primes should be used, e.g. bitumen emulsions.
- The addition of lime to increase the pH to in excess of 10 will also suppress the solubility of the more soluble salts.

Even for the lowest classes of road, the effects of excessively saline materials can lead to a rapid and total loss of the bituminous seal and precautions should thus be taken for all road classes. The use of non-bituminous surfacings should be considered over saline materials.

5.4.4 Soft clays

Causes

Widespread problems, mostly in coastal estuarine (lagoon) and marshy areas result from the presence of very soft alluvial clays in these areas. Deep soft clays in estuarine areas are formed mostly as a result of periodic fluctuations in seal level. Inland soft clays tend to be much shallower having been deposited in marshy areas. Soft clays are generally, but not necessarily saturated and normally consolidated to lightly over-consolidated (as a result of fluctuating water tables). The materials thus have low shear strengths, are highly compressible and their low permeabilities result in time-related settlement problems. In addition, the frequent occurrence of organic material in the clays affects their behaviour and the determination of their properties.

As noted above, the presence of these materials is predominantly in the coastal areas although they can also be associated with large mature river systems. The shear strength of these clays would normally be between 10 and 40 kPa, making them impossible to difficult to walk on. Soft clays are seldom uniform with depth and are usually interlayered with silts and sands, which provide more permeable drainage paths than would be determined from oedometer testing of undisturbed clay samples. However, the depths and strengths of the materials are such that inspection of the materials in test pits or auger holes is not recommended.

Potential future rising of seal-level is likely to introduce larger areas of soft clays and lead to increased road construction problems in coastal areas.

Recognition

The in situ condition of these materials is one of their most important properties that need to be considered – testing of disturbed samples will usually provide results that are meaningless. It is thus better to use in situ test methods such as Standard Penetration Testing (SPT), vane shear or Cone Penetration Testing (CPT) to determine the depths, presence of silt or sand layers, strengths and if possible, permeabilities. If these can be identified with a reasonable degree of confidence, estimates of the quantity and rate of settlement and the potential stability of embankments over the materials can be made.

Adaptations

Road embankments built on soft clays thus need careful control during their construction to avoid stability failures as pore water pressures increase under the applied loads. It is recommended that embankments in these areas are constructed slowly, layer by layer, while monitoring pore water pressures and additional layers are only added once the pore water pressures have dissipated adequately. Despite even these measures, long-term settlement continues and problems are often encountered with large differential settlements between the approach fills founded on the clays and bridges founded on piles. These long-term differential settlements require ongoing maintenance to provide an adequate performance of the road.

The use of the wide range of geosynthetic products as separation layers and to facilitate and accelerate drainage has contributed to improved construction over such areas in the past decade or two, and specialist advice in this respect should be obtained.

5.4.5 Wet areas/high water tables

Causes

It is possible that some non-clayey areas have a water table close to the natural ground surface, which makes the placement of road structures difficult and can affect their structural integrity. Unlike the clay areas, the problem is not the low strength or settlement potential, but the effect of the water (and high pore-water pressures under traffic loading) on the pavement structure.

High water tables result in a steady, high in situ moisture but it is also possible that fluctuating high moisture content conditions within the pavement sub-structure may occur as a result of seasonal precipitation and longer-term climate change characteristics. A good understanding of the moisture conditions and environment needs to be defined during any investigation involving subgrade materials.

Various moisture indices such as Thornthwaite's Moisture Index or water surplus maps can provide very useful information on potential problems in this regard. Many of the problems encountered in roads are common to specific moisture zones, and these have been highlighted under their respective headings in this document.

Recognition

It is usually easy to recognise potential wet conditions, which are characterised by areas of standing water, specific types of vegetation (reeds, papyrus grasses, etc.), localised muddy conditions and often the presence of crabs and frogs. However, with the changes in climatic conditions, particularly increases in periods of extreme storm events, roads constructed at or near natural ground level could become impassable for longer periods of time.

Adaptations

The treatment of wet areas for roads can be costly if the aim is to reduce the water tables using sub-surface drainage systems. These would seldom be warranted for low volume roads.

The best and most cost-effective measures for low volume roads are to raise the level of the road to at least 750 mm above the natural ground level, with a permeable gravel or rock fill layer (at least 100 to 150 mm thick) on the natural formation (after removal of the topsoil and vegetation). Properly designed and graded side drains should also be constructed to avoid the presence of standing water adjacent to the road.

The installation of sub-soil drainage systems is seldom warranted for low volume roads because of the high cost and the ongoing need to maintain them diligently. However, in cases where they are considered to be essential, they should be designed by a drainage/ground-water specialist based on the local water regime and flow-paths.

5.4.6 Collapsible soils

Recognition

Collapsible soils result from a unique condition in which “bridges” of fine materials (usually clays or iron oxides) within a framework of coarser and harder particles (mostly quartz) become weak when wet and collapse under load. The important condition is that the material must be in a partially saturated condition and then wetted up and loaded simultaneously, which is a common situation beneath road structures. They tend to be more prevalent in drier areas.

Collapsible materials can occur on both residual and transported materials. Many granites and feldspathic sandstones when weathered result in the feldspar altering to kaolinite with the quartz particles staying intact. This forms a honeycomb type of structure, which, when wetted up and loaded, results in shearing or “collapse” of the clay bridges and a settlement or reduction in volume of the material. Certain basalts and dolerites with dry densities of 1200 to 1300 kg/m^3 have also shown collapse potential.

Indications of the possibility of collapsible materials are:

- A very low density, because of the large number of voids separating the quartz framework
- Densities of less than about 1600 kg/m^3 (mostly in the range 1000 to 1585 kg/m^3)
- The presence of “pinholing” or voiding observed during the soil profiling
- Usually more than 60% of the mass of the material lies in the 0.075 to 2 mm range and less than 20% is finer than 0.075 mm
- When the material excavated from a pit is insufficient to fill the pit again (the collapse structure will be disturbed and the material will decrease in volume).

The expected climatic scenario of longer drought periods followed by potentially extreme storm events will have a major impact on unidentified or un-engineered collapsible soil areas. Wetting of the subgrade after extended drought periods followed by the application of traffic loads is expected to result in significant road surface deformation. The result of collapse of the subgrade is mostly manifested by the development of a deeply rutted and often uneven road surface and significant deterioration of the riding quality of the road (Figure 33).

Figure 33: Typical manifestation of collapsible subgrade

Adaptations

If potentially collapsible soils are identified, specialist assistance should be used for their treatment underneath paved roads to avoid excessive rutting. In general, a high degree of wet vibratory compaction is required to remove collapse potential. However, as most of these materials are located in relatively arid areas, the use of high energy impact compaction (without the addition of scarce water in these areas) has proved to be effective. Deformation that is likely to affect unpaved roads will be removed during conventional routine grader blading and no significant precautions are necessary.

5.5 Drainage (water from within road reserve)

Description

Water falling directly onto the road carriageway, shoulders and embankment slopes and which ultimately flows into the side drains requires particularly good control. The primary objective is to make sure that this water does not get into the pavement structure, whether it is an unpaved or a paved road. Other requirements are that the water does not accumulate on the surface of unpaved roads (leading to softening and deformation), the water flows off paved roads so as to minimise the risk of skidding/aquaplaning, movement of the water off the surface does not lead to erosion of the road surface (paved or unpaved) or the shoulders and that the water actually gets into the side drains where it can be effectively removed from the road environment.

Most of these problems are solved by ensuring that the road surface is even with a uniform crossfall towards the shoulders and a slightly larger crossfall on the shoulders towards the shoulder breakpoint if unpaved. Rutting and potholing will interfere with the water flow and increase any potential problems. Similarly, the common practice in SSA of building up the shoulders, usually with either grass or soil, but often both (Figure 34), results in accumulation of water at the edge of the surfacing, which then flows into the shoulder and edges of the pavement structure, often leading to extensive outer wheel-path failures.

Figure 34: Grassed and built-up shoulders negating effectiveness of drainage from road surface

Adaptation

5.5.1.1 Unpaved roads

To avoid the access of water into the wearing course and underlying layers, the road surface needs a good shape and a pronounced camber, preferably about 4-5%. Any depressions (potholes) in the surface (carriageway and shoulders, usually consisting of the same materials) will accumulate water, which will soften the layer and result in enlargement of the depression, at the same time allowing the water to seep into the underlying layers. This can only be ensured by regular maintenance, using a motor grader operated by an experienced and competent operator.

On grades steeper than 5 or 6% and cambers or super-elevations steeper than 5%, runoff of water causes erosion of most material types, other than good compacted granular gravels complying with the specifications outlined in Section 5.3.1.3. On grades up to 6%, the camber should be steeper than the grade as far as possible to ensure that precipitation runs off the road laterally into the side drains and not down the grade, where it can gather enough speed to cause significant erosion. A number of techniques are available for capturing this water and moving it off the road at the necessary spacings. These include humps, rubber strips or wooden boxes and each needs to be assessed in terms of its suitability.

5.5.1.2 Bituminous paved roads

The access of water into sub-layers in bituminous paved roads usually occurs through unsealed cracks, unpatched potholes and poorly maintained shoulders. Again, only the correct application and management of routine and periodic maintenance, assuming that the original surfacing design was appropriate and the seal was well constructed, will ensure an impermeable surfacing.

Unpaved shoulders on paved roads should be handled in the same manner as a gravel wearing course. As described above, it is essential that road shoulders are slightly lower than the paved surfacing and that they slope away from the road at a suitable camber to remove water without suffering from excessive erosion. Good and frequent maintenance of the shoulders is essential to ensure that they retain their draining capacity.

5.5.1.3 Side drains

The water from both unpaved and paved road and shoulder surfaces must move into properly shaped and graded side drains along the road as soon as possible. These should allow the water to flow, without any ponding, and be conducted into mitre drains at suitable intervals from where the water can be moved away from the vicinity of the road into adjacent fields and natural water courses. The side drains should be at the base of the formation or embankments, preferably at least 2 m from the breakpoint of the shoulder.

Three main shapes of side drains are used: V-shaped, rectangular or trapezoidal. Those with trapezoidal cross-sections are normally the easiest to maintain and are best constructed and maintained using manual labour. They should be at least 500 mm wide with a minimum longitudinal gradient of 1%. If motor graders are to be used for maintenance, V-shaped drains should be constructed.

The drains should be designed using conventional techniques to limit flow velocities such that erosion/scour does not occur. Should scour be unavoidable due to material and topographic constrains, the installation of scour checks or even concrete or mortared stone linings in the drain should be considered. Scour checks should be spaced such that the water in the drains do not build up a high velocity with typical spacings of about 5 m on steeper gradients (10%) and about 15 m on gradients less than about 5%.

Additionally, by removing the water from the side drains into the mitre drains at regular intervals the water flow velocities and potential erosion in the side drains will be reduced. Water should be moved into the mitre drains on the same side of the road as the side drain to reduce the number of culverts along the road. Typical spacings of mitre drains depend on the gradient of the side drain and the natural materials in the drain and suggested values are provided in Table 12.

Table 12: Suggested intervals of mitre drains as a function of gradient and material cohesion

Side drain gradient (%)	Maximum mitre drain interval in material type (m)	
	Non-cohesive materials	Cohesive materials
12	10	50
10	10	60
8	20	75
6	30	100
4	40	150
2	50	300

Note: At a gradient of less than about 2%, water velocities are low and siltation and grass growth may become a problem. This requires regular maintenance.

Mitre drains should lead off from the side drains at an angle of between 30 and 45° and the side drains should be blocked off to “force” the water to move from the side drain. Mitre drains should have a gradient of 2 to 3% and should lead gradually away from the side drains getting progressively shallower and wider.

In flat terrain, dissipation of the water is often difficult and arrangements should possibly be made with adjacent land-owners to create shallow sumps where the water can accumulate and penetrate the ground slowly. These can be used as temporary water sources for irrigation and/or stock in most cases. Mitre drains that stop within 7 or 8 m of the road should be avoided and the end should be below road level and be able to dissipate the water collected fast and effectively (Figure 35).

Figure 35: Short mitre drain that is unable to dissipate collected water effectively

5.6 Drainage (water from outside road reserve)

Description

The water from outside the roads reserve is characterised by the precipitation that is collected in catchment areas and moves downslope towards the sea or large dams or can be the result of local flooding of large rivers. This water crosses the roads at strategic points, typically the lowest part of the valley, and usually requires a bridge, culvert or some other (major) structure to permit the water to flow underneath (or sometimes over) the road. It should be borne in mind that the major catchment areas of large rivers (e.g. Limpopo, Zambezi, Volta, etc.) may be located outside the country's boundaries – this, together with the presence of large dams that allow river flow to be controlled, could make quantification of river flows very difficult in-country.

The expected higher temperatures, higher rainfall, more intense storms and more frequent and larger storms could have a devastating effect on the bridge and culvert infrastructure. These climate change factors will lead to the need to cope with generally more water, more frequent floods, and faster and more destructive water velocities. Thus much of the historic data on which hydrological design depends will no longer be valid. Consideration in this regard is discussed later in this section. However, it will be important to:

- identify the most vulnerable structures and increase the 'safety factor' inherent in their designs;
- ensure that the drainage systems are well maintained and functioning correctly; and
- identify critical areas or high priority roads where the consequences of failure and closure are severe. Local realignment, if appropriate, may be required, but this will usually only be considered as part of a repair and rehabilitation project after storm damage has occurred.

Increasing the safety factor includes:

- using drifts and vented drifts that can be safely overtopped instead of culverts or small bridges that can become blocked by debris
- adding additional protection to culverts that might be blocked by debris

- better surface drainage so that water is dispersed off the road more frequently
- reducing water concentration by means of additional cross drains and mitre drains to reduce the volume of water that each one needs to deal with.

Bridges are generally the costliest component of the road infrastructure and require additional protection. Increased intensity of storms will produce more water with higher flow velocities, which the bridge may need to cope with, leading to erosion of abutments (Figure 36) and increasing the potential for damage to the bridge structures through debris in the water. Figure 37 shows an example of the total loss of an embankment and culvert during a severe storm with the final location of the 2 m diameter metal pipe 100 m downstream**.**

Figure 36: Flood damage to bridge abutment after overtopping of embankment

Figure 37: Damage to steel culvert after storm with total loss of embankment. Photograph on right shows final location of metal pipe

Debris carried by the river during flooding (e.g. large trees) often cause direct damage to bridges or else block the bridge inlets leading to changes in hydraulic capacity and overtopping of the structure.

In 1919, Lewis published a paper in which he stated that “Too much importance must not be attached to the formula (for calculating maximum floods). No formula is likely to be discovered, which will apply to all drainage areas. The maximum flood depends on too many uncertain circumstances, such as intensity of rainfall, size and shape of catchment and channel and permeability of the ground surface". This is still true today, nearly 100 years later, particularly in terms of the changing intensity of the rainfall and changing permeability of the ground surface.

In the design of major structures, the expected maximum flow related to the catchment area of the river/stream is usually used to determine the bridge flow capacity and required openings. The rain falling in the catchment area is determined on the basis of the expected return period of specific storm events usually based on past measurements. It is this return period that is likely to change (i.e. under more severe storm event scenarios the amount of rain falling during a future storm with a return period of 100 years will be more than that currently experienced during a 100 year return period storm) and needs to be modified for future designs. Extreme events after extended dry periods will result in more of the precipitation being "absorbed" by the ground, but high intensity precipitation will also result in rapid flows before the water can soak into the ground, depending on the hydrologic properties of the ground surface.

Research carried out in Ghana (COWI, 2010), as an example, indicated that the present 100-year storm in Ghana, can be expected to occur once every 18 years in the future (2050) based on existing predictions for Ghana – nearly five times more frequently than a 100-year storm would be expected today.

Water crossings need to be designed with a capacity to handle the expected change in rainfall intensity and runoff such as to balance construction costs with the economic and societal costs of not having sufficient drainage capacity and consequently suffering excessive erosion damage or even collapse of larger structures. The high costs of structures relative to overall low volume rural roads costs should certainly dictate the increased use of appropriate fords and drifts that are designed to be "overtopped" for limited periods, without damage to the structures.

Existing bridge structures near the coast will also need to be carefully re-assessed. Sea-level rise will result in new water levels for the rivers/estuaries, reducing the bridge opening and potentially leading to overtopping and damage to bridges during flooding. A marked increase in sedimentation in these areas can be expected, which will, however, reduce the potential for scour of foundations of existing bridges due to the deeper water.

One of the main potential problems with actual bridge structures is the effect of changes in temperatures on the volumetric characteristics (expansion and contraction) of the bridge components. Differential expansion at different parts of the bridge structure and those parts constantly in shadow will result in increased stresses developing within the bridge components.

The type of bridge has a major impact on the thermal effects. Steel, concrete or wooden structures all have different coefficients of thermal expansion and thus behave differently. Wooden structures are probably the least affected by thermal gradients and seldom require specific thermal design considerations. Thermal effects on steel structures on the other hand can be modelled relatively simply as the coefficients of expansion of the steel are generally known and fairly uniform throughout the structure. Reinforced concrete on the other hand is a composite material including aggregate, cement paste, sand and steel, all with potentially different thermal characteristics.

The major factors influencing thermal movements in concrete are:

- The nature of the aggregate;
- The moisture content of the hardened concrete;
- The percentage of aggregate in the concrete mix by volume; and
- The amount and distribution of reinforcement in the concrete.

The effects of other factors such as cement type, design strength and age of concrete and curing techniques are less significant. The coefficient of expansion of partially moist concrete is higher than that of completely dry or saturated concrete resulting from the thermal behaviour of cement paste, which has a maximum coefficient at intermediate moisture contents and lower coefficients in the saturated and the completely dry condition. Values for the coefficients of thermal expansion of aggregates range between 3.5 and 12.5 microstrain/°C for temperatures up to 65°C with non-quartzitic materials being the lowest and quartz-rich materials having the highest values (Owens, 2009).

The coefficient of thermal expansion of hardened cement is between 11 and 16 microstrain/°C for normal air temperatures. Rocks having an arithmetical average coefficient of expansion in all crystallographic directions greatly differing from this value may be deleterious in concrete (Owens, 2009) due to differential expansion, particularly if the coefficients of thermal expansion are low in relation to those of the concrete. Complicating matters, the inclusion of reinforcing steel results in different volumetric movements within the actual concrete members.

The effect of higher temperatures certainly needs to be considered by structural engineers in the design of concrete bridge structures and it may be prudent in fact to increase the use of wooden structures in certain low volume road situations in order to minimise potential problems. In addition, higher temperatures (and stronger ultra-violet radiation) will have a significant impact on the durability of rubber-based expansion joints, which will deteriorate more rapidly and require more frequent maintenance and replacement.

It should be noted that roadway embankments are not normally designed as flood control structures, although in certain areas they could well be. There are also significant differences between riverine and coastal flood and erosion mechanisms, which impact on the most effective way of minimising road embankment damage due to flooding. Common failure mechanisms of road embankments are overtopping, seepage, piping, wave erosion, lowering of material strength by soaking and lateral sliding over the foundation soil. There is a wide variety of adaptation techniques and countermeasures that cannot be comprehensively covered in a document of this nature and reference to, for instance, NCHRP Synthesis 496 (2016) should be made for such measures.

Bridges are designed by structural engineers, most of whom should be aware of impending climate changes that are likely to affect bridges during their design life, and should take such considerations into account.

The other issue affecting bridge structures is undermining or loss of support of piers due to water scour (Figure 38). All rivers undergo natural scour, but the construction of piers and abutments of bridges changes the flow characteristics of the river flow (direction, velocity ad increased turbulence) leading to additional scour adjacent to the new structures. This effect depends on the characteristics of the river channel configuration as well as the volume and velocity of the water. With the expected increases in storm intensities, such damage is likely to increase and the designs will need to incorporate scour and erosion protection measures. Numerous techniques for predicting and handling scour are available (TRL, 2000). In general, the shape of piers should be designed to reduce turbulence up- and down-stream from them.

Figure 38: Subsidence of bridge deck due to scour damage of support pier

Scour around footing foundations is generally limited (Figure 39) but the footings should be designed or protected to avoid such problems.

Figure 39: Localised scour arround bridge pier footing

The need for protection of the soil surrounding culverts from erosion must also not be underestimated. It is essential that adequate head and wing-walls are provided. Examples are frequently seen where the wing walls “separate” from the head wall allowing water behind the wing-wall and eventually leading to erosion and collapse (Figure 40).

Figure 40: Separation of wing-walls from headwall on relatively new culvert

Ensuring that the drainage system is working correctly is essentially a maintenance issue although there will be examples of poorly designed culverts with improper alignment or grade relative to the channels and ditch lines that will need to be repaired or replaced, usually after failures have occurred.

It is important that the road does not reduce floodable areas significantly, or else the potential larger volumes of water would be constricted to narrower flowpaths resulting in higher peak flow velocities and more potential for erosion.

Adaptation

There are many guidelines and codes available for the design and construction of larger structures using concrete and steel, such as Overseas Road Note 9 (TRL, 2000). However, little guidance is generally available concerning small structures. In this respect, the guideline document *Small Structures for Rural Roads: A Practical Planning, Design, Construction & Maintenance Guide* (Larcher et al, 2010) provides comprehensive information to assist engineers and technicians in the planning and provision of small road structures.

5.6.1.1 Bridges

Various issues regarding bridge design need to be taken into account as bridges will normally be designed to last between 50 and 100 years (or more for bigger structures). Apart from the loadings that bridges are designed to carry, they need to be designed to handle the expected volume of water that will flow through them during peak flooding as well as other potential issues described below:

Maximum water flows*:*

Maximum water flows can be calculated using various standard techniques which are not described in detail here. However, these make use of return period, which are probabilistic determinations of the frequency of the calculated peak flows for different storm intensities. The only changes to conventional design methods for bridges will be in terms of the return periods. These will need to updated on a regular basis using the latest predictions of expected rainfall, determined from local climate modelling. In the absence of such revised return periods it is also possible to use actual worst case scenarios based on specific rainstorm intensities, but these will normally result in more conservative designs.

The water flow quantities and velocities are also based in various surface characteristics (e.g. soil type and exposure, vegetation cover, etc.). With climate change these too are likely to change with time and issues such as this will also need to be considered in the calculation of river flows. Changes in vegetation are also likely to affect the type of debris transported by the rivers (increased or decreased tress, bigger or smaller trees, larger boulders, etc.) and this should also be considered in the design.

Abutments:

The materials behind bridge abutments must be as resistant to erosion as possible and compacted to as high a density as possible to avoid damage during flooding. They should also be protected from water flows by raising wing-walls, applying mortared rip-rap or other erosion protection methods (gabion baskets or Reno mattresses) and minimising turbulent flow around them.

Piers:

Piers are primarily damaged by scouring of their foundations. Scouring is a function of turbulent flow upstream, downstream and surrounding the foundations. This is best reduced by ensuring the optimum shape of the piers and founding the supports on material unlikely to be scoured. The depth and extent of scouring is estimated from various models (TRL, 2000) and this, together with the type of foundation and substrate material should be used to optimise the design. The stream-bed characteristics will usually have the most influence on the type of foundation, which will have an effect on the scour potential as well as being affected by the induced scour. If the stream-bed has only thin alluvial material deposits, footings directly on the bedrock or other competent layers can be used. If the stream-bed has thick deposits of fine material, piles are normally used. These can be either end-bearing piles if the bedrock or other hard layers are not too deep, or friction piles where excessive deposits of fine materials occur. Friction piles should be designed to ensure that should scouring occur, the length of the unexposed pile is still adequate to provide the necessary frictional support.

Structures:

The effects of increased temperatures and larger seasonal and diurnal changes on bridge structures and their components will need to be taken into account during their structural design. These rare normal design considerations but should just be given a little more thought to handle expected conditions in 50 or 100 years' time. Increased expansion of the materials will require larger expansion joints, which in turn will require better waterproofing and sealing materials, as well as increased maintenance to ensure their continued serviceability. The use of monolithic structures avoiding bearings could also be considered.

A challenge with bridge expansion joints is that they are a flexible component and require a high amount of maintenance. Some types of joints are themselves an entrance point for water which is able to leak onto substructure elements and accelerate deterioration. The amount of expansion in the bridge depends on the actual structure type, temperature changes, the length of bridge, and the type of material used (reinforced concrete, steel girder, etc.). Monolithic bridge structures avoid the use of potentially problematic bearings.

5.6.1.2 Culverts

It is essential that culverts are aligned carefully along the road, preferably perpendicular the steams and drainage paths crossing the road. Where moving water has to change direction suddenly, the potential for severe erosion is rapidly increased. Similarly, the protective measures around the culvert should be such that erosion of the adjacent formation or embankment is minimised during normal water flow events. It is not economically possible to protect long distances of embankment from erosion, other than to ensure that the embankment is covered with a good deep-rooted local grass, which is kept well maintained.

The capacity of the culverts, like bridges, should be designed to move the expected water through them without causing and damming upstream. Examples have been observed, for instance, where a railway line running parallel to and slightly uphill of a road had a number of culverts each consisting of 3 one-metre square boxes. The parallel road had culverts in the same locations downhill of the railway culverts but these consisted of only one 600 mm pipe – the capacity was thus obviously inadequate and damage would be expected to occur to the road embankment during heavy rainstorms.

Where overtopping of the culvert is likely, low points should be eliminated and the road should be as flat as possible to avoid localised turbulent flow over the embankment. The downstream slope of the embankment over the length of potential overtopping should also be flattened to be reduce water velocities and minimise erosion and undercutting.

5.7 Construction

A number of climatic change factors could impact on the construction of future road and bridge infrastructure, some negatively and other positively.

During the predicted extended dry periods in some areas (also being hotter), the availability of construction water may be limited for longer periods and longer haulage distances may be necessary. The cost of the water is also expected to rise as construction competes with other uses for its limited availability. Simultaneously, the water applied to the layers during these periods for compaction will evaporate much quicker and greater quantities of water will be required.

Where stabilization of materials is used on a wide scale (e.g. the sands of central Mozambique), the working time of the stabilization (i.e. from the addition of water until the time of final compaction and trimming) will be significantly reduced under higher working temperatures.

The rates of other chemical reactions affecting stabilisation and mineral degradation may also be increased under high temperatures. A possible benefit, however, of higher temperatures may be longer windows for bituminous paving through the year, i.e. shorter cold periods).

Adaptation

In terms of construction, differentiation should be made between existing infrastructure, which cannot be changed overnight, and infrastructure that needs to be constructed anew. In case of the latter, ample opportunity would be available to introduce more climate resilient road infrastructure solutions.

In the case of existing infrastructure, the outcomes of a risk analysis would dictate which actions would require immediate attention (e.g. retrofitting of drainage systems). Adaptation actions could be phased in over time (e.g. during scheduled maintenance or rehabilitation/upgrading) depending on the priorities.

Climate change could require some adjustments in construction processes. Drought conditions, for instance, are likely to lead to greater shortages of water, which will drive up the cost of water and simultaneously the cost of construction projects, unless surfactants (compaction aids) are used and/or compaction methods are adapted to cater for this water scarcity (e.g. high-energy impact compaction).

In future, construction seasons may shorten or lengthen, and could shift earlier or later within the year. These changes are unknowns at this stage, and will depend from country to country, but relevant ministries or road departments should be made aware of this possibility, record changes to the status quo and plan accordingly.

In order to minimise problems with climatic changes on roads it is essential that construction at least complies with the minimum requirements in the recommended standard specifications, if not exceeds them. For example, compaction (of subgrades, formations, embankments, abutments and pavement layers) to higher densities than those specified immediately increases the stiffness, reduces permeability and erosion potential and reduces voids and rutting potential. Compaction is one of the cheapest construction activities and should not be skimped on.

The loss of water during construction on hot and dry days can be minimised by constructing at night as well as by using recycling equipment for the addition of water. If these are not feasible, quicker delivery of greater quantities of water (more water bowsers on site) and decreased construction processing time (construction of shorter lengths, additional rollers and graders, etc.) will be necessary.

Various other construction practices will need to be modified to cater for climate change. With cement stabilisation for instance, it may be necessary to construct shorter sections at a time, to use alternative slower reacting cements for stabilization (CEM IV and CEM V) or even blends of lime and fly ash. The breaking times of bitumen emulsions will be much quicker on hot days, which would also require modification of standard construction techniques.

There is nothing that can be done about more rapid deterioration of non-durable materials in the road structures under higher temperatures – it will be necessary to make sure that all materials used are acceptably durable, although few examples of material deterioration have been observed in low volume roads. On the contrary, durability is seldom a specification requirement for low volume road materials.

When large concrete members are being constructed during hot weather, precautions should be taken to limit any significant heat build-up in the concrete. If final set occurs when the concrete is in an expanded condition due to high temperatures, additional "thermal" shrinkage may result in a large potential overall shrinkage of the member. Similarly, the risk of early age plastic shrinkage cracks or thermal cracking due to temperature gradients may define the requirements for curing and protection of the concrete. Furthermore, increase temperatures mean increased evapotranspiration, therefore the concrete skin should be protected properly against evaporation until a certain maturity or strength is obtained in order to ensure sufficient strength and durability. Methods and tools to help the concrete producer plan and predict the hardening process of a concrete structure under various and changing ambient conditions will need to be improved. Increased temperatures may also require the placement of mass concrete for structures and pavements at night

5.8 Maintenance

Description

Maintenance is a fundamental area that will certainly need to be addressed. Road maintenance should not be seen or evaluated as an adaptation measure - maintenance is not related to climate change but has always been necessary irrespective of the climatic conditions. The techniques are unlikely to change significantly: however, the frequency and types of maintenance will need to be adapted to changes in climate, especially extreme weather events.

Particular attention will need to be paid to mowing of any more luxuriant grass growth, more frequent pruning of shrubs and bushes in the road reserve and drains (to minimise fire risks and obscuring sign boards), cleaning of roads, (particularly of flood debris and wind-blown sand), **cleaning and maintenance of drainage systems**, removal of storm damage, etc.

It has been identified that about one-third of road expenditure in many African countries is on maintenance. Based on international best-practice, about half of road expenditure should be on maintenance and the other half on new road investment. It is thus clear **that current maintenance expenditure is inadequate** and the need for additional maintenance expenditure to cope with possible climate changes is going to be inevitable in most areas.

Adaptation

It has been suggested that the optimal measure to adapt to climate change will be to maintain the roads so that they are always in as near to perfect condition as possible in which case their resilience to climate impact is at all times at a maximum (COWI, 2010). This is, however, usually easier said than done, mostly as a result of funding, skills and resource challenges.

The establishment of a comprehensive road database with regular visual condition assessments will be crucial to effective maintenance strategies[5]. This will allow the monitoring of changing maintenance requirements over time, which can be continuously related to changing climatic conditions and can be used to identify changing trends and budget needs. Issues such as cracking of paved roads, edge-break and potholes will be identified during visual condition surveys and such distress needs to be rectified before rainfall is experienced to avoid large-scale damage to paved roads.

Drainage maintenance in particular will be critical. There is a strong possibility that, due to extended periods of drought that are predicted, drainage maintenance may be reduced or neglected. However, within these drought periods, the potential for more intense and severe storms will be much higher and the consequent damage to the infrastructure could be devastating if the drainage maintenance has been neglected and is poor. It will be important to ensure that the side, mitre and cross-drains are all clean, well graded and effective at all times.

In areas where drier (and windier) conditions are expected, the approach to vegetation control on formation, embankment and cut slopes will need to be such that it is regularly cleared by cutting in order to minimise the potential for uncontrolled burning during wild-fires. In specific areas, the actual grasses planted will need to be selected to provide a mix of deeper rooted grasses as well as surface (or rhizomous) grasses in order to both protect the surface from erosion, the roots from severe fire damage and to provide some soil stabilization effects. The grasses will need to be appropriate for the area (local and drought resistant where necessary) and planted on flattened slopes where necessary to assist their growth, bearing in mind that it is usually difficult to establish vegetation on slopes steeper than about 1:1. It may also be necessary to change the species in areas as climatic changes occur in order to encourage more drought resistant plants, for instance.

The maintenance personnel will need to be carefully trained in the actual maintenance techniques and operations so as to ensure that they are carried out competently and effectively, ensuring a full understanding of the reasons for doing various activities and the implications of these not being done properly.

It is also important that the correct balance between equipment and labour-based maintenance is achieved. Certain operations cannot be effectively done using manual maintenance techniques and it is essential, for instance, that a motor grader is used periodically to restore shape to an unpaved road – the removal of ruts and depressions on unpaved roads cannot be done effectively using labour, for instance.

Where labour-based maintenance is likely to be efficient and effective, community-based maintenance systems should be instituted. This usually results in increased ownership of the facilities as well as the motivation and resources to carry out quick and effective repairs as required.

Optimising maintenance for climate resilience is similar to normal maintenance programmes in requiring a number of inputs and phases as follows:

- Develop a database for road maintenance
- Prioritise maintenance and drainage upgrades in areas that are most at risk of flooding
- Increase the frequency of drainage maintenance that is discussed in the manuals in relationship to the increased frequency of large storms

[5] AfCAP is currently funding a research and capacity building project on **asset management** for rural roads

- Repair and clean channel and drainage structures in high-risk areas before the rainy season, although this is likely to become less predictable in future
- Allocate more funds for maintenance of the current roads.

Climate resilient maintenance procedures and day-to-day actions should be developed in manuals specific to the environment within a district or region.

One aspect of maintenance that must not be underestimated is that of **emergency repairs** following intense storms or flooding. It is inevitable that damage to roads and bridges will occur periodically, and systems and procedures should be in place to facilitate rapid deployment of resources to restore mobility and access following such events. Normal procurement processes are inappropriate in such cases and appropriate resources must be available at short notice.

In line with the above, operational response to climate extremes will have to be actioned by relevant road authorities, where warranted and feasible. This will include emergency teams being on standby to impose access restrictions on certain roads, clear debris on roads, divert traffic to alternative roads (if feasible), and implement actions to restore accessibility. In addition to the above, communication should be in place to inform communities on impaired road links and associated actions to restore accessibility.

5.9 Other issues

Other issues should not be underestimated in the effects of climate change. These are mostly related to increased temperatures.

An example has been noted where the expansion of metal guard-rails has affected the rails. Where the anchorages were loosely tightened to allow movement, this occurred and no deformation was observed (Figure 41a). Where the rails were tightly bolted to the support (wooden in this case), they had been disrupted and some deformation of the guard rails and anchor points was noted (Figure *41*b).

Figure 41: Effect of expansion of metal guard rails: a) loosely tightened and b) tightened so as to avoid thermal movements and cause deformation

A similar issue related to sustained higher temperature conditions is the impact of road markings. Most rural low volume access roads do not have markings (centre-lines, etc.), but where they are found, particularly on asphalt, they are often associated with significant cracking around them. This is an effect of the differential temperatures between the heat absorbing dark asphalt and the heat reflecting white road paint and the consequent differential expansion. Such cracking would require regular maintenance.

5.10 Summary

The potential *adaptation* measures for each climate variable and *engineering* issue are summarised in the following tables (Table 13 to Table 19).

Table 13: Hazards related to increased precipitation

FACILITY	CONSEQUENCE - POSSIBLE PROBLEMS AND DAMAGE	PROPOSED PREVENTIVE MEASURES SUGGESTED REMEDIES
Un-engineered earth roads	Flooding (excessive surface water) Softening of material Impassability Erosion of surface Loss of shape Blockage of drains	Upgrade to engineered earth road standard
Engineered earth roads	Flooding (excessive surface water) Softening of material Impassability Erosion of surface Loss of shape Blockage of drains	Improve construction processes Improve drainage Upgrade to gravel road (raise riding surface and improve drainage).
Gravel roads	Softening of material Erosion of surface Loss of shape Blockage of drains	Improved material selection Improved construction Improved maintenance
Paved roads	Loss of strength of layer materials Damage to thin surfacings Damage to pavement edges Blockage of drains and culverts Erosion of unpaved shoulders	Use appropriate structural designs Ensure high quality construction Use appropriate surfacings Good maintenance (especially of surface cracking and potholes)
Earthworks	Increased slope instability Saturation and weakening of soils Erosion of surface and drains Undercutting Excessive vegetation growth Siltation and blocking of drains	Higher compaction efforts Good drainage Good design (higher factors of safety) More slope stabilization measures Increased maintenance Bio-engineering techniques to stabilize slopes.
Subgrade soils	Expansion and cracking Collapse and settlement Softening of support More movement of saltine materials Deformation of rigid structures Erosion	Correct identification of problem subgrades Correct remedial actions for problems Avoidance or appropriate treatment of problem subgrades Good design Good drainage
Drainage (water from within road reserve)	Accumulation of water adjacent to road Erosion of road surface and drains Softening of materials beneath road	Good drainage design and construction Regular, high quality maintenance

FACILITY	CONSEQUENCE - POSSIBLE PROBLEMS AND DAMAGE	PROPOSED PREVENTIVE MEASURES SUGGESTED REMEDIES
Drainage (water from outside road reserve)	Erosion of embankments and abutments of culverts and bridges Silting/sedimentation of culverts and bridges Scour of bridge foundations Overtopping of bridges Damage to bridges by debris	Modify return periods in design or use expected extreme rainfall Increase culvert and bridge openings Good design including potential for overtopping (embankments and drifts at natural ground level Good maintenance Design to minimise effects of debris (removal or upstream barriers/traps)
Construction	Excessive moisture in materials – construction delays Reduced working periods and increased delays Water damage to partially completed works	Difficult to mitigate against Construct in dry season Greater use of unslaked lime
Maintenance	Additional maintenance necessary More bush clearing Additional damage to drains Need to retain good shape of unpaved road surfaces Improved unpaved shoulder maintenance Pothole patching and crack sealing of paved roads	Adequate resources and systems in place Local community maintenance programmes Good training of maintenance inspectors and teams More regular maintenance Good quality maintenance

Table 14: Hazards related to decreased precipitation

FACILITY	CONSEQUENCE - POSSIBLE PROBLEMS AND DAMAGE	PROPOSED PREVENTIVE MEASURES SUGGESTED REMEDIES
Un-engineered earth roads	Increased wear and loss of gravel from drier surface Increased dust emissions over longer periods Increased development of loose material and roughness (corrugations) More rapid deterioration of gravel due to loss of cohesive fines	Compact material better Upgrade to engineered standard
Engineered earth roads	Increased wear and loss of gravel from drier surface Increased dust emissions over longer periods Increased development of loose material and roughness (corrugations) More rapid deterioration of gravel due to loss of cohesive fines	Improve construction processes Increase compaction Increase maintenance Upgrade to gravel or paved standard
Gravel roads	Increased development of roughness (corrugation) Increased material losses Longer dust period	Improved material selection Improved construction Improved maintenance Upgrade to paved standard
Paved roads	Damage to thin surfacings and asphalt More rapid binder deterioration	Use appropriate structural designs Ensure high quality construction Use appropriate surfacings and binders Good maintenance

FACILITY	CONSEQUENCE - POSSIBLE PROBLEMS AND DAMAGE	PROPOSED PREVENTIVE MEASURES SUGGESTED REMEDIES
Earthworks	Drying out and cracking Rapid ingress of moisture into tension cracks in slopes (slope failures from shrinkage and tension cracks) Increased erosion from more intense storms Damage to vegetation by more wild-fires More difficult to establish erosion protection through bio-engineering	Good drainage to dissipate periodic intense rain quickly Good design Bio-engineering techniques to stabilise slopes Keep vegetation short to avoid wild-fires Use drought resistant plants and grasses
Subgrade soils	Drying out of materials Shrinkage and cracking	Correct identification of problem subgrades Correct remedial actions for problems Good design Construct at estimated in-service moisture condition
Drainage (water from within road reserve)	More erosion More silting and sedimentation	Good drainage design Vegetate drains
Drainage (water from outside road reserve)	More erosion More silting and sedimentation Overtopping of bridges Damage to bridges and culverts from debris	Modify return periods in design Design to avoid scouring after drought periods Good structural design Good maintenance
Construction	Insufficient water for construction Quicker loss of compaction water due to evaporation	Use of innovative compaction techniques and water reducing agents Larger or different rollers Modified construction techniques
Maintenance	More unpaved road surface maintenance More maintenance to drain damage Increased surface erosion repairs	Maintenance management system Keep grass and bush short to avoid fires Keep drains and culverts well-maintained

Table 15: Hazards related to increased temperatures

FACILITY	CONSEQUENCE - POSSIBLE PROBLEMS AND DAMAGE	PROPOSED PREVENTIVE MEASURES SUGGESTED REMEDIES
Un-engineered earth roads	More rapid drying out of road Increased cracking Increased development of roughness (corrugation) Quicker generation of loose material	No mitigation Improve to gravel road standard
Engineered earth roads	More rapid drying out of road Increased cracking Increased development of roughness (corrugation) Quicker generation of loose material	No mitigation Improve to gravel road standard
Gravel roads	More rapid drying out of road Increased cracking Increased development of roughness (corrugation) Quicker generation of loose material	Improved material selection Improved construction Improved maintenance Application of dust palliatives
Paved roads	More rapid ageing of bituminous binders Softening of bitumen in asphalt and more rapid deformation when hot Expansion and buckling of concrete roads and structures	Use more appropriate surfacings Use different (harder) binders in asphalt Changes to concrete mixes and reinforcing More frequent maintenance
Earthworks	More rapid drying out and cracking Loss of vegetation (or change of species) on side slopes (insufficient water) More wildfires causing loss of root binding	Better compaction and slope protection to minimise drying out Improved soil surface material selection Use of deep-rooted, drought resistant vegetation on soil slopes Bio-engineering techniques to stabilize slopes. Keep grass and bush cut low
Subgrade soils	Minimal effects Some shrinkage of soils	Isolation of susceptible soils to minimise drying out. Use of deep-rooted, drought resistant vegetation on soil slopes
Drainage (water from within road reserve)	More rapid drying out, cracking and erosion Loss of vegetation (or change of species) on side slopes More wildfires causing loss of root binding	Increased maintenance Better surfacing material or type selection
Drainage (water from outside road reserve)	Greater expansion/contraction of bridge elements	Good design – concrete and reinforcement Good maintenance
Construction	Quicker reactions when cement stabilising Quicker drying of concrete	More rapid construction processes (recycling machines) Larger or different rollers Better concrete curing required

FACILITY	CONSEQUENCE - POSSIBLE PROBLEMS AND DAMAGE	PROPOSED PREVENTIVE MEASURES SUGGESTED REMEDIES
Maintenance	Ensuring vegetation is kept cut to minimise wild-fires Regular maintenance of bridge movement components	More frequent maintenance Maintain vegetation at low heights

Table 16: Hazards related to decreased temperatures

FACILITY	CONSEQUENCE - POSSIBLE PROBLEMS AND DAMAGE	PROPOSED PREVENTIVE MEASURES SUGGESTED REMEDIES
Un-engineered earth roads	No effects except at extreme altitudes – freezing of water in road surface	-
Engineered earth roads	No effects except at extreme altitudes – freezing of water in road surface	-
Gravel roads	No effects except at extreme altitudes – freezing of water in road surface	-
Paved roads	Reduced windows for construction of bituminous surfacings Less rapid ageing of bituminous binders More brittle fracture of bitumen when cold	Use appropriate surfacings and binders More frequent maintenance
Earthworks	Minimal effect	-
Subgrade soils	Minimal effect	-
Drainage (water from within road reserve)	Minimal effect	-
Drainage (water from outside road reserve)	Minimal effect	-
Construction	Reduced working periods for certain operations (paving, stabilization)	Use of innovative designs
Maintenance	Increased maintenance of bituminous surfacings (crack sealing and pothole repair	-

Table 17: Hazards related to increased windiness (and consequent wild-fires)

FACILITY	CONSEQUENCE - POSSIBLE PROBLEMS AND DAMAGE	PROPOSED PREVENTIVE MEASURES SUGGESTED REMEDIES
Un-engineered earth roads	More rapid drying out Increased deterioration rates due to fines loss Increased accumulation of sand	Improve to gravel road standard Precautions against sand accumulation (increased maintenance, sand traps, etc.)
Engineered earth roads	More rapid drying out Increased deterioration rates due to fines loss Increased accumulation of sand	Improve to gravel road standard Precautions against sand accumulation (increased maintenance, sand traps, etc.)
Gravel roads	Increased deterioration rates due to fines loss Increased accumulation of sand	Improved material selection Improved construction Improved maintenance Precautions against sand accumulation (increased maintenance, sand traps, etc.)
Paved roads	Increased accumulation of sand Possible damage to bituminous surfacings caused by fire	Precautions against sand accumulation (increased maintenance, sand traps, etc.)
Earthworks	Loss of vegetation due to burning Higher erosion of side slopes	Bio-engineering techniques to stabilize slopes. Keep vegetation low
Subgrade soils	No effect	-
Drainage (water from within road reserve)	Loss of vegetation due to burning More erosion of drains	Good drainage design Regular, high quality maintenance (short vegetation to minimise fire risk)
Drainage (water from outside road reserve)	Greater wind-load on bridges Loss of vegetation due to burning More erosion of drains More debris in flood waters due to fire damage Fire damage to bridges (wooden mainly but also concrete)	Design stronger bridges Maintenance of vegetation and bush to avoid fires
Construction	More dust Quicker evaporation of construction water	Dust palliation Modified construction techniques
Maintenance	Increased unpaved road maintenance to minimise corrugations resulting from dust loss Regular clearing of river debris and catchment vegetation	Dragging of roads for corrugations Clearing of drainage facilities

Table 18: Hazards related to sea-level rise and storm-surges

FACILITY	CONSEQUENCE - POSSIBLE PROBLEMS AND DAMAGE	PROPOSED PREVENTIVE MEASURES SUGGESTED REMEDIES
Un-engineered earth roads	Flooding and storm damage	No mitigation possible Improve to higher standard
Engineered earth roads	Flooding and storm damage	No mitigation possible Improve to higher standard
Gravel roads	Flooding and storm damage Increased subgrade moisture contents Erosion and siltation	Improved material selection Improved construction Improved maintenance Place on raised embankment
Paved roads	Damage to road surfacings by salts and water impact Deposition of debris Increased subgrade moisture contents and reduced support	Use appropriate surfacings Use soaked subgrade designs More frequent maintenance
Earthworks	Increased moisture contents with sea-level rise Fluctuating moisture levels with surges Reduced soil strengths	Protection by barriers Reconstruction to increase road level above natural ground level Concrete drifts and pavements
Subgrade soils	Increased moisture contents	Thicker pavements to protect weak subgrades
Drainage (water from within road reserve)	Accumulation of water adjacent to road Erosion Softening of materials	Good drainage design Regular, high quality maintenance
Drainage (water from outside road reserve)	Scour of foundations Deposition of debris Increased salt damage to concrete and steel	Increase protection (barriers) Use chloride resistant coatings on concrete Good design Good maintenance
Construction	Wetter conditions Saline waters	Innovative construction procedures Take soluble salt precautions
Maintenance	Increased maintenance in coastal and low-lying areas	Ensure adequate drainage Use vegetation for moisture control (bio-engineering)

Table 19: Hazards related to changes in ground-water level

FACILITY	CONSEQUENCE - POSSIBLE PROBLEMS AND DAMAGE	PROPOSED PREVENTIVE MEASURES SUGGESTED REMEDIES
Un-engineered earth roads	Wetter or drier subgrades	No mitigation Improve to gravel road standard
Engineered earth roads	Wetter or drier subgrades	No mitigation Improve to gravel road standard
Gravel roads	Wetter or drier subgrades	Thicker or thinner pavement structures as necessary Sub-soil drains where necessary
Paved roads	Wetter or drier subgrades More saline conditions affecting pavement structures	Thicker or thinner pavement structures as necessary Precautions against soluble salt damage Sub-soil drains where necessary

FACILITY	CONSEQUENCE - POSSIBLE PROBLEMS AND DAMAGE	PROPOSED PREVENTIVE MEASURES SUGGESTED REMEDIES
Earthworks	Slope instability (localised)	Incorporation of slope stabilization measures
Subgrade soils	Volumetric movements possible	Design for problem soils
Drainage (water from within road reserve)	Localised seepage and springs	Incorporate sub-surface drains
Drainage (water from outside road reserve)	Changes to surface type for assessment of run-off Otherwise as for any other structure	No special requirements
Construction	Difficult working conditions	Use of innovative construction techniques and water reducing agents
Maintenance	No marked changes	Possible sub-surface drain maintenance to be added to normal maintenance

6 Non-Engineering Options

6.1 General

Non-engineering options and activities to address adaptation for road infrastructure and asset management tend to be more strategic in their nature and are generally used in conjunction with engineering options in their application. Recognised components of these options and activities are set out below, and further expanded on in Section 6.2:

Modify policies and plans

Climate change considerations for (rural) road infrastructure should be incorporated into government policies and plans; these could be general statements focussing attention to potential issues, or targeted statements at specific types of vulnerabilities (e.g., sea-level rise). Policies and plans should be adaptive and robust, and steer the incorporation of climate change into spatial planning, long-term improvement plans, facility designs, maintenance practices, operations, and emergency response plans, amongst others.

Alignment, master planning and land use planning

Planning is the most important aspect of long-term climate adaptation to avoid recognised vulnerabilities for access and economic development. Climate change considerations, such as high and low risk categories for development, land use and future road alignments, should be incorporated in short- and long-range plans. These plans could then guide, for instance, the location of coastal infrastructure to avoid potential damage related to sea level rise and increased storm surges.

Vulnerability and adaptation can be incorporated into planning as follows**:**

- Develop long range goals, objectives and strategies for adapting to potential impacts from climate change
- Incorporate climate change vulnerability assessment planning tools, policies and strategies into existing transportation and investment decisions (e.g. regional planning, programming, project planning)
- Integrate climate change preparation into existing sustainability plans, risk management plans, or other long-range plans
- Integrate adaptation strategies into local comprehensive plans
- Constrain locations for high risk infrastructure.

Improved network and programme management to anticipate and mitigate impacts

Climate changes will unfold over decades and centuries, thus ostensibly allowing time for decision makers to plan and respond. However, current climate variability could bring about abrupt changes that could make planning difficult. If these changes were to occur more frequently, it would necessitate the introduction of different design criteria, asset management policies, maintenance cycles, operational strategies, and therefore also different funding requirements/models.

The following activities will enable more effective management of the network:

- Improved investment decision tools (e.g. risk assessment, cost-benefit analysis, return on investment) and decision rules for prioritisation of adaptation options and investments
- Establishment and implementation of adaptation plans to provide primary and alternative access routings, from a transportation perspective, to mitigate impacts
- Establish emergency routings that have climate resilience.

Climate change should become a routine consideration, factored into a road authority's day-to-day decision making processes rather than a discrete risk to be managed independently. A road authority's Adaptation Strategy should be aligned with the adaptation provisions and strategies at the national level. It should be (Highways Agency, 2008):

- Aligned with the road authority's responsibilities and corporate objectives;
- Focused on the activities of the road authority, and how they need to change in response to a changing climate;
- Identifying priority areas for action;
- Integrated, where possible, with the ways in which the road authority fulfils its current responsibilities;
- Establishing clear responsibilities for developing and implementing adaptation actions in specific areas of activity, and also facilitating strategic oversight of progress and residual risk;
- Offering flexibility to enable the adaptation process to evolve to accommodate changing demands placed on the road authority, developments in climate science and the results of research and/or monitoring.

In countries often exposed to climate effects causing design thresholds to be exceeded frequently, it may be prudent to appoint a Climate Change Adaptation Programme Manager who will have the responsibility for the overall management of the implementation of the Adaptation Strategy. Key responsibilities could include:

- monitoring legislative and other policy developments;
- developing training materials for technical and operational specialists;
- monitoring developments and updating climate trends information;
- maintaining the vulnerabilities schedule;
- dissemination and communication;
- agreeing an annual programme of work with asset managers for options analysis and the development of adaptation action plans; and
- producing activity and progress reports.

The following four recommendations are made in connection with the Adaptation Strategy:

1. assign sufficient resources to adaptation activities, to provide the capability to implement a phased and consistent approach to addressing climate change risks;
2. develop a programme of training and piloting of the Adaptation Strategy for technical and operational specialists;
3. agree programmes of vulnerabilities to be progressed to options analysis and action plan development;
4. initiate a 'quick-wins' programme leading to the early implementation of adaptation actions where these are straightforward, low cost and their benefits are clear.

Improved asset management resilience

The following activities will improve resilience of the network:

- Catalogue asset inventory
- Map, potentially using GIS, infrastructure assets in vulnerable areas; inventory assets that are susceptible to climate change impacts; collect elevation information as standard practice; use standard data collection systems between districts so that asset information can be compiled nationally
- Manage construction and operations to minimise effects of seasonal weather extremes

- Updating operating procedures to take account of the impacts of climate change. For example, updating the procedure for working in high temperatures
- Incorporate procedures to augment operational management covering:
    - Road weather programmes
    - Disaster preparedness planning
    - Alternative transportation access
    - Evacuation planning

Maintenance planning and early warning

Current weather variability and the short and long-term effects of climate change will necessitate more frequent maintenance, rehabilitation and reconstruction of road infrastructure associated assets (e.g. access roads, geotechnical structures, bridges and drainage structures), as well as different design requirements, impacting on the budgets of road authorities. In recent years, funds allocated for core road maintenance are often diverted to address emergency access requirements in the wake of extreme weather events. If this trend continues, the outcome will be fewer properly maintained roads, a long term reduction in rural access and a range of associated disbenefits. Hence, there is a need to:

- identify the most cost-effective adaptation options in order to design and construct assets that are more climate resilient and to ensure that (all-weather) rural accessibility can be sustained;
- develop and implement risk reduction climate adaptation strategies and action plans;
- perform periodic maintenance with the view of also rectifying emerging problem areas; and
- allocate funding for emergency repairs and for short to long-term climate strengthening of infrastructure.

For affected infrastructure that is already in place, preparing emergency and maintenance contingency plans and budgets will enable quicker response for the most vulnerable areas. This reduces extended periods of road closures and more serious consequences of disasters. Furthermore, maintenance planning systems can include early warning systems to anticipate extreme events so that crews and contractors can be prepared for an upcoming high rainfall event (for instance) and possible damage.

Condition assessment and performance modelling will be improved by:

- Monitoring asset condition in conjunction with environmental conditions (e.g., temperature, precipitation, winds) to determine the degree and extent by which climate affects performance;
- Incorporating risk appraisal into performance modelling and assessment;
- Identification of high-risk areas and highly vulnerable assets;
- Use of smart technologies to monitor the condition of infrastructure assets;
- Keeping records of maintenance activities, including specific location; and
- Keeping records of road closures due to, for instance, flooding.

Environmental management

Environmental buffers moderate damage from floods, droughts, and landslides. Examples include ensuring increased vegetative land cover and preserving and conserving mangroves, wetlands, and forests, which help to regulate the hydrologic cycle. Adjustments can also be made to environmental management plans by selecting more drought- and heat-tolerant indigenous species during post-construction rehabilitation works. Other improvements include:

- Restoration of natural form and processes such as allowing streams and rivers to take natural courses;
- allowing unstable slopes to collapse and limiting shoreline armouring;
- restoring shorelines; and
- targeted removal of dikes.

Research

The main purposes of research are:

- to build greater certainty in climate change predictions;
- to provide better understanding on the likelihood and consequences of a risk for the network;
- to find ways to cope with climate change (e.g., determining cost-effective and sustainable adaptation options with a reasonable level of confidence, and providing substantiated arguments for implementing changes to norms and standards); and
- to reduce uncertainty in climate change adaptation.

Demonstrations and trials linked to monitoring and evaluation programmes are valuable ways of assessing the products of research, and to educate stakeholders on methods and outcomes.

Do nothing or do minimum

In many cases there is just not enough budget to deal with all affected areas, roads and structures, or that the consequences of climate change are too severe to justify comprehensive physical adaptation. In these circumstances, a planned programme of dialogue with affected communities, well dispersed information and contingency programmes are necessary to minimise the adverse effects of these decisions. Minimum actions necessary to maintain a safe and serviceable network would include:

- developing contingency plans;
- monitoring changes; and
- for assets, doing patch-and-mend repairs/like-for-like replacements.

Development of a pre-planned response for when/if climate change risks are realised is useful so that their immediate effects can be managed. This option could apply where nothing can reasonably be done to mitigate an identified risk, during the period until other measures are put in place, or where there is a residual risk, despite adaptation actions being employed.

6.2 Building adaptation capacity into roads policy, planning and standards

The principles adopted in this section broadly follow guidance contained within the ADB Guidelines for Climate Proofing Investment in the Transport Sector Road Infrastructure Projects (2011).

6.2.1 Implications for policies and planning

Integrating adaptation at policy and planning levels achieves clear recognition of climate risks and the need for adaptation within relevant national policies. Incorporating climate change at this level means that it cascades into sector plans and other levels of decision making. In the case of roads and transport, and for infrastructure development generally, guidance intended to strengthen cross-sector cooperation between Ministries will also be helpful. Integrated planning around geographically vulnerable areas can produce high-quality development plans for disaster-prone areas. Moreover, climate change impacts are not set by national boundaries; their effects require regional coordination. Harmonisation between national and regional road network development activities requires coordination at this level.

Incorporating adaptation considerations into, for example, transport master plans will further secure the likelihood of meeting the given transport-related objectives and may also identify new priorities. The simplest way for a transport plan to incorporate climate change adaptation is to acknowledge the relationship between climate change impacts and the plan's goals, such as safe and effective road networks.

Transport planning sets out the goals and priorities for transport infrastructure development, maintenance, and decommissioning. A number of planning factors, or objectives, are often established, such as to increase the transportation system's safety for motorised and non-motorised users; increase the accessibility and mobility of people and freight; protect and enhance the environment; promote energy conservation; improve the quality of life; promote consistency between transportation improvements; and promote efficient system management and operation.

To date, there has been a lack of information about climate change, poor inter-ministerial coordination (such as between meteorological focal points and transport focal points), weak implementation capacity and resources, and a lack of experience in designing, implementing and managing climate change adaptation across Africa. Therein lays the difficulty with policy mainstreaming: merely mentioning climate change in policy documents does not ensure its implementation. For these reasons, many of the first climate change adaptation funds have advocated learning by doing or through pilot project initiatives. Establishing some implementation experience can inform the development of appropriate policy-level guidance.

Another approach for developing policy experience that has been tested is policy-driven information gathering, or the explicit link between pilot project and policy mainstreaming. Adaptation strategies are tested and evaluated in the context of a given policy sphere and successful measures are fed back up into the given policy. This integration can help improve the policy's general direction and achievement of its objectives.

In Mozambique, future rural infrastructure policy strategy is made to be flexible, adaptive and robust. The long term increases in engineering costs due to climate change are important, but not excessive if dealt with proactively in the regular planning and design processes. The development of a land-use map/database, developed on a number of catchment principles and zones helps identify a range of criteria that should be used in the event of further wide scale transport network disruption due to a climate impact. The following is a list of potential parameters that can be inputted into the GIS database (ANE, 2016):

- Catchment Area
- Population demographics
- Agricultural or Industrial outputs (timber, maize, live-stock, vegetables, etc.)
  - Scale
  - Monetary Value
  - Seasonal or yearly production/harvesting
  - Time sensitive for market delivery
- Alternate routings to urban centres or markets
- Access to schools, doctors, hospitals, work, etc.
- Hot Spots (Vulnerability / Reoccurrences)

By establishing such a database on land-use, developed in conjunction with the roads network, it is now possible to better analyse and prepare for future events. It also allows for the overlay of hydraulic data and this too can be used as part of the asset management package to address maintenance and emergency requirements and funding requirements/budgets.

6.2.2 Sector policies and plans

Decisions pertaining to priority areas, alignment, land zoning, spatial planning, technology, and implementation plans are made at policy and sector planning levels (ADB, 2011). Many of the examples of international adaptation strategies rely on the participation of multiple partners, such as ministries of infrastructure and ministries of environment, which is more readily established if set at the policy level.

The Organisation for Economic Co-operation and Development (OECD, 2009) identifies the national and sector levels as policy entry points that may be useful for adaptation mainstreaming. National policies and plans include national visions, poverty reduction strategies, multiyear development plans, and national budgets. Sector development plans, such as transport master plans and their budgets, often flow from national plans and policies. Projects support sector plans and in some cases also national plans, particularly those that are cross-sector, regional, and of extremely high priority. Therefore, influencing these overarching frameworks can affect which projects are prioritised and the criteria they must meet in order to be financed.

Although future development patterns are difficult to predict, data suggests population expansion will continue at a high rate and that there will be a very large demand for new development over the next 50 years. Where this development locates and what form it takes, will have an influence on the location and types of access improvements that will be necessary.

A useful summary of policy options for adapting the transport sector to climate change was developed by the Bipartisan Policy Center (BPC, 2010). It is presented in Table below.

Table 20: Policy Options for Adapting the Transport Sector to Climate Change (BPS, 2010)

Research/Policy Overview	Policy Description
Develop appropriate model outputs	Integrate climate data and projections, and more information about the likelihood and extent of extreme events, into transport planning.
Inventory assets	Inventory of transport infrastructure and locations that are vulnerable to climate impacts.
Identify secondary impacts	Conduct research on demographic responses to climate change and land use interactions, and how these responses impact the transport sector.
Support decision making	Provide modelling and adaptation planning tools to local governments to help identify vulnerabilities.
Coordination and collaboration	Facilitate and support cross-disciplinary coordination and collaboration among the public sector, private sector, and local stakeholders to assess impacts, vulnerabilities, and adaptation options.
Emergency preparedness planning	Develop climate change strategies to integrate emergency response into transport infrastructure design and operations.
Expand planning timeframes	Transport agencies need to incorporate the effects of longer-term climate change into their planning processes.

Research/Policy Overview	Policy Description
Refine risk analysis tools	Planners/engineers require support to develop and use probabilistic techniques in risk analysis tools to address uncertainties that are inherent in projections of climate phenomena.
Land use	Work with appropriate agencies to influence land use decisions and avoid inappropriate development in high-risk areas.
Develop risk assessment and adaptive management approach	Adopt an iterative risk management approach to provide transport decision makers a more robust picture of the risks to various components of the transport network.
Develop new design standards	Develop new design standards and codes to incorporate projected changes in climate conditions.
Update regulations	Require climate change adaptation screening in environmental impact assessments.
Institutional changes	Make institutional changes to facilitate integration of climate change impacts into the decision-making process for transportation planning and investment.
Assessment of costs and benefits	Provide guidance to identify opportunities for adaptation and to assess cost estimates and benefits for adaptation initiatives and programs.
Performance measures	Develop performance measures to inform prioritisation and decision making on adaptation approaches and projects.

Road and transport ministries should incorporate the following measures into their implementation plans:

- Introduce climate change vulnerability and adaptation considerations to criteria used for selecting projects for implementation and financing
- Develop sector-specific and country-specific screening tools to identify projects at risk
- Incorporate contingency budgets for specific adaptation interventions as the need arises
- Adjust zoning regulations for transport infrastructure (for example, to avoid flood zones)
- Design flexible transport infrastructure that can accommodate incremental changes over time
- Incorporate climate change indicators into budgeting frameworks to ensure accountability.

6.2.3 Emergency planning, maintenance operational budgets and early warning

Road and Transport sector ministries will need to coordinate more effectively with other line ministries in dealing with climate change issues. There are a number of options for doing this (Gallivan et al., 2009):

- Establish or enhance cross-ministerial committees for managing adaptation to climate change, including for transport.
- Strengthen departments of disaster risk management and meteorology to improve information on which to make decisions.
- Introduce early warning and response systems for transport ministries to improve maintenance schedules and to respond quickly to post-disaster recovery needs.
- Promote low-risk adaptation strategies that will have development benefits regardless of the nature of climate changes that may take place. This is a useful approach where

uncertainty is high regarding climate change and capital investments cannot be justified for large-scale infrastructural changes.

- Incorporate climate change adaptation into environmental impact assessments and strategic environmental assessment guidelines. This can take place specifically in the transport sector or, preferably, as part of the national standards. Road and transport ministries can test tools and adaptation approaches by applying strategic environmental assessments with climate change to their sector policies and plans.

For infrastructure that is already in place, increasing maintenance contingency budgets in areas where climate change impacts are acute will allow more intensive supervision and monitoring of the most vulnerable areas (ADB, 2011). This can reduce road closures and more serious consequences of disasters. Furthermore, maintenance management systems can include early warning systems to anticipate extreme events so that crews and contractors can be prepared for an upcoming high rainfall event and possible landslides. On the one hand, this will ensure that forced road closures are kept to a minimum. On the other hand, pre-emptive road closures may minimise losses of property and life. This suggests the presence of a trade-off between increased capital costs today with less operating expenditures and damages in the future. Generally, financial resources are already insufficient to address day-today maintenance problems and emergency repairs caused by current weather variability, much less to make investments on the basis of changes that may or may not occur years or even generations into the future.

In Mozambique, each road within a network serves a catchment area, with the national road network covering the whole country and with the secondary and tertiary roads subdividing each national road catchment area into smaller catchment areas. A break in the national road network would in essence be a severance for a large region. Following that through a break in the secondary or tertiary road network would mean severance for smaller catchment areas. Taking this notion, a step further and applying this inference it is easy to appreciate the importance and prioritisation of addressing breaks in the hierarchical road network starting with the national roads first. However, in instances where climate events lead to many breaks in the road networks, some form of further hierarchical approach to prioritising reinstatement of the network will be required, particularly in terms of roads of similar hierarchical nature. (ANE, 2016)

In Tanzania, there is recognition at policy level that the backlog of damage from recent extreme weather events may take years to address and that routine maintenance funds must not be diverted to emergency activities.

6.2.4 Augmenting standards and design guides

Operational responses are geared to addressing near-term impacts of climate change. To make decisions today about rehabilitating or retrofitting transportation facilities, especially those with long design lives, transport planners and engineers must consider how climate changes will affect these facilities 50 years or more from now. Adapting to climate change will also require re-evaluation, development, and regular updating of design standards that guide infrastructure design (TRB SR290, 2008).

Updated design requirements, including technical standards and specifications, should provide additional capacity/functionality for adaptation and to reduce vulnerability. These updated requirements could apply to designs for new structures or new roads, as well as to designs for maintenance, renewal and improvement works. Typically, it will be appropriate to adopt a precautionary approach for the building of greater resilience in designs, so that the asset/activity will perform satisfactorily throughout its useful life.

Development of design standards follows a time-consuming and systematic process that involves professional organisations in an extensive research and testing programme over a period of decades. Once the standards are in place, engineers are reluctant to change them. A combination of the length of time required to modify or develop new standards, the institutional procedures for approval of standards and the use of well-established standards as evidence of "good practice" in litigation lead to a conservative approach to change. Developing standards to address climate change in a timely manner thus will require leadership by the scientific community and professional associations and, given the scope of potential impacts, a broad-based, country sponsored research programme. (TRB SR290, 2008)

As the effects of climate change result in more regular and abrupt impacts on road pavements, more regular re-evaluation and updating of design rules, standards and specifications for road pavements will be required. This will also require more intensive, short- to medium-term research, development and implementation efforts to develop and validate these new design rules, standards and specifications.

6.2.5 Road safety

Road user safety should feature prominently in any climate change risk assessment process (PIARC, 2012). Risks that could be attributed directly to climate change effects include:

- Aquaplaning of vehicles on water accumulated on the road surface;
- Skidding of vehicles caused by lack of friction during or shortly after intense precipitation events, or as a result of bleeding of the bituminous road surface caused by high temperatures;
- Lost control over a vehicle as a result of severe wind conditions, high currents during flooding, etc.;
- Reduction in visibility during intense precipitation events and sand storms;
- Impairment as a result of, for example, flooding, landslides and mud flows.

Most of these direct risks can be dealt with proactively by improving the functional and structural characteristics of the road pavement and the road environment. Others will require emergency response, such as network restrictions or even road closures to uphold safety.

In addition to the direct risks, there are indirect risks that also need to be considered, such as, for instance, the inability to access disaster areas and emergency facilities as a consequence of road closures. Indirect risks would require a different set of emergency responses such as the provision of alternative access (e.g. alternative roads and air rescue).

It is expected that, as a consequence of extreme climate effects, road pavements and other infrastructure may require more regular maintenance than is currently the norm. This may require road workers to work on the network more often and also may require them to work during extreme climatic events; hence the need to also include the safety of road workers in the risk assessment process.

6.3 Capacity building

In order to establish and implement climate adaptation successfully, national capacity will need to be developed across all relevant stakeholders. This includes road and transport ministries, departments and agencies/authorities, and will include a wide range of participants from central government agencies cascading all the way through to village groups. Specific attention will be needed for national road fund boards, scientific ministries and environmental agencies, with the cooperation and buy-in of the road authorities. Typical deliverables could include:

- *Establishment of a knowledge-exchange network* (e.g. web-based) between organs of state, the private sector and academia; innovative aspects could include how to assess and manage current maintenance backlogs already caused by extreme climate effects;

- *Dissemination of potential options* for climate adaptation and resilience strategies;
- *Dissemination workshops*;
- *Training Workshops.*

Initially, there should be an emphasis on **awareness and knowledge building**, followed by dissemination, capacity building and uptake. Training and capacity building will be important for:

- *Understanding* the challenges
- *Participation* and knowledge sharing/exchange
- *Agreeing* a methodology and programme for implementation climate adaptation
- *Developing* physical and social resilience
- *Disseminating* knowledge and experience.

The following is a five-step process that could be considered for systematic capacity building:

1. ***Engage stakeholders on capacity development***

   An effective capacity building process must encourage participation by all those involved. Engaging stakeholder's who are directly affected allows for more effective decision-making, it also makes development work more transparent.

2. ***Assess capacity needs and assets***

   Assessing pre-existing capacities through engagement with stakeholders informs what areas require additional training, what areas should be prioritised, and in what ways capacity building can be incorporated into local and institutional development strategies.

3. ***Formulate a capacity development response***

   The capacity building response could be based on:

   - *Institutional arrangements* – policies, procedures, resource management, organisation, leadership, frameworks, and communication;
   - *Leadership* – high level involvement will help priority setting, communication and strategic planning;
   - *Knowledge* – knowledge is the foundation of capacity;
   - *Accountability* – the implementation of accountability measures facilitates better performance and efficiency.

4. ***Implement a capacity development response***

   Implementing a capacity building program should involve the inclusion of multiple systems: national, local and institutional. It should involve continual reassessment and expect change depending on changing situations. It should include evaluative indicators to measure the effective of initiated programs.

5. ***Evaluate capacity development***

   Evaluation of capacity building promotes accountability and feeds into a programme of continuous improvement.

7 Summary and Conclusions

Africa is one of the most vulnerable regions in the world with respect to impacts of climate change. In the past four decades, African countries have experienced more than 1,400 recorded weather related disasters resulting in the death of more than 600,000 people, left 7.8 million people homeless (99 per cent due to flooding and storms) and affected an estimated 460 million people.

Limited funding for adaptation and mitigation is challenging AfCAP partner countries to acknowledge the threats that are posed by climate change, develop adaptation approaches, incorporate changes into immediate, mid-range and long-term development plans, and secure funding for the proposed and necessary adaptations.

The majority of the low-volume rural road network in Africa is used for accessibility, as opposed to mobility. With the expected changes in climatic conditions (le Roux et al, 2016) resulting from climate change, the on-going and periodic deterioration of the existing low-volume rural road networks in SSA can thus be expected to continue on a more frequent and increasing scale.

This report 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 rural access low volume roads. In addition, in the report by le Roux et al (2016) and in this report, evidence of economic and social benefit links to rural communities arising from more resilient rural access are provided to support wider policy adoption across Africa. They concentrate on future road scenarios in Mozambique, Ghana and Ethiopia, for which detailed climate projections have been developed within this overall project. The general findings, however, cover a wide range of scenarios and should be applicable to similar scenarios that unfold in other SSA countries.

The objectives are delivered through the following:

- Conceptual climate vulnerability and adaptation strategies
- A methodology for mitigation and adaptation
- Provision of options to create resilience
- Provision of guidance for building adaptation strategies into roads policy, planning and standards.

This report should be used in close conjunction with the *Climate Adaptation: Risk Management and Resilience Optimisation for Vulnerable Road Access in Africa - Climate Threats Report* (le Roux et al, 2016).

In Chapter 2, climate change effects are summarised under:

- Temperature changes
- Precipitation Changes
- More frequent extreme events
- Sea level rise
- Migration of the tropical cyclone belt
- Increased wind speeds.

This chapter also provides a summary of climatic classifications currently used in road engineering.

Chapter 3 presents an inventory of all road elements that should be considered when addressing climate change effects.

Chapter 4 sets out detail of adaptation strategies, a 20-step methodology approach, prioritisation needs and options. Engineering and non-engineering options are introduced.

Chapter 5 identifies the potential hazards relating to the different expected climate stressors for all relevant facilities. Adaptation techniques for handling the expected changes in temperature and precipitation, windiness, seal-level rise and more frequent extreme events are identified and discussed. These are specifically related to unpaved roads, paved roads, subgrade materials, earthworks and drainage within and outside the road reserve, as well as possible implications for construction and maintenance activities.

The critical importance of adequate drainage, with timely and good maintenance practices, is also highlighted and guidance given.

Chapter 6 addresses *non-engineering* adaptation options and activities covering:

- Modification of goals and policies
- Alignment, master planning and land use planning
- Improved network and programme management to anticipate and mitigate impacts
- Improved asset management resilience
- Maintenance planning and early warning
- Environmental management
- Do nothing or minimum
- Research
- Building adaptation capacity into roads: Policy, Planning and Standards

It also explains the role of capacity building in order to implement climate adaptation successfully. National capacity will need to be developed across all relevant stakeholders. This includes road and transport ministries, departments and agencies/authorities and will include a wide range of participants from central government agencies cascading all the way through to village groups. Specific attention will be needed for national road fund boards, scientific ministries and environmental agencies, with the cooperation and buy-in of the road authorities. A five-step process is set out for systematic capacity building.

In conclusion, the report provides a valuable sensitisation platform from which climate threats and adaptation options can be identified and implemented. In order to build permanent knowledge and capacity, a sustained programme of demonstration sites, followed up by a top-down and bottom-up capacity building programme should be implemented.

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APPENDIX A: Requirements for Hazard Assessment in the Field

Unpaved roads

The main issues to be considered in assessing unpaved roads are:

- Surface evenness
- Water shedding ability
- Side drainage
- Gradient
- Erosion susceptibility

Surface unevenness – does the surface have ruts, potholes, corrugations, etc. that will cause water to accumulate for extended periods

Water shedding ability – is the shape of the road and shoulders such that all water will flow off the road surface evenly into side drains without causing excessive erosion or scouring.

Is the side drainage capable of moving the water sufficiently far away from the road as to avoid its influence on the subgrade?

Is the longitudinal gradient such that erosion/scour of road surface could occur (e.g. in hilly and mountainous terrain)? On grades up to 6%, is the camber of the road steeper than the grade?

Paved roads

The main issues to be considered in assessing paved roads are:

- Surfacing condition
- Water shedding ability
- Side drainage
- Shoulder condition

Surface condition – Is the paved surface in a condition that will avoid water entering the pavement structure i.e. no cracking, unpatched potholes or severe edge-break?

Water-shedding ability – is the shape if the road such that water will not accumulate on the road, i.e. adequate cross-fall, no deep ruts, depressions, compacted patches, etc.?

Side-drainage – are the side drains clean, properly graded and capable of leading water away from the edge of the road into cross-drains or mitre drains leading into adjacent fields?

Shoulder condition - Is the shoulder effective in removing water, i.e. is there no high drop-off at the edge of the paved surface and no depression along the edge of the paved surface in the shoulder that will accumulate water?

Slopes

During the inspections of slopes, the deformation or unusual state of the slope such as cracks, depression, expansion, deformation of slope protection works and conditions of drainage systems should be major points of inspection. Focus should be fundamentally on water flow in slopes as it often causes, when concentrated and at high flow rate, erosion and failures, not only on cut slopes but also on original ground and embankment. It is important to inspect water runoff especially at the shoulder of slopes, drainage systems and seepage points, noting the volume and its variation. For slope surfaces and slope protection structures, observations should be made of growth of vegetation, existence of rocks, loose portion, cracks, expansion and their variation with time. When symptoms of a large scale failure are observed, it is necessary to consider monitoring the area using instruments as well as to take emergency measures.

The standard values of precipitation for closing highways are generally based on the relationship between various indices of precipitation and monitoring records of landslides. The levels, however, depend on factors such as type and section of highways, maintenance period after opening and state of slope protection structures. The standard values are usually expressed in Japan in terms of continuous precipitation or the combination of continuous precipitation and hourly precipitation. The antecedent rainfall is also important – when significant rain has fallen prior to a storm event, the potential for failure is much higher. When the area has been dry for a significant period (6 weeks of more) before the storm event, the potential for failure is usually significantly less.

The issues that need to be specifically assessed during the visual rating of cuttings are shown on the following table:

Parameter	Issues	Examples
Rock type	Dipping into road	Poor lithology (shale, phyllite, sandstone, etc.)
Material strength	Low strength discontinuities	Shale, mudrock,
Moisture	Seepage in slope	Seepage, reed growth, etc.
Tension cracks	Allow build-up of water pressure	Cracking at top of slope
Damage to other structures	Will affect bridges or buildings	

Embankments

When assessing the vulnerability of embankments, it is necessary to concentrate on the potential for erosion/undercutting, slope failures and possible damage due to overtopping. Slopes that are excessively steep should be specifically noted.

Assessment

The assessment should rate the specific issues according to the probability and consequences summarised in Appendix B. The data provided are tentative and will need to be included in the visual assessment criteria that will be developed by the ReCAP Asset Management Project.

Hazard	Probability			Consequences			Action
	Low	Medium	High	Low	Medium	High	
Landslides in cuts							
Erosion							
Overtopping of embankments							
Undercutting of embankments							

APPENDIX B: Determination of Vulnerability

The determination of vulnerability frequently uses a 5-point rating scale for the estimation of probability of occurrence and consequences of the event. It is, however, deemed simpler and more appropriate to use a 3-point scale for rating vulnerability of low volume roads, without detracting from the validity of the results.

The Probability would be rated according to the following scale:

Rating	Likelihood of recurring events
High	Could occur several times per year
Medium	May arise once in five years, or has happened during the past 5 years but not in every year
Low	Unlikely during next 10 years, or has not occurred in past 5 years

The Consequences would be rated according to the following scale:

Rating	Consequence on the relevant infrastructure
High	Significant permanent damage and/or complete loss of the infrastructure and the infrastructure service. Loss of infrastructure support and translocation of service to other sites.
Medium	Limited infrastructure damage and loss of service. Damage recoverable by maintenance and minor repair.
Low	No infrastructure damage, little change to service

The ratings obtained during the visual survey are then plotted on the following chart for the different infrastructure units or uniform sections to obtain a vulnerability classification.

		Probability		
		Low	**Medium**	**High**
Consequences	**Low**	Acceptable	Acceptable	Undesirable
	Medium	Acceptable	Undesirable	Unacceptable
	High	Undesirable	Unacceptable	Unacceptable

APPENDIX C: Bioengineering Measures

The information presented below has been extracted from the *Resource Manual on Flash Flood Risk Management – Module 3: Structural Measures* published by the International Centre for Integrated Mountain Development (ICIMOD), GPO Box 3226, Kathmandu, Nepal.

This publication, the third module of a resource manual to support the training of planners and practitioners in managing flash flood risk, deals with structural measures. It presents bioengineering techniques, physical measures for slope stabilisation and erosion control, and physical measures for river training. It also presents the concept of integrated flood management as a component of integrated water resource management. It emphasises that structural measures are most effective and sustainable when implemented together with appropriate non-structural measures. The manual is aimed at junior to mid-level professionals with a civil engineering background working on flash flood risk management at the district level

C.1 General

Bioengineering is the application of engineering design and technology to living systems. In terms of flash flood mitigation, it refers to the combination of biological, mechanical, and ecological concepts to reduce or control erosion, protect soil, and stabilize slopes using vegetation or a combination of vegetation and construction materials (Allen and Leech, 1997; Bentrup and Hoag, 1998).

Bioengineering techniques used in combination with civil and social engineering measures can reduce the overall cost of landslide mitigation considerably (Singh, 2010). Bioengineering offers an environmentally friendly and highly cost and time effective solution to slope instability problems in mountainous and hilly areas and is a technique of choice to control soil erosion, slope failure, landslides, and debris flows, and thus ultimately to help minimise the occurrence of floods and flash floods.

One of the major differences between physical construction techniques and bioengineering is that physical structures provide immediate protection, whereas vegetation needs time to reach maximum strength. Thus the combination of physical and vegetative measures offers a combination of immediate and long-term protection, as well as mitigation of the ecologically damaging effects of some physical constructions.

C.2 Functions of Vegetation

Hydrological functions

Plants play a significant role in the hydrological cycle. Particularly riparian vegetation influences hydrological processes through effects on runoff; control of uptake, storage, and return of water to the atmosphere; and water quality (Tabacchi et al., 2000). The hydrological functions of vegetation can be summarised as follows:

- **Interception**: The vegetation canopy intercepts raindrops and reduces their size and mechanical strength, thus protecting the soil from erosion caused by rain splash.
- **Restraint**: The dense network of coarse and fine roots physically binds and restrains soil particles in the ground, while the above ground portions filter sediment out of runoff.
- **Absorption**: Roots absorb surface water and underground water thus reducing the saturation level of soil and the concomitant risk of slope failure.
- **Infiltration**: Plants and their residues help to maintain soil porosity and permeability, thereby increasing retention and delaying the onset of runoff.
- **Evapotranspiration**: Vegetation transpires water absorbed through the roots and allows it to evaporate into the air at the plant surface.

- **Surface runoff reduction**: Stems and roots can reduce the velocity of surface runoff by increasing surface roughness.
- **Stem flow**: A portion of rainwater is intercepted by trees and bushes and flows along the branches and stems to the ground at low velocity. Some rainwater is stored in the canopy and stems.

Engineering functions

- **Catching**: Loose materials have a tendency to roll down a slope because of gravity and erosion, and this can be controlled by planting vegetation. The stems and roots can catch and hold loose material.
- **Armouring**: Some slopes are very water sensitive. They start moving and/or are easily liquefied when water falls on them. Vegetation can protect the surface from water infiltration and erosion by rain splash.
- **Reinforcing**: The shear strength of the soil can be increased by planting vegetation. The roots bind the grains of soil. The level of reinforcement depends on the nature of the roots.
- **Supporting**: Lateral earth pressure causes a lateral and outward movement of slope materials. Large and mature plants can provide support and prevent movement.
- **Anchoring**: Layers with a tendency to slip over each other can be pinned to each other and the stable underlying layer by penetration of woody taproots from vegetation which function as anchors.
- **Draining**: Water is the most common triggering factor for slope instability. Surface water drains away more easily in areas with dense rooted vegetation. Thus draining can be managed by planting small and dense rooted vegetation such as durva grass.

Choice of appropriate species

In general, it is best to use local species of vegetation in bioengineering as they are already adapted to the growing conditions, are more likely to be resistant to local diseases, are more readily available, and are likely to be a lower cost option.

It can also be useful to choose species that can be used for other purposes as they mature, for example, providing fruit or with branches and leaves that can be used for fuelwood, fodder, or other domestic purposes. This increases the benefit to local people and their acceptance of the measures.

The bamboo plant, in particular, is ideally suited to mitigate the effects of climate change through rapid reforestation, slowing soil erosion and repairing damaged ecosystems.

C.3 Bioengineering in Flash Flood Risk Management

Bioengineering can be used in various ways to reduce flash flood risk. It can be used to stabilize slopes and thus reduce the risk of landslides and debris flows occurring. It can be used to increase infiltration, to form structures to temporarily capture and store runoff, and to lower the velocity of runoff, all of which hinder the formation of flash floods after cloudbursts. And it can be used to change the flow pattern of rivers downstream in order to reduce the impact of floods that do occur. Bioengineering is often used in combination with structural techniques, either to reinforce structures or as a complementary approach to increase the overall impact of the measures.

Bioengineering techniques to control slope failure phenomena

Bioengineering can be used to increase slope stability in a variety of ways (Li and Clarke, 2007; Lammeranner et al., 2005), in particular

- mechanical reinforcement,
- controlling erosion,
- increasing the infiltration ratio,
- reducing runoff, and
- soil moisture adjustment.

Reinforcement. The dense network of coarse and fine roots from vegetation can work as a reinforcement mechanism on the slope by binding and stabilizing loose materials. The stabilizing effect of roots is even greater when roots are able to connect top soil with underlying bedrock, with the root tensile strength acting as an anchor. Small dense roots also contribute to the shear strength of a slope and thus reduce the risk of landslides and debris flows. Trees and bamboos can stabilize the whole soil layer in slope terrain, whereas bush and shrub roots mainly protect soil up to 1 m deep, and grasses can conserve top soil to a depth of around 25 cm (Jha et al., 2000).

Erosion control. Bare soil-covered slopes are easily affected by the splash effect of intense rain leading to heavy erosion. The surface runoff rate is also very high, and the flowing water can carry the soil particles away and trigger a debris flow. A dense cover of vegetation protects the soil from splash effects and reduces runoff velocity, while the roots bind the soil particles, thus hindering surface erosion.

Soil infiltration. As decayed roots shrink, they leave a gap which provides a passage for water seepage, which leads water away from the surface and reduces the likelihood of surface soil saturation. This reduces slope instability and hinders the development of debris flows.

Reducing runoff. Vegetation can be used to reduce runoff in a number of ways including trapping of moisture in leaves and branches, slowing the flow of water across the rough surface, increasing infiltration, and through structures designed to deflect flow away from the top of a slope and channel it along a desired pathway down the slope.

Soil moisture adjustment. Soil moisture is a key factor in slope stability. Vegetation can directly influence soil moisture through interception and evapotranspiration. In interception, precipitation is captured by the vegetation canopy and returned directly to the atmosphere through evaporation. The rate of interception varies according to various factors including leaf type and size, canopy density, temperature, and humidity. In evapotranspiration, the plants channel moisture from the soil to the leaves and stems, from where it returns to the air via evaporation. These two processes combine to reduce the overall soil moisture content.

Choice of techniques. Different bioengineering techniques are used to control erosion and slope failure in different parts of the world. The techniques suitable for a particular area should be selected on the basis of availability of resources, site condition, and required function. Table C.1 shows the appropriate bioengineering techniques for controlling different types of landslide and debris flow hazards.

Bioengineering to reduce the volume and velocity of runoff

High runoff can directly cause development of a flash flood from a small catchment following a heavy localised rainfall event. The aim of bioengineering in this case is to slow and trap the runoff in order to reduce the rate of outflow from the catchment. Appropriate techniques include palisades, grassed water ways, brush layering, bamboo fencing, wattle fencing, and similar measures.

River training

The impact of a flash flood can be reduced by measures designed to direct and reduce the speed of the flood wave in the river downstream. These measures are a part of so-called 'river training' techniques, which are undertaken to improve a river and its banks in order to change the waterway pattern and reduce the velocity of flow, hinder erosion, reduce transportation of sediment, and guide flood waves into a less destructive path. The most common river training measures involve construction of physical structures such as banks and spurs. However, used alone, these techniques may have a marked negative effect on the environment and landscape, as well as being expensive. Bioengineering techniques used alone or in combination with physical measures offer a low-cost approach that is easily implemented by local communities and provides an environmentally friendly environment for local flora and fauna.

The use of bioengineering techniques alone is mainly confined to river bank stabilization. By their nature, river banks provide a good environment for growth of vegetation. Left alone, banks usually have dense vegetation as the river provides nutrients in the form of silt and water to support growth. If vegetation is sufficient, both on the bank and in the river bed, it can stabilize the bank, lessen erosion, reduce the speed of flowing water, and reduce scouring by a flood wave. Where vegetation has been reduced or removed, it can be replaced by carefully selected planting of appropriate species to achieve the desired effect. Structures formed from a combination of dead and living plant material can also be used to guide the river course and prevent flood surges entering into settlements and farmland. The plants can provide additional benefits for the local population like fodder, fruit, and firewood, but this is secondary to the protective function.

As in slope protection, bioengineering can involve building a structure such as a fence to provide immediate protection, but using living branches that will take root and become an increasingly strong barrier. It can also involve a combination of dead and live vegetation, with a framework made of bamboo or timber, intertwined with living plants to grow and strengthen the structure. Placed in the water or in regularly flooded areas of the bank, these structures trap silt in which they slowly become embedded, creating a strong stable self-sustaining bank with bamboo or timber reinforcement held together by roots and vegetation.

In general, bioengineering is used in combination with physical techniques in river training rather than on its own. It is highly recommended as a means of reducing the impact of physical measures on the local ecology and landscape, and also for providing long-term strengthening of structures such as embankments.

Table C.1: Basic techniques for bioengineering

Phenomenon	Erosion problem and condition	Suitable bioengineering techniques
Landslide	Deep-rooted landslide (>3 m depth) Slumping Planar sliding Shear failure Cut and fill area at deep and shallow-rooted landslide (<3 m depth) Bare and steep slope or newly exposed surface	Smoothing to a suitable slope gradient Diversion canals, channel lining, catch drains, waterways Stone pitching and planting of trees, shrubs, and grass slip Bamboo fencing with live poles, planting and seeding grass Terracing and planting with bamboo, trees, shrubs, grass Live peg fence, wild shrubs, live check dams Contour strips planted with grass, shrubs, and pegs Fascines, brush layering, and palisades Planting bamboo with or without a structure Check dams planted with deep-rooted species (e.g., bamboo, trees)
	Cracking zone	Bamboo fencing above zone; zone covered with polythene sheet Catch drain with vegetation Fascines, brush layering, and palisades
	Head scarp of landslide or slope failure	Slope excavated to an appropriate gradient and rounded (when high and steep) and planted with deep-rooted plants (e.g., bamboo, trees) Bamboo fencing, planting grass, seeding, and mulching Fascines, brush layering, and palisades Jute netting or straw mat covering soil, seeds, and compost mixture; turfing Stone pitching; planting of trees, shrubs, and grass slip Planting grass slip and seeding grass
Debris flow	Sediment production zone	As for landslides
	Sediment transportation zone	Series of gabion check dams, retaining wall, and side wall planted with deep-rooted species (e.g., bamboo, trees) Bamboo fencing; grass planting, seeding, and mulching
	Sediment deposition zone	Diversion canal, channel lining, retaining wall, and side wall planted with trees, shrubs, and grasses Plantation of deep-rooted species (e.g., bamboo, trees)
Soil Erosion	Sheet and rill erosion	Planting of bamboo, trees, shrubs, and grass with or without terracing Live peg fence, wild shrubs, and live check dams Contour strips planted with grass, shrubs, trees, and pegs Fascines, brush layering, and palisades with wild and thorny shrub species.
	Gully erosion	Diversion canals, channel lining, catch drains, waterways, cascade retaining wall, and side wall, planted with trees, shrubs, and grasses Bamboo fencing with live pegs Planting of bamboo, trees, with or without check dams Series of retaining walls and plantation Vegetated stone pitching in small gullies and rill beds
	Erosion on bare land, degraded steep sloped land, dry and burnt area	Planting of deep-rooted species (e.g., bamboo, trees) Bamboo and live peg fencing and live check dams Vegetated stone pitching in small sheets and rill beds Stone pitching and planting of trees, shrubs, and grass slip
	Degraded shifting cultivation areas, newly excavated or exposed areas on terrace bund, degraded forest, and grazing land	Bamboo fencing with live poles, planting and seeding grass Planting of bamboo, trees, shrubs, and grass with or without terracing and structure Live peg fencing and live check dams Vegetated stone pitching in small gullies and rill beds Contour strips planted with grass, shrubs, trees, and pegs Planting fascines, brush layering, and palisades
	Water induced degraded land (spring, water source damaged area, canal command area)	Planting of bamboo, trees, shrubs, and grass with or without terracing and structure Stone pitching and planting of trees, shrubs, and grass slip Planting of deep-rooted species (e.g., bamboo, trees) Live peg fences and live check dams Vegetated stone pitching and loose stone masonry walls or check dams
	Cut and filled area or newly exposed area on slope*	Jute netting and straw mats covering soil, seeds, and compost Live peg fences and stone masonry walls Plantation, seeding, and planting grass Live wattling with terracing and seeding

*Exposed slope surfaces must be carefully maintained. A cut and newly exposed slope surface should usually be covered, depending on the type of soil material and other factors.

C4 References

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