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World Bank

Making Transport Climate Resilient

Country Report: Mozambique

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0 Executive summary

This report is the output of the World Bank-financed study on Making Transport Climate Resilient for Mozambique, which is a Sub-Saharan Africa initiative to respond to the impact of climate changes on road transport.

The climate scenarios
The study is based on four climate scenarios selected by the World Bank to be consistent with the scenarios used in the study Economics of Adaptation to Climate Change. The scenarios span from a "global dry" future with higher temperatures than today to a "global wet" future with more rain than today and an increase in heavy rain so that a 10- year storm in 2050 will be 27% more intensive than today. The foreseen increases in average temperatures range from -2 ^{O}C to 2 ^{O}C by 2050.

The design and maintenance of roads
The largest problems facing the current Mozambican road network seem to be overloading and missing maintenance and repair. The most influential climate impact on roads in Mozambique will in the future come from changes in rain patterns and only to a smaller extent from increased temperatures, sea level rise and cyclones.

A climate-resilient road in the future in Mozambique will be very similar to a climate-resilient road right now. Mozambique has the knowledge as expressed in the current excellent Road Sector Strategy needed to design and keep their roads up to standard. The key element to ensuring climate resilience after the initial construction is sufficient maintenance. Without routine maintenance, there is no possibility for a road to meet its design life in today's climate, let alone the future climate. The climate changes predicted do not suggest that the problems in the future cannot be accommodated with today's engineering solutions in Mozambique.

The draft SATCC standards are together with local standards on hydraulic issues the main road design guidelines in Mozambique, but they are not mandatory as designers are encouraged to evaluate various alternatives in a specific situation to find the most optimal solution fulfilling the specific local needs. The engineering solutions needed to make a climate-resilient road can to a very large extent be found in the existing manuals, from solutions to hydraulic-related problems such as scour and sedimentation to problem soils and subgrade problems as well as slope stability and surface drainage solutions.

The adaptation measures
The measures to deal with the predicted change in precipitation volumes and patterns will primarily be:

Design:
- Revise parameters used for the design storm that is in order to create a robust standard design flood estimation method for all drainage systems and structures.
- Design culverts that cause limited damage to roads during floods
- Investigate the use of spot improvements in high risk areas
- Design gravel roads and community roads with a variety of materials suitable for the climate and topography
- New alignments need to consider likely future changes to the environment considering increases in rainfall, groundwater, sea level raise, storm surge, and the impacts on e.g. flooding and transboundary rivers.

Maintenance:
- Prioritize 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
- Repair and clean channel and drainage structures in high risk areas before the rainy season

Research:
- Create database for bridges and culverts.
- Further research on suitability of marginal materials on road construction.
- Establishment of a database with an extensive inventory of road building materials.
- Add a chapter to the design manuals focusing on climates impacts on roads and bridges investigating engineering solutions.
- Continue improving models for the prediction of floods magnitudes and probability of these floods updating them with latest climate change scenarios data.

The economic assessment
The costs of climate changes in the period 2010 - 2050 are roughly estimated at around 0.5 - 0.6 billion USD in 2009 net present value - of which increased maintenance costs are far more important than the costs of changed designs.

The costs to road users due to climate-related incidents may be substantial even with today's climate if measures are not taken. Adapting to climate changes by eliminating the increase in road user costs completely is likely to be a feasible strategy for some new road infrastructures - especially culverts and riverbank protection. For other structures, the specific conditions decide if it is economic feasible to fully adapt to the climate change.

For the existing network, an adaptation strategy is expected to be preferable where adaptation takes place because the life time of the infrastructure is exceeded or in cases where the infrastructure is destroyed by climate (or other) related incidents.

The policy implications
The road owners will experience increased costs to maintain current service levels for both existing and new infrastructure.

Yearly reconstruction costs for existing roads will increase because of a higher risk of damage each year in combination with higher unit reconstruction costs.

New climate resilient roads are more costly to build so investments budgets have to be increased or the amounts of new roads to be constructed will have to be reduced.

Increasing sea levels and the large variation in ocean tides is a big challenge for the relatively small part of the road infrastructure and the cities located in low areas in Mozambique. Basically, the choice is either to protect existing road infrastructure and city by investing in protective coastal defenses, e.g. sea walls, or gradually relocate the infrastructure (and the population) to more stable areas. In cities protection measures for roads are integrated with protection of other types of infrastructure and should be treated this way.

Design parameters are recommended to be reviewed every 5 to 10 years to continuously search for the optimal balance between climate risks and adaptation costs in the country.

The key element to ensuring climate resilience after the initial construction is sufficient maintenance. Strengthened focus on road maintenance and significantly more spending will be a vital cost effective adaptation measure. Maintenance is also an important measure after cyclones to protect the infrastructure from further damage. This will also benefit the road users dramatically but it requires a big change is current spending patterns in the road sector.

The general implication is that only in exceptional cases it will be economically beneficial to reconstruct or strengthen existing roads and structures before they are damaged/normal life time is expired.

Research to strengthen knowledge about the existing climate including areas like hydrological data and models is essential for cost-effective design and investment decisions. Finally, it is essential to record and analyze results of the ongoing innovative road and bridge constructions in Mozambique.

The proposed strategy
In the short term (within the next 5 years), the following initiatives are recommended:

- Research is needed in the accuracy of the design parameters in predicting sedimentation and runoff and identification of flood prone coastal areas.

- Based on this research, the design storm parameters for new roads and structures are recommended to be adjusted to reflect significant climate changes - after due consideration of an acceptable future safety level.
- The design manuals used today are recommended to be revised so that the climate-related issues and solutions are presented clearly e.g. in an additional chapter. Having a chapter dedicated to the climate and environmental impacts on the road would make it easier for the designer to choose quickly and efficiently and also consider thoroughly locations of new roads in climate safe areas.
- As the maintenance need will increase according to the expected more frequent heavy rainfall It is recommended to investigate if it is feasibly to change and/or enlarge the drainage system in specific areas prone to erosion and flooding to reduce the risk of total failure and consequential damage and for reduction of the climate change related need for increased maintenance.

In the long term, the following initiatives are recommended:

- Establishment of a process to review climate-related parts of the design guidelines at regular intervals (5 or 10 years) to take account of most updated information on observed climate change impacts and the need to balance climate risks and economic feasibility
- Ensure that the excellent maintenance strategy in the current Road Sector Plan is implemented
- Development of reliable and accurate hydrology models as it is a common problem that this is lacking

1 Introduction and background

1.1 Introduction

1.2 Summary of conclusions

1.2.1 Climate change scenarios and predictions

The observed trends in climate change in Mozambique over the last 4 decades shows:

- slightly increased average temperatures;
- increased number of hot days and nights;
- slight decrease in average annual rainfall;
- slight increase in precipitation falling in heavy events; and
- no significant change in frequency for cyclones

The weighted climate change predictions found and reported by UNDP in the Climate Change Country Profile for Mozambique has been used to present a general description of trends of climate change. However, the 15 different CGM climate models used in the UNDP report shows different results and illustrate the uncertainty of predicting climate change.

The specific analyses in this study are based on 4 climate scenarios for 2050 - chosen by the World Bank and consistent with the scenarios used in the Economics of Adaptation to Climate Change (EACC) project- to illustrate the spread in climate predictions for the country representing the driest and wettest expectations from the available set of all Global Circulation Models and SRES emissions scenarios:

No.	Scenario name	GCM Climate Model Applied	IPPC Emission scenario
1	"Global Wet"	NCAR-CCSM	SRES A2
2	"Global Dry"	CSIRO-MK3.0	SRES A2
3	"Mozambique Wet"	IPSL,	SRES B1
4	"Mozambique Dry"	UKMO*	SRES A2

Note: * This scenario does not have data for 2046 - 2065 nor temperature data, so for it can not be used for most of the analyses

The "Global Dry" and the "Mozambique Wet" scenarios result in higher temperatures than today and the "Global Wet" scenarios in lower temperatures. The "Mozambique Wet" scenario results in less annual precipitation. All scenarios result in the same or slightly higher intensity of precipitation than today.

The main findings from the specific climate scenarios can be summarized as follows:

- The mean temperature increase will range from -2 ^{O}C to 2 ^{O}C and the number of annual days with heat waves will increase with 0 to 1 days/year. The most dramatic impact could be higher asphalt temperature, dust, increased evaporation
- The annual rainfall increase will range from - 7% till 9%. The impacts of more rain is increased runoff, increased river flow, soil moisture, groundwater
- Heavy rain will be more frequent and the design storms for roads etc. will increase with an estimated 19-35% in intensity for a 10-year storm and with 19% - 37% for a 100-year storm. The impact is increased frequency of flash floods, erosion, sediment and landslide and a large need for more.

The results of the climate models clearly demonstrate that future rain patterns are complicated to predict and much still has to be learned to understand what will happen with a higher degree of certainty which can lead to more substantiated risk assessments when designing infrastructure.

The 4 climate scenarios do not offer predictions for rising sea level, storm surge and cyclones. Recent studies in Mozambique operates with:

- sea level rise from 20 - 100 cm by 2060
- increase in extreme sea levels at 10 year return periods of 20 - 100 cm by 2060 in Maputo and similar increases in Beira and Nacala

- less frequent tropical cyclones in the Mozambique Channel but with more intensive precipitation when they occur

The study has produced a first estimate of new design curves for roads which are used to estimate the need for enlargement of drainage facilities for roads and for estimates of the increase in precipitation and frequency of critical storms that exceed the old design level for the existing structures. From a design point of view the two "wet" scenarios results in almost identical requirements to changes in design parameters.

1.2.2 The current road network

Mozambique has an estimated classified road network of approximately 30,000 km of which around 6,300 km are paved. In 2006 it was assessed that half of the unpaved roads were in poor condition and that only 57% of them were fully transitable by normal traffic, but the conditions in the dry periods are fairly good. For paved roads only 11% were in poor condition. In addition the road network comprises approximately 2,000 bridges, but an accurate number can not be given as an up to date bridge management system is not available. Mozambique has a number of large rivers and therefore rather large bridges and their conditions has to be monitored specifically. The number of culverts is not recorded.

Mozambique's transport sector is governed by the Road Sector Strategy 2007-2011, the associated PRISE Implementation Plan and the Roads and Bridge Management and Maintenance Program. The strategy provides an excellent basis for future road maintenance including approaches to cope with climate change.

ANE (Mozambique Road Authority) uses the SATCC 2001 draft standards for design and has own standards for hydrology and hydraulic standards. The standards are only guidelines and are not mandatory, so design consultants can propose and use other standards - which they do.

The type of road in Mozambique varies extremely from a limited number of 4 lane high speed highways to low volume community roads. The success of these roads relies on similar factors:

- choice of location (alignment), design and construction;
- climate and topography the road passes through;
- traffic loading; and
- maintenance.

Many of the current problems that are seen in Mozambique are not climate-related, but are amplified by the climate. For example, overloading of heavy trucks will have damaging effects on a road regardless of climate; the damage is amplified when the soils and materials beneath are overly saturated. The same can be said about routine maintenance. Maintenance is a requirement on all roads, and without it roads will deteriorate quicker than their design life.

1.2.3 Climate change impacts on roads

The largest problems facing the current Mozambican road network seem to be overloading and missing maintenance and repair. The most influential climate impacts on roads will in the next 40 years come from changes in rain patterns and to a smaller extent increased temperatures.

Change in precipitation volumes and patterns - structures
One of the main threats to bridges from an increase in precipitation is the increase in peak flow and floods and associated scour and bank erosion. The preferred method to deal with scour would be to account for it correctly in the design phase and implement sufficient countermeasures to handle the expected scour.

The success of a bridge is dependent on its hydraulic capacity, the stability of the channel and its interaction with the bridge substructure. The assessment of current bridge designs indicate that they are built with a surplus of hydraulic capacity - also in view of the climate changes predicted in the climate scenarios. The lack of a reliable bridge inventory in the country is a challenge when assessing conditions of bridges and future needs.

There is already today a need to invest more into scour protection during initial construction. Maintenance needs to be increased in not only the protection of the substructure from scour, but also ensuring the hydraulic capacity of the channel by removal of sediment and debris. If maintenance cannot be assured, then it is recommended to invest in more permanent bank and scour protection, or design bridges with larger capacity to handle the sedimentation.

Reinforced concrete pipe culverts are not designed to have capacity for large scale floods, greater than 25-50 year return interval, but they should be designed so that the road they are covered by is not washed out during large floods. Culvert sizes should be increased in areas where the potential for damage is greatest, such as in areas with large fills. Maintenance needs to be increased for all culverts in high risk areas.

Change in precipitation volumes and patterns - roads
The problems seen today in the primary and secondary roads are the result of a combination of different factors such as lack of maintenance, poor drainage, and design that cannot accommodate the overloaded traffic. More effort needs to be spent on investigation on the sub-grade materials for community roads, as well as drainage of the road section. Maintenance becomes even more critical with increased or more intensive rain.

The stability of slopes will be adversely affected by an increase in precipitation. The investment spent on preventing landslides is normally only cost beneficial if it is a vital link. A review of existing material indicates that slope stability is not a very big challenge in Mozambique. It is better to invest in slope protection measures and use best practices during construction for the lower class roads. Landslides are a natural occurrence and the road design needs to have the least amount of impact to the surrounding environment to lessen its chances of

failure. Road location becomes more important with increased flooding, and the suitability of building roads in river valleys needs to be investigated. Slope re-vegetation could be required on all impacted slopes.

Drainage systems should be upgraded in areas that have historically experienced flooding. Investigations should be done to find if it is cost beneficial to upgrade the drainage systems in these areas before a drainage failure occurs, or afterwards during repair or reconstruction.

Sea level rise, storm surge and cyclones
The main effects from these types of event is that infrastructure in low coastal areas is in larger risk of being damaged, especially if measures to protect the coast are not taken, but the situation for the next half century is not predicted to be much different from today and the impacts are of a very local nature. Only a small part of the main road infrastructure is located in areas threatened by rising sea level. In such areas, primarily in and around Maputo, Beira and Nacala, the measures to be taken against climate change are to protect the city infrastructure in general. Roads are only a minor part of the city infrastructure and can not be considered or protected in isolation and the costs of climate change measures such as constructing seawalls for the cities can not meaningfully be considered road costs.

Temperature increases
The main effects from changes in temperatures will be for bridges and bituminous pavements.

Bridges are already designed with temperature gradients in mind. The change in temperature in Mozambique over the next 50 years is not expected to require a change in the methodology of designing bridges, but the design temperature should be higher The increase in maintenance required will not be substantially higher than what it should be already.

Temperature has an affect on the stiffness of asphalt. A poor asphalt mix will have a greater chance of cracking and other deformations if the temperature gradients are not accounted for correctly in the design. The expected life of a newly constructed road is estimated to be about 10 to 15 years for the upper most asphalt layers. Adjustments in pavement design with respect to binder selection can be made at regular service / reconstruction intervals. Designing for different temperature gradients in the future is not considered to have an effect on the cost of resurfacing when this is done within the normal time cycle as asphalt cost is almost the same for the different types of penetration grade asphalt.

Maintenance needs
Maintenance to the drainage network becomes all the more important with increases in number of high intensity storms. Routine maintenance, before, during and after the rainy season and after the more frequent very heavy events will help to alleviate total failures requiring replacement. Investments in drainage systems will be quickly lost if they are left to deteriorate or fill up with

sediment. Effective cleaning of culverts and drainage systems after storm surges or cyclones is essential to protect the infrastructure.

The maintenance need will increase according to the more frequent heavy rainfall causing larger and more frequent flow in the system and more sediment from erosion of the surrounding areas or the roadside drain it self. It should be investigated if it is feasibly to change and/or enlarge the drainage system in specific areas prone to erosion and flooding to reduce the risk of total failure and consequential damage and for reduction of the climate change related need for increased maintenance.

1.2.4 Design guidelines

Existing guidelines generally
ANE uses the SATCC design manuals, which are created for a rather diverse region, as general guidelines supplemented with own guidelines on hydraulic issues. The current Road Sector Strategy takes the view that the designers shall be guided towards evaluation of various alternatives and consider their pros and cons in the Mozambique context including availability of materials and skills before a decision on a specific design is taken. Therefore mandatory design standards are not used.

The engineering solutions needed to make a climate resilient road can be found spread out in the used guidelines. Hydraulic problems such as scour and sedimentation are addressed in the Bridge and Drainage manuals. Soils and subgrade problems are addressed in the Pavement Design manuals. Surface drainage and slope stability issues are also part of the manuals.

Specific recommendations to the manuals
It is suggested to organize the manuals so that the climate-related issues and solutions are presented clearly in a separate chapter. A chapter could be added to the manuals focusing on environmental conditions; similar to what Tanzania Ministry of Works has done with their Pavement and Materials Design Manual. Having a chapter dedicated to the climate and environmental impacts on the road would make it easier for the designer to choose quickly and efficiently. This should also include a dedicated focus on thoroughly evaluation of locations for new roads and urban development, especially in coastal areas.

The recommendations listed in this report cover review of design manuals for drainage and river and stream crossings with a view to the design curves developed from the climate scenarios. In addition, it is recommended to adjust requirements for testing of subgrade materials. Finally, the manuals for low cost engineering solutions are recommended to be updated, which will be fully in line with the current Road Sector Strategy.

1.3 Engineering costs of climate change

It is not expected that climate changes in the near future will require large changes to the methodology or economics of classified roads in Mozambique

For new construction, rehabilitation or upgrading the major cost items for roads are shown below together with (for illustrative purposes) the distribution of costs for an asphalt paved Double Bituminous Surface Treatment standard road with an average cost of around 333,600 USD per km (2007 costs based on specific design study) including structures. In addition an estimate of typical additional construction costs has been made if a new road was to be constructed so it is fully adapted to the predicted climate changes in the applied scenarios in year 2050 compared to the current design standards.

Table 1-1 Road construction cost distribution today and the estimated increase in costs if the roads should be designed to the predicted climate in 2050

Cost item	Percentage of total cost today	Percentage cost increase "Global Dry"	Percentage cost increase "Mozambique Wet"
Preliminary and general	28.7%	0%	0%
Earthworks	10.9%	5-10%	10-20%
Subbase, road base and gravel wearing course & bituminous surfacing	36.1%	5-15%	10-25%
Drainage	13.1%	19%	36%
Road furniture	0.6%	0 %	0 %
Miscellaneous	0.5%	0%	0%
Structures	7.2%	19%	37%
Dayworks	2.9%	2%	5%
Total	***100.0%***	***6.3% -10.4%***	***12.2% -18.7%***

The largest single cost elements of a typical km asphalt road today are by far the earth works and the road base and surfacing. The main cost items which are likely to increase in order to make a typical Mozambican road adapted to predicted climate change are earth works and the road base and surfacing, but in the end the actual costs will depend heavily on the specific local conditions. A best estimate is that costs in average will increase between 6% and 19% for a new or newly reconstructed road due to climate change for the same risk profile between now and 2050

High standard gravel roads are expected to require cost increases in the same areas as paved roads, plus the additional cost of sealing in areas with high gradients and high rainfall. The cost of a new climate resilient gravel road is therefore roughly expected to increase between 10% and 25%.

The costs of making urban roads can not be judged independently from the general situation for cities and towns where the drainage and sewerage systems are the key determinants for the implications for roads.

1.4 Economic costs and benefits of adaption

The frequency of disruptions of roads must be expected to increase if adaption measures to climate change are not taken. Although observed information on typical frequencies of disruption and number of people affected can not be obtained, an attempt has been made to assess potential costs using standardized but realistic assumptions about frequency of disruption, number of people affected, waiting times and likely detours.

The costs of climate changes in the period 2010 - 2050 are roughly estimated at around 0.5 - 0.6 bill. USD in 2009 net present value - of which increased maintenance costs are far more important than costs of changed designs. Other conclusions are:

- The cost to road users due to climate-related incidents may be substantial even with today's climate and are expected to increase with as much as 20% in year 2050

- Adapting to climate changes by eliminating the increase in road user costs completely (full adaptation) is likely to be a feasible strategy for some new road infrastructure - especially culverts. For structures the specific conditions decide if it is economic feasible to adapt fully to the predicted climate change. The situation for drainage ditches has to be assessed together with the expected maintenance strategy

- For the existing network, an adaptation strategy where adaptation takes place as the life time of the infrastructure is exceeded or the infrastructure is destroyed by climate (or other) related incidents is expected to be preferable.

- For the existing road network the climate changes will incur costs on both road users and the road agency. The major cost item is expected to be increased maintenance in order to keep the roads up to design standards.

1.5 The strategy forward for climate change adaption in the road sector

A future strategy needs to be flexible, adaptive and robust - and acknowledge that the current scenarios and climate models show a large variability in predicted rainfall patterns, which are the most important design criteria for roads and structures.

Taking the mean of the climate scenarios/climate models used in this study as the most likely future development, the long term increase in engineering costs due to climate change may be important but not excessive if dealt with proactively in the regular planning and design processes.

A climate resilient road in the future in Mozambique will be very similar to a climate resilient road right now. Mozambique has the principle knowledge to design and keep their roads up to standard. A key element to ensuring climate

resilience after the initial construction is sufficient maintenance. The current Road Sector Strategy is an excellent tool for ensuring high quality and cost effective road maintenance in the future given the situation in Mozambique. In addition, it provides many good approaches to ensure adaptation to climate change.

In the short run (next 5 years) the following initiatives are recommended:

- Research is needed in the accuracy of the design parameters in predicting sedimentation and runoff
- Based on this research the design storm parameters for new roads and structures are recommended to be adjusted to reflect significant climate changes - after due consideration to an acceptable future safety level.
- The design manuals used today are recommended to be revised so that the climate-related issues and solutions are presented clearly e.g. in an additional chapter. Having a chapter dedicated to the climate and environmental impacts on the road would make it easier for the designer to choose quickly and efficiently and to select locations/alignments in climate safe areas.
- As the maintenance need will increase according to the expected more frequent heavy rainfall It is recommended to investigate if it is feasibly to change and/or enlarge the drainage system in specific areas prone to erosion and flooding to reduce the risk of total failure and consequential damage and for reduction of the climate change related need for increased maintenance.

In the long run the following initiatives are recommended:

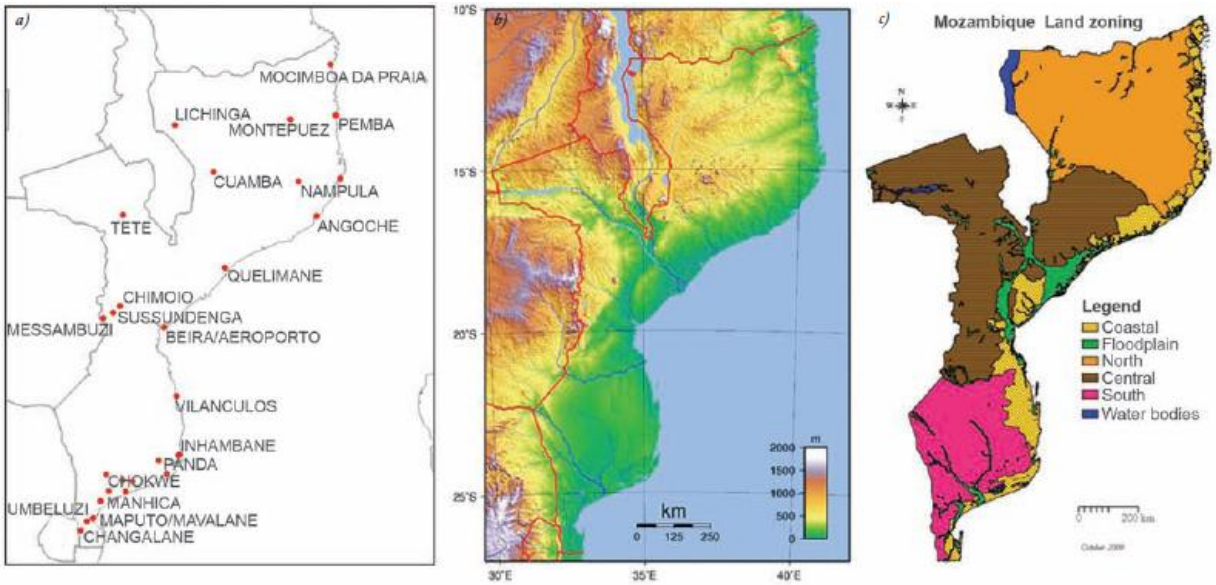
- Establishment of a process to review climate-related parts of the design guidelines at regular intervals (5 or 10 years) to take account of most updated information on observed climate change impacts and the need to balance climate risks and economic feasibility
- Ensure that the excellent maintenance strategy in the current Road Sector Plan is implemented
- Development of reliable and accurate hydrology models as it is a common problem that this is lacking

2 Climate risk scenarios for Mozambique

2.1 Climate characteristics for Mozambique

The overall characteristics for Mozambique are illustrated below.

Figure 2-1 Weather stations, topography and land zoning for Mozambique



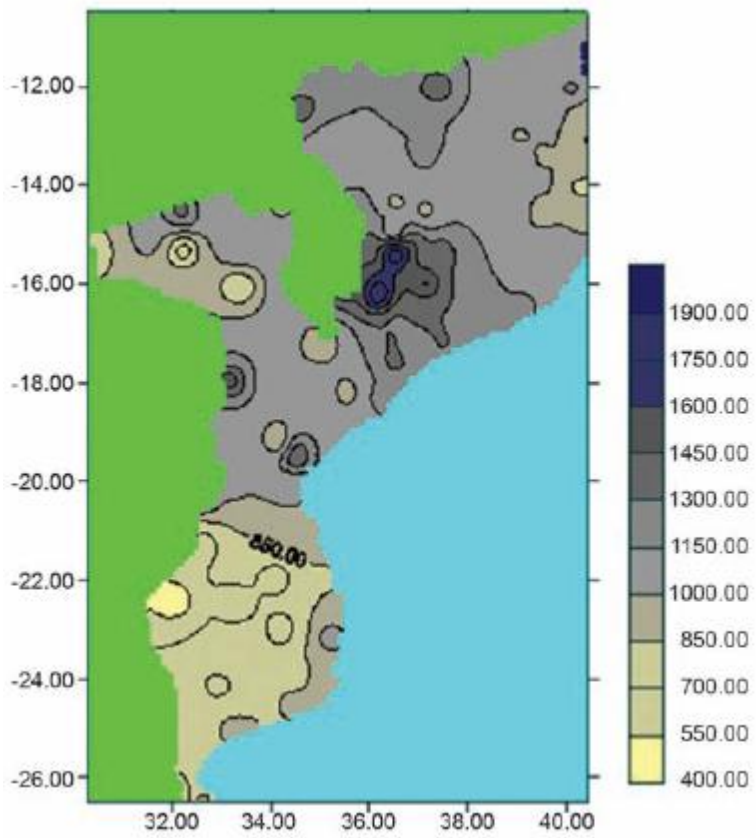
Mozambique[1] is located on the eastern coast of southern Africa at 11-26˚ south of the equator, and has a tropical to sub-tropical climate which is moderated by the influence of mountainous topography in the north-west of the country. Seasonal variations in temperature are around 5°C between the coolest months (June, July and August) and the warmest months (December, January and February). Geographically, temperatures are warmer near to the coast, and in the southern, lowland regions compared with the inland regions of higher elevation. Average temperatures in these lowland parts of the country are around 25-27°C in the summer and 20-25° C in winter. The inland and higher altitude northern regions of Mozambique experience cooler average temperatures of 20-25° C in the summer, and 15-20° C in winter.

[1] The description of the climate in Mozambique builds on the UNDP Climate Change Country Profile for Mozambique.

The wet season lasts from November to April, coinciding with the warmer months of the year. The Inter-tropical Convergence Zone (ITCZ) is positioned over the north of the country at this time of year, bringing 150-300mm of rainfall per month whilst the south receives 50-150mm per month. Topographical influences, however, cause local variations to this north-south rainfall gradient with the highest altitude regions receiving the highest rainfalls. Mozambique's coastal location means that it lies in the path of highly destructive hurricanes and cyclones that occur during the wet season. The heavy rainfall associated with these events contributes a significant proportion of wet season rainfall over a period of a few days.

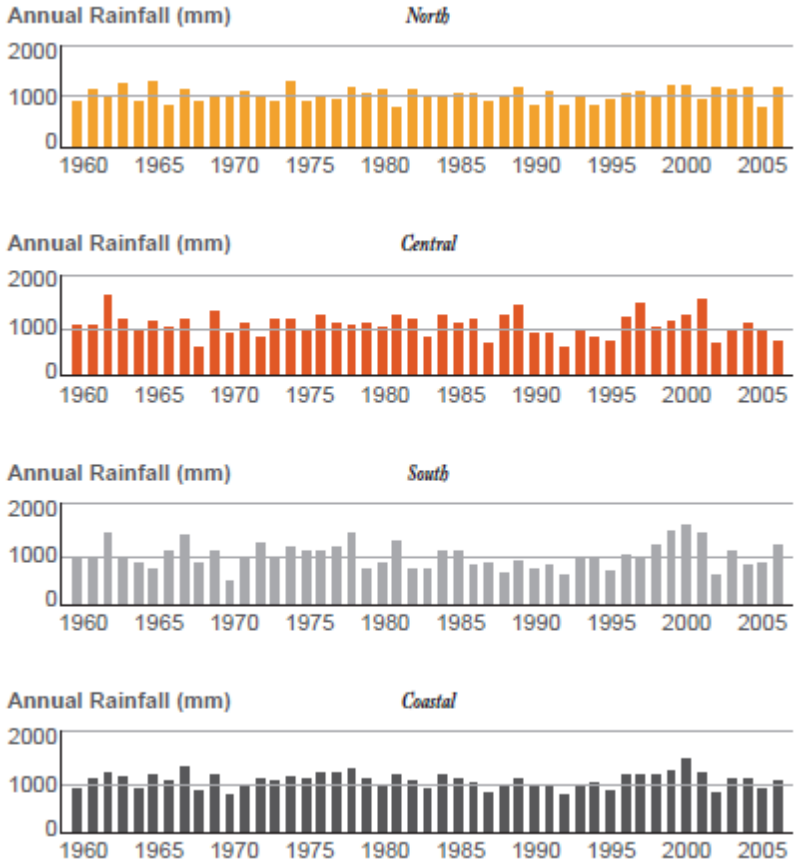
Inter-annual variability in the wet-season rainfall in Mozambique is also strongly influenced by Indian Ocean Sea Surface Temperatures, which can vary from one year to another due to variations in patterns of atmospheric and oceanic circulation. The most well documented cause of this variability is the El Niño Southern Oscillation (ENSO) which causes warmer and drier than average conditions in the wet season of Eastern Southern Africa in its warm phase (El Niño) and relatively cold and wet conditions in its cold phase (La Niña)."

Figure 2-2 Mean annual precipitation in mm



Source: INGC

Figure 2-3 Mean seasonal historical precipitation for different areas in Mozambique

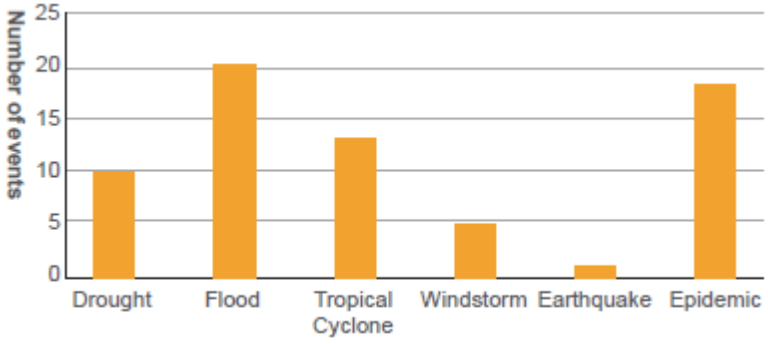


Source: INGC

2.1.1 Experienced droughts, floods, cyclones etc in Mozambique

The main disasters events affecting Mozambique are weather related phenomena's, associated with an outbreak of epidemics. Country wide the most common events affecting Mozambique are floods, epidemics and tropical cyclones. Figure 2-4 shows that floods count for about 30%, epidemics for 27% and 19% for tropical cyclones of natural disasters.

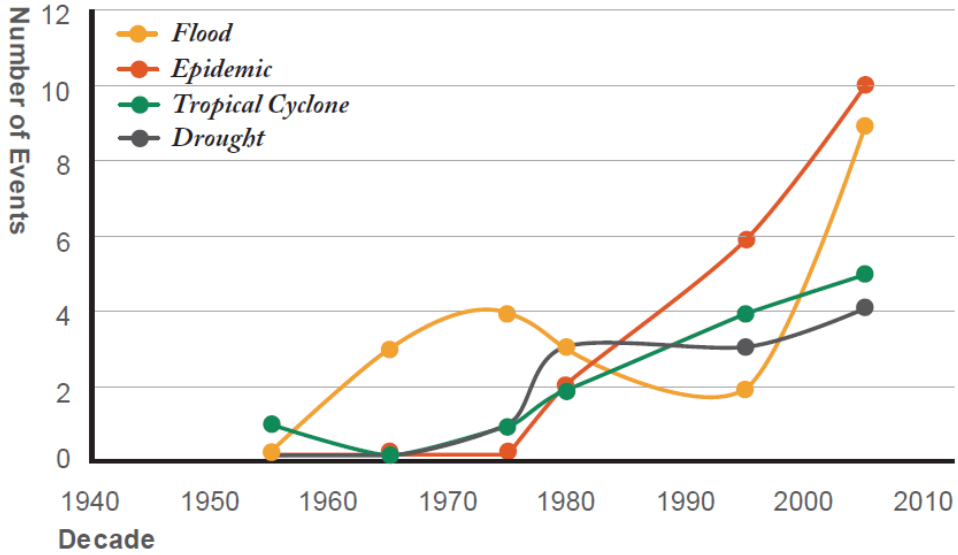
Figure 2-4 Frequency distribution of total number of natural disasters occurred from 1956 to 2008 (67 events), Mozambique



Source: INGC

Although data consistency is a concern there seem to have been as a significant increase in the number of disasters since the 80's, with the growing rate of floods and epidemics dominating the last two decades of 20th and early 21st centuries.

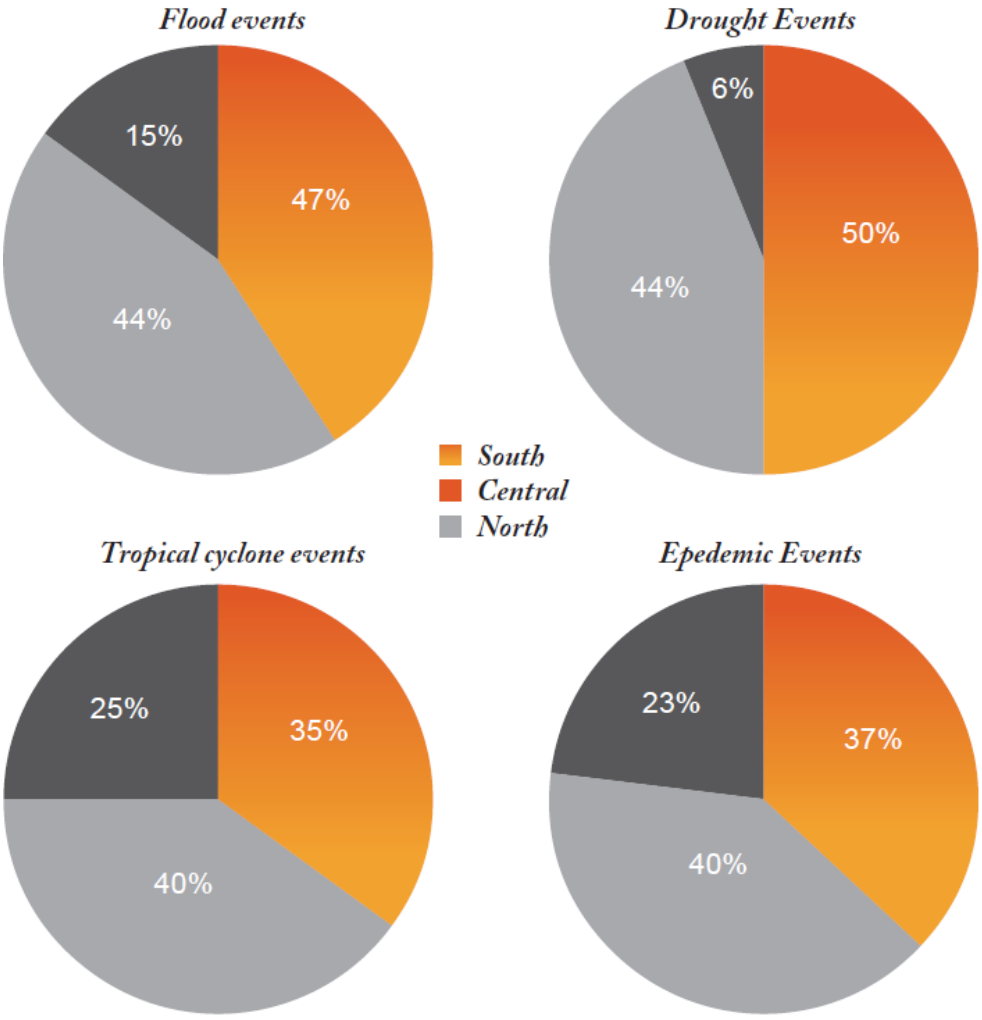
Figure 2-5 Total number of the four common events occurred in the different regions; Mozambique.



Source: INGC

For a better understanding of the level of vulnerability by region (South, Central and North) the total number of events by disaster type is described for different regions (Figure 2-6). It is observed that the Centre is the most disaster prone followed by the South, while the North is likely to have fewer disasters.

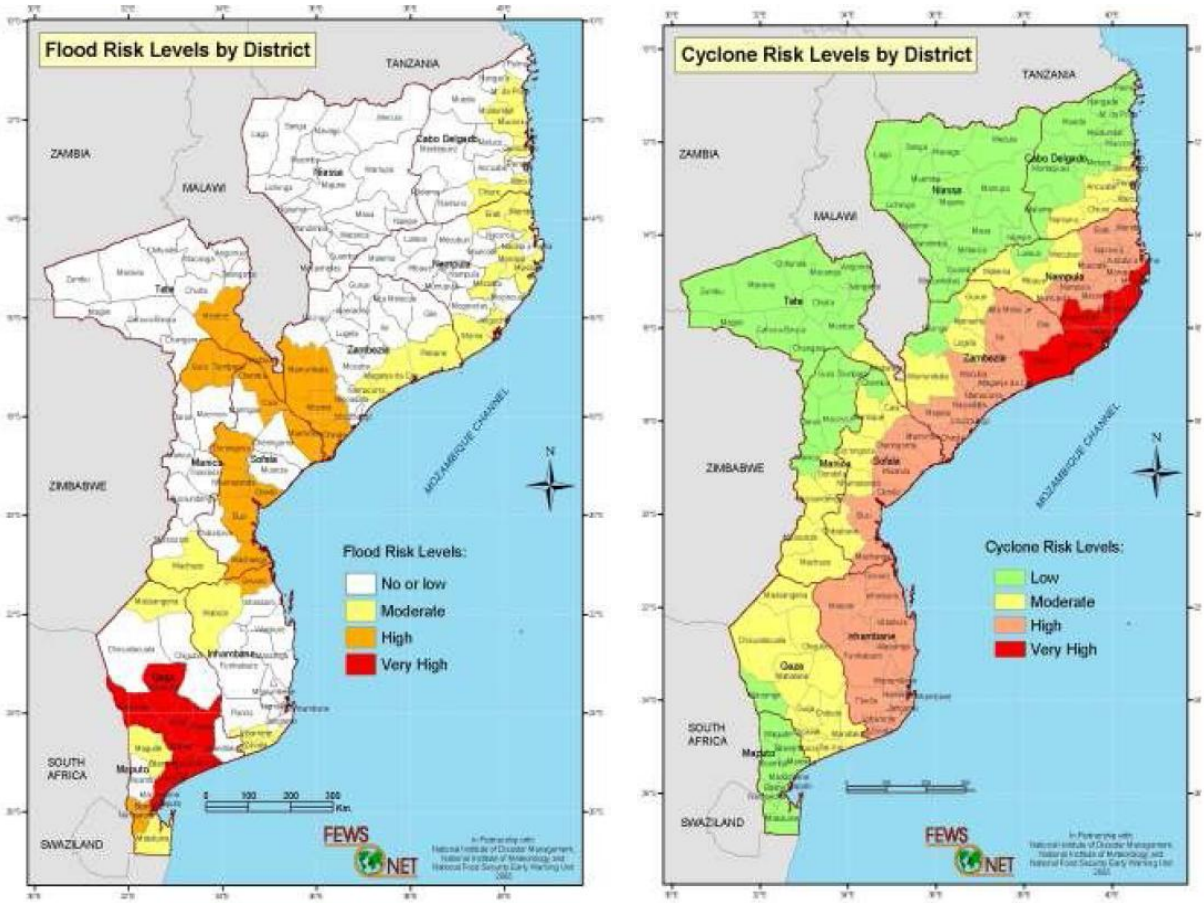
Figure 2-6 Historical trend of natural disasters in Mozambique (1956 -2008)



Source: INGC

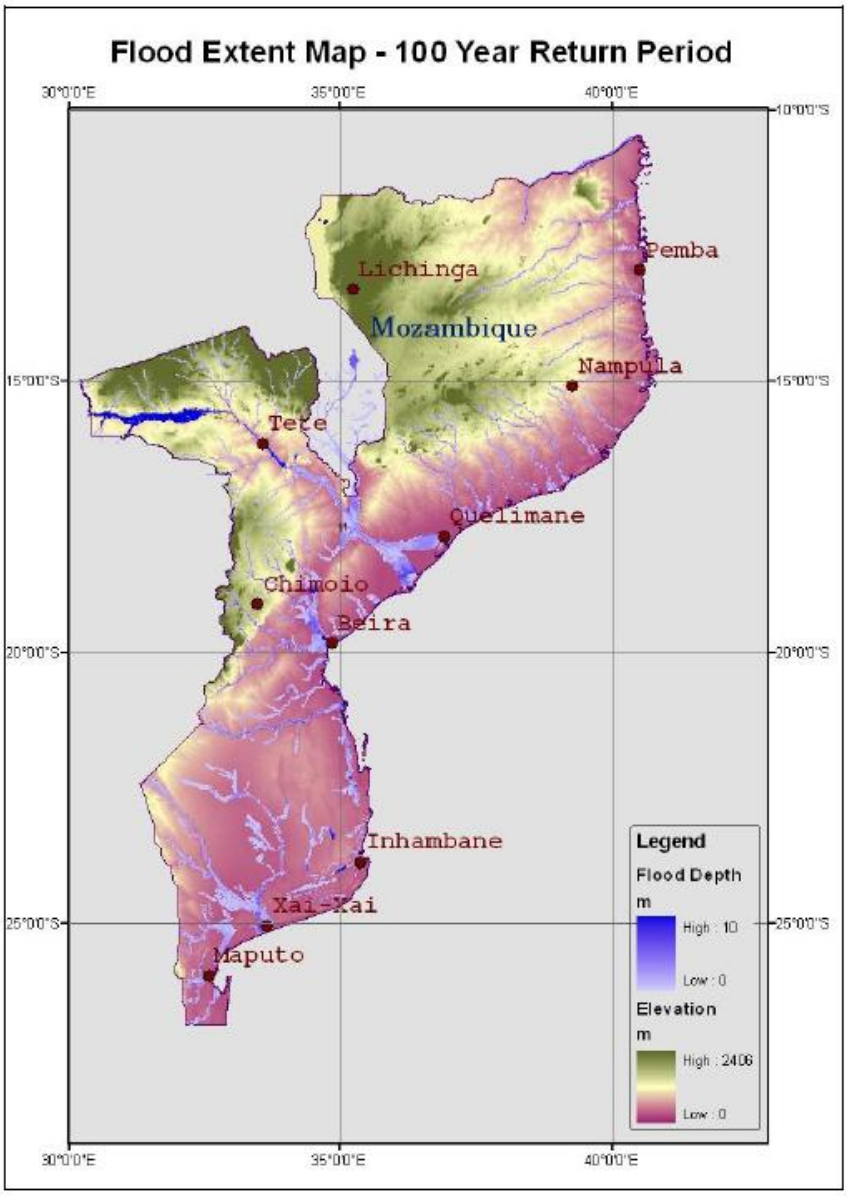
Floods are much common in the Centre and South; tropical cyclones affect more of the Centre and South. Droughts occur more frequently in South and Centre of the country. Epidemics are likely to affect the Centre and the South. However, the North is less prone compared to other regions it is noted that tropical cyclones and epidemics are matter of concern in this region.

Figure 2-7 Flood Prone Areas and Cyclone Risk Levels in Mozambique



Source: Ref. FEWS-NET.

Figure 2-8 Flood extent for a 100 year return period



Source: Ref. World Bank, Mozambique: Economic Vulnerability and Disaster Risk Assessment, Sept 2009. RMSI.

2.1.2 Trends in climate change so far

The trend in climate change so far shows:

- slightly increased annual mean temperature (about 0.13°C every ten years),
- significant increased in number of hot days and nights (7-8% every ten years)

- decrease in mean annual rainfall per month (3% every ten years) but an
- increase in precipitation falling in heavy events (2.6% every ten years)
- increased frequency of tropical cyclones

In the UNDP Climate Change Country Profile the recent climate trends (1960-2006) are described briefly as:

Temperature:

- **Mean annual temperature** has increased by 0.6°C between 1960 and 2006, an average rate of 0.13°C per decade. This increase in temperature has been observed in the seasons DJF, MAM, and JJA only, at a rate of 0.15-0.16°C per decade, but no discernible warming has been observed in the season SON.
- Daily temperature observations show significantly increasing trends in the **frequency of 'hot' days[1] and nights** in all seasons.
  - The average **number of 'hot' days per year** in Mozambique has increased by 25 (an additional 6.8% of days) between 1960 and 2003. The rate of increase is seen most strongly in MAM when the average number of hot MAM days has increased by 3.2 days per month (an additional 10.2% of MAM days) over this period.
  - The average n**umber of 'hot' nights** per year increased by 31 (an additional 8.4% of nights) between 1960 and 2003. The rate of increase is seen most strongly in DJF when the average number of hot DJF nights has increased by 3.6 days per month (an additional 11.6% of DJF nights) over this period.
- The **frequency of cold days[3] and nights** have decreased significantly since 1960 in all seasons except SON.
  - The average number of 'cold 'days per year has decreased by 14 (3.9% of days) between 1960 and 2003. This rate of decrease is most rapid in MAM when the average number of cold MAM days has decreased by 2.1 days per month (6.7% of MAM days) over this period.
  - The average number of 'cold' nights per year has decreased by 27 (7.4% of days). This rate of decrease is most rapid in MAM when the average number of cold MAM nights has decreased by 2.9 nights per month (9.5% of MAM nights) over this period.

Precipitation:

- Mean annual rainfall over Mozambique has decreased at an average rate of 2.5 mm per month (3.1%) per decade between 1960 and 2006. This annual decrease is largely due to decreases in DJF rainfall, which has decreased by 6.3mm per month (3.4%) per decade.
- Daily precipitation observations indicate that despite observed decreases in total rainfall, the proportion of rainfall falling in heavy events has in-

creased at an average rate of 2.6% and 5- day annual rainfall maxima have increased by 8.4 mm per decade, with largest increases in the wet season, DJF.

2.1.3 Climate zones

Mozambique can be divided into five climate zones:

The lowland Plains and Coastal: occupies the Indian Ocean coast of Mozambique and the transitional zones between the planalto and coastal areas with less than 200m above sea level. Bimodal rainfall is observed in most years, drought occurrence is reported in some years.

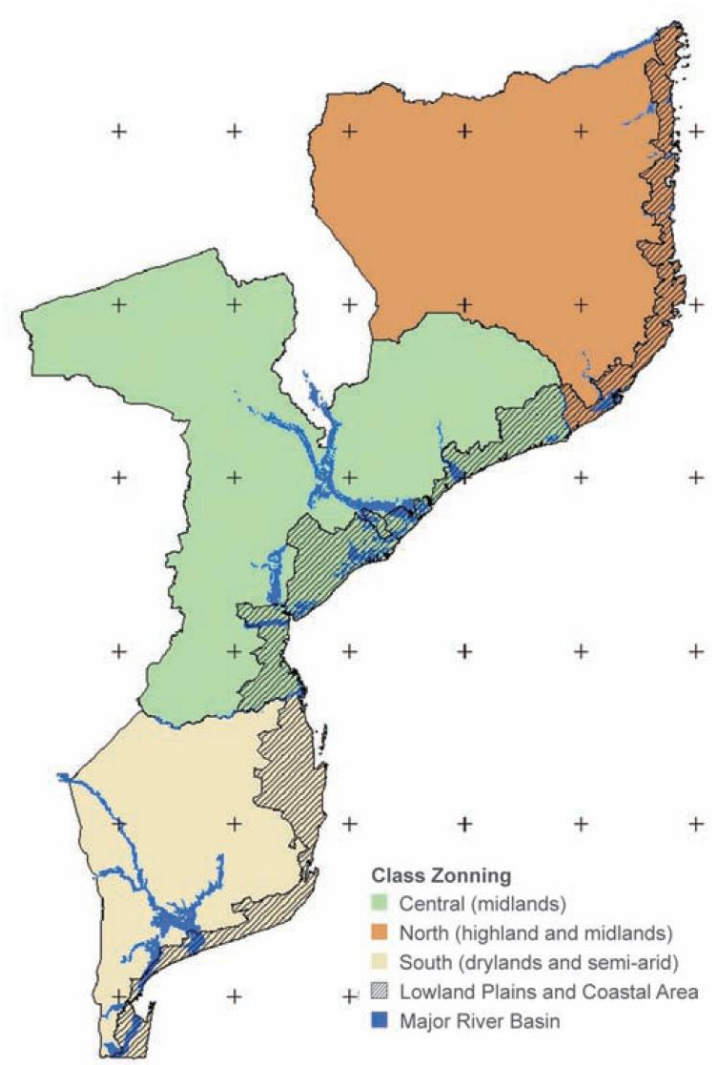
Major River Basin: occupies the lower elevation of the river valleys of major rivers in the country including the Zambezi-Chire river basin, Lugenda river basin, Lurio river basin, Buzi-Save river basins, and the Limpopo river basin. This is exposed to risks of periodic flooding with the possibility of crop and property damages.

The North (highland and midlands): is characterized by high altitude often more than 200m above sea level

The Central (midlands): is the medium altitude region of the central part of Mozambique, includes lowlands < 200m, mid altitude areas 200-500m, and sub and planaltic zones 500-1000m a.s.l. covering Manica and Sofala provinces. Rainfall ranges in general from 800-1200mm (wet semi-arid and sub-humid climates).

The South (drylands and semi-arid): is mainly located in the southern part of the country with rainfall less than 600 mm per year.

Figure 2-9 Zoning according to climate and characteristics for the topography in Mozambique



Source: INGC

2.2 Emission scenarios and climate models

2.2.1 SRES emissions scenario by IPCC

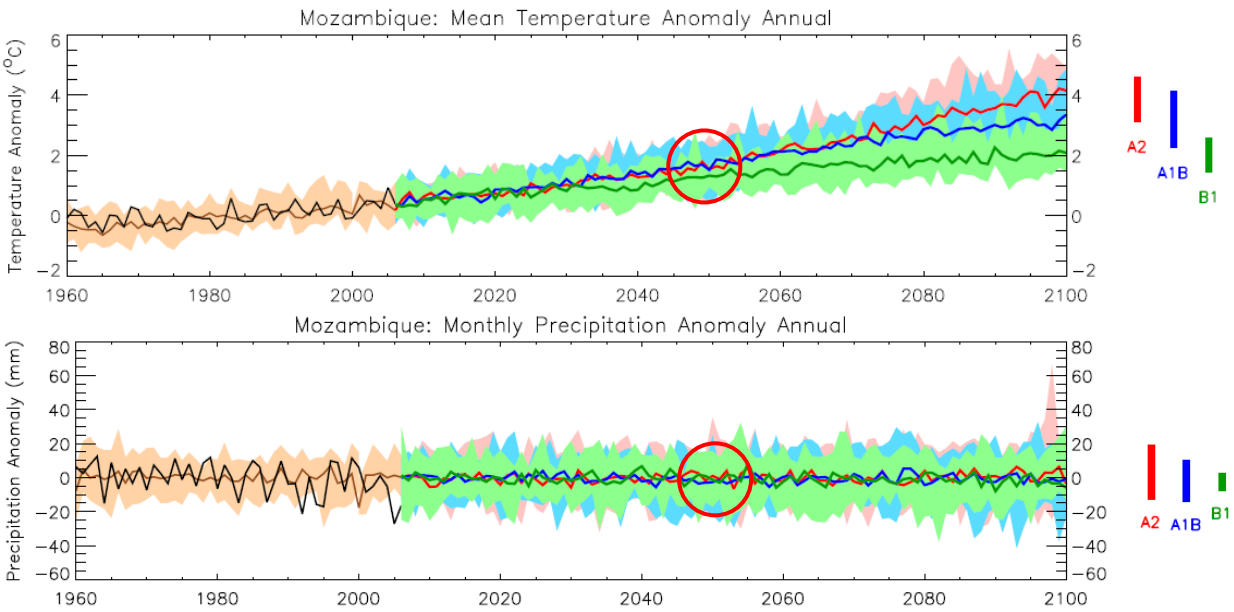
IPCC has given four main emission scenarios and more sub-scenarios in the IPCC Special Report on Emissions Scenarios, 2000, (SRES).

The A2 storyline and scenario family describes a very heterogeneous world. The underlying theme is self-reliance and preservation of local identities. Fertility patterns across regions converge very slowly, which results in continuously increasing global population. Economic development is primarily regionally oriented and per capita economic growth and technological changes are more fragmented and slower than in other storylines.

For Mozambique the long-term climate changes caused by SRES A2 scenario seems to be slightly larger than caused by SRES A1B scenario, which has been used for some studies in the region. The climate changes in the next 40 -50 years until 2050-60 seems to be of the same magnitude for SRES A2, A1B and B1 scenarios as presented in the figure below. The change in temperature is lowest in the "optimistic" SRES B1 scenario.

This study covers the period up to year 2040-2060. In this period the climate changes are limited and of the same magnitude for the individual SRES scenarios, while change in temperature seems to accelerate in the period from 2040 to 2100. The average monthly precipitation does not change during the period up to 2100 in any of the SRES.

Figure 2-10 Comparison of climate consequences in Mozambique caused by SRES A1B, SRES A2 scenario and SRES B1 scenario. (UNDP Climate Change Country Profile)



2.2.2 Climate models

IPCC used results from 22 climate models (GCM, General Circulation Model) for the fourth Assessment Report (AR4), published in 2007.

The grid size is around 200x200 km (2.5 x 2.5^{O}). These models show different results and have different focus. Therefore it is common to use all or some of the GCMs to find the average consequences, by given individual weight on the different results and parameters found in the chosen GCMs. It is not recommended to use only one GCM, but to use a weighted average.

In this study it is chosen to use the weighted climate change predictions found and reported by UNDP in the Climate Change Country Profile for Mozambique for the general description of the expected climate change in Mozambique.

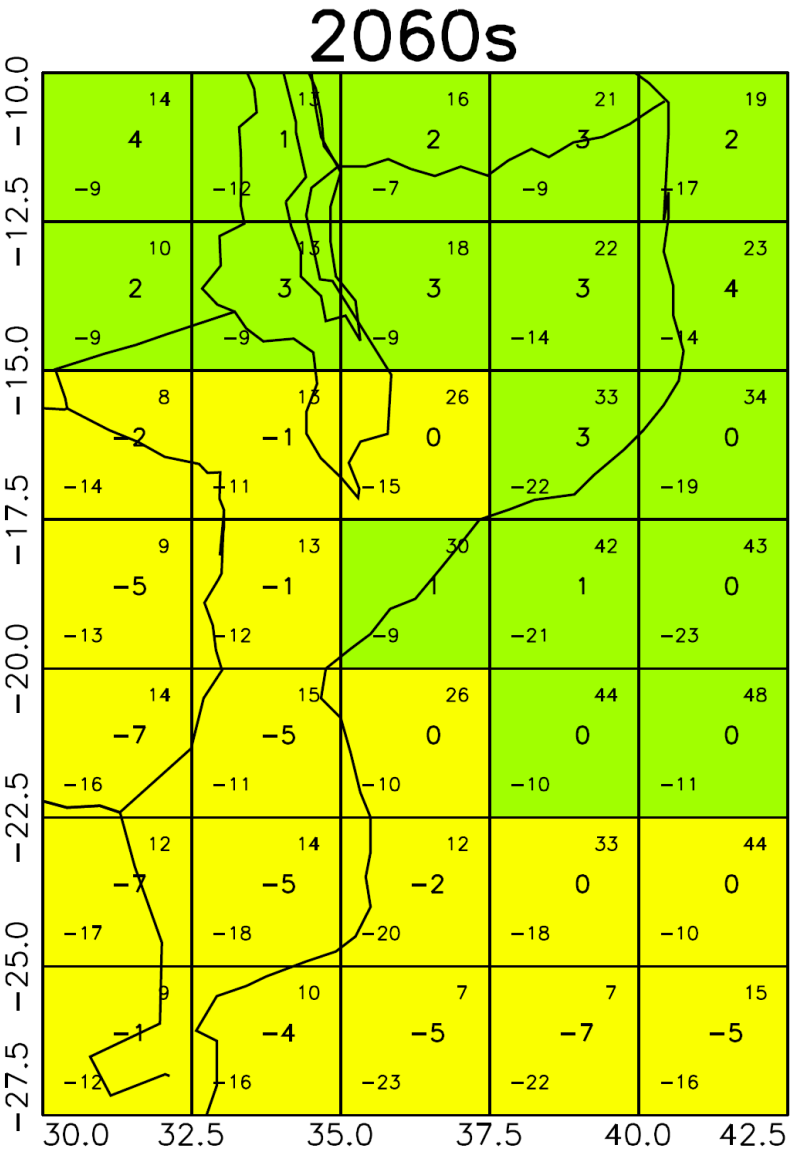
More detailed information on the estimated climate change consequences for the four selected climate scenarios for this study is given in Chapter 2.4.

The climate models used by UNDP are a sub-set of 15 from the 22-member ensemble used by IPCC in AR4. The models included are those which had the most complete availability across the different variables required. See the Documentation report for the UNDP Climate Change Country Profile for further details: http://country-profiles.geog.ox.ac.uk.

To illustrate the differences in results from different climate models and the uncertainties related to climate modeling there are given two examples related to Mozambique. These illustrations should argue for a relaxed relationship to the accuracy in the results and forecasts based on different SRES and GCM.

Example 1:

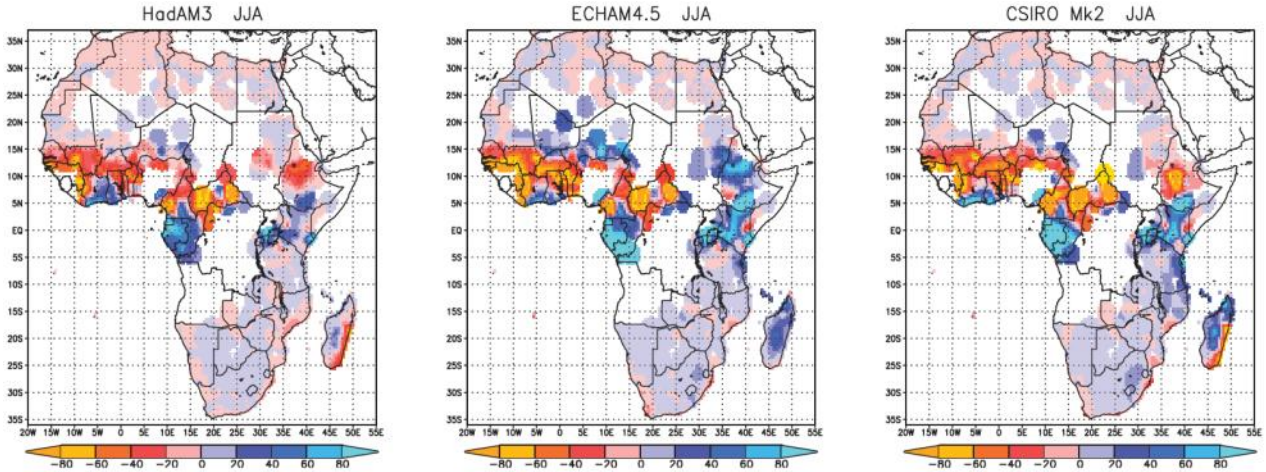
Figure 2-11 UNDP illustration of maximum, weighted average and minimum for %-change in monthly precipitation (annual average) in Mozambique from the period around 1985 until the period around 2060. Results from 15 GCM, as 10 years average for each model. SRES A2 scenario



The models show in all cells big variations and there is no significant trend in any of the cells. In all cells there are models indicating decrease and models indicating increase in monthly precipitation. On average there seems to be a minor decrease (-5%) in monthly precipitation in the south and a minor increase (+3%) in the north.

Example 2:

Figure 2-12 Predicted anomaly of mean monthly precipitation (mm) for the summer rainy season, JJA, using daily data downscaled from three GCMs. SRES A2 scenario and change from around 1990 to 2085. ref.: AR4, WG1 (chapter 11)



The predicted change in monthly precipitation up to 2070-2100 shown above illustrates that the differences are larger than seen for the shorter time horizon until 2050, which is used in this study. But the forecasts show very clearly that there is difference in the predicted monthly precipitation in the northern part of Mozambique between HadAM3 indicating -20 mm and CSIRO Mk2 indicating +40 mm.

2.3 Climate change characteristics

2.3.1 Climate change in general for Mozambique

Following general comments on climate change in Mozambique until 2060 are based on the information in the UNDP Climate Change Country Report for the SRES A2 scenario. For specific climate changes related to the four chosen climate scenarios for this study see Chapter 2.4.

Temperature

- The mean annual temperature is projected to increase by 1.0 to 2.8oC by the 2060s. Under a single emissions scenario, the projected changes from different models span a range of up to 1.8 ^{o}C.
- The projected rate of warming is more rapid in the interior regions of Mozambique than those areas closer to the coast.

- All projections indicate substantial increases in the frequency of days and nights that are considered 'hot' in current climate.
  - Annually, projections indicate that 'hot' days will occur on 17-35% of days by the 2060s.
  - Nights that are considered 'hot' for the annual climate of 1970-99 are projected to increase more quickly that hot days, occurring on 25-45% of nights by the 2060s.
- All projections indicate decreases in the frequency of days and nights that are considered 'cold' in current climate. These events are expected to become exceedingly rare, and do not occur at all under the highest emissions scenario (A2) by the 2090s.

Precipitation

- Projections of mean rainfall do not indicate substantial changes in annual rainfall. The range of projections for 2090s from different models is large and straddles both negative and positive changes (-15 to +20mm per month, or -15% to +34%). Seasonally, the projections show a more coherent picture, with the projections tending towards decreases in dry season rainfall (JJA and SON), offset partially by increases in wet season rainfall (DJF).
  - Projected changes in JJA rainfall range from -54 to +19% with ensemble median changes of -11 to -24% and in SON, -48 to +26% with ensemble median values -10 to -12%.
  - Projected changes in DJF rainfall range from -9 to +25% with ensemble median values of +1 to +8%. The increases in DJF rainfall are largest in the north of Mozambique.
- Overall, the models consistently project increases in the proportion of rainfall that falls in heavy events in the annual average under the higher emissions scenarios, of up to 15% by the 2090s (7% by the 2060s).The proportion of total rainfall that falls in heavy events is projected to increase in DJF in projections from all models and all scenarios, by up to 18%. Models are also broadly consistent in indicating increases in MAM, but decreases in JJA and SON.
- The models consistently project increases in 1- and 5-day rainfall maxima by the 2090s under the higher emissions scenarios of up to 20mm in 1-day events, and 34mm in 5-day events. These also generally increase in DJF and MAM, but decrease in JJA and SON.

Other Climate Change Information

- Tropical cyclones are poorly captured by GCMs and thus potential changes in intensity and tracks of tropical cyclones in the future are very uncertain. Whilst evidence indicates that tropical cyclones are likely to become, on the whole, more intense under a warmer climate as a result of higher sea-surface temperatures, there is great uncertainty in changes in frequency, and changes to storm tracks and their interactions with other features of climate variability (such as the El Niño Southern Oscillation) which introduces uncertainty at the regional scale (Christensen et al., 2007).
- The uncertainty in potential changes in tropical cyclones contributes to uncertainties in future wet-season rainfall. Potential increases in tropical cyclone activity, which may not be captured in the GCM projections, may add to the projected increases in wet-season rainfall in the region (Christensen et al., 2007).
- Model simulations show wide disagreements in projected changes in the amplitude of future El Niño events. Mozambique's climate can be strongly influenced by ENSO, thus contributing to uncertainty in climate projections for this region.
- Mozambique's coastal lowlands may be vulnerable to sea-level rise. Sea-level in this region is projected by climate models to rise by the following levels by the 2090s, relative to 1980- 1999 sea-level:

  - 0.13 to 0.43m under SRES B1
  - 0.16 to 0.53m under SRES A1B
  - 0.18 to 0.56m under SRES A2

- For further information on climate projections for Africa, see Christensen et al. (2007) IPCC Working Group I Report: 'The Physical Science Basis', Chapter 11 (Regional Climate projections): Section 11.2 (Africa).

The Intergovernmental Panel on Climate Change (IPCC) issued its 2007 report summary on 2 February. It says that sea level has risen 150 mm in the past century and will increase by 300 mm or more by 2100. It also reports that "it is likely that future tropical cyclones (typhoons and hurricanes) will become more intense, with larger peak wind speeds and heavier precipitation".

More detailed evaluations are done in the report "Assessment of the Impacts of Climate Changes to Sea Level Rise at Costa do Sol Beach in Maputo – Mozambique. July, 2008" by Jafar Ruby, Sinibaldo Canhanga, & Obadias Cossa, INAHINA - National Institute of Hydrography and Navigation, Maputo, Mozambique.

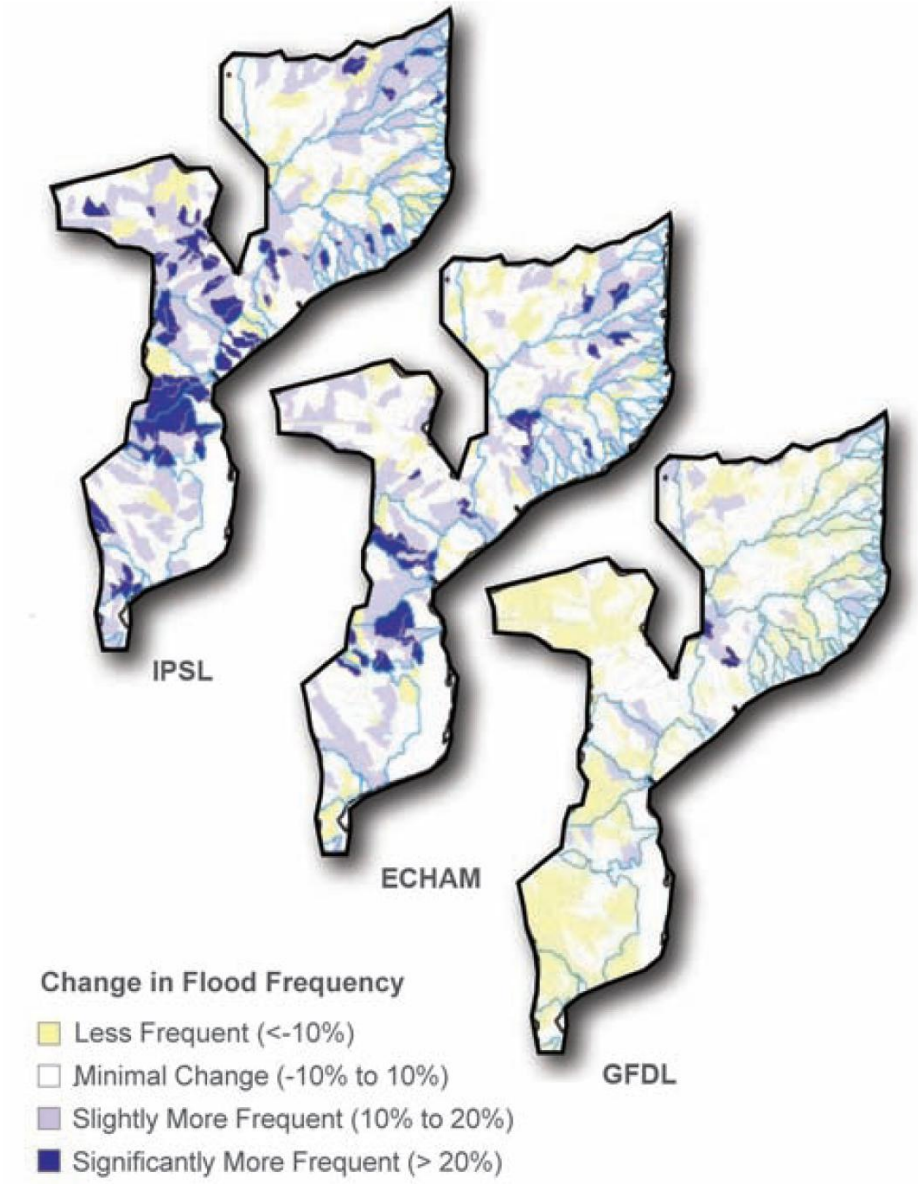
"*Calculations made by the study for the period 2000 - 2008, show that the average resection rate at Costa do Sol beach vary between 1.06 and 5.34 m/year, with an average net coastal resection of 42.75 m observed during the indicated period. These figures refer to the contribution of both, SLR and Anthropogenic effects.*

The computed sea level trends based on the observed data at Maputo and the neighboring stations (Richards Bay and Durban) were used to estimate the projection of three sea level rise scenarios: 0.2m, 0.5m, and 0.8m. The results show that the sea level will rise in Maputo region, 0.2 m by year 2034 (2008 used as reference); 0.5 m by 2073; and 0.8m by 2114. These projections are well in agreement with estimates using IPCC (Intergovernmental Panel on Climate Change) model, which is based on improved models (AOGCM, and SRES-IPCC, 2001).

Assuming that Local Authorities hypothetically adopt measures to adapt to climate changes based on "no action" (no special protection measures of the coastal areas, and costs are related to a planned retreat), the likely average response to global warming at Costa do Sol beach area would be as follows:
- SLR scenario of 0.2 m would cause a coastline recession of about 150 m,
- SLR scenario of 0.5 m would cause a coastline recession of about 380 m, and - SLR scenario of 0.8 m would cause a coastline recession of about 610 m."

The INGC report has considered scenarios of flood risk until 2060, using tree climate models (IPSL, ECHAM and EFDL) combined with a stream flow model. See Figure 2-13. The results depend very much on the specific basin It is concluded that the average river flow in the northern basin is largely unaffected. Increased river flow is expected in central Mozambique. Major reductions in the interior countries could significantly reduce flow in upper Zambezi. The rivers of southern Mozambique are wetter in two models and dryer in one model. However, the simulations do not show increased magnitude of flood peaks in any major basins. While increases are observed in isolated sub-basins, several major basins including Zambezi and Limpopo show reductions in maximum flood peaks. Significant increases in frequency of flooding occur in portions of the Buzi and Save basins and slight increase are observed in several small basins in the north. Flood frequency is slightly reduced or unchanged in major portions of the Zambezi and Limpopo.

Figure 2-13 Floods frequency maps. Calculated change in flood frequencies, for different river basins in Mozambique, based on GCMs and river flow models.



Source: INGC

2.3.2 Climate change with most influence on roads and transportation in Mozambique

The most relevant climate changes related to road and transportation in Ethiopia are:

- Temperature (and evaporation)
- Rain (intensity/frequency and volume)
- Sea level rise

There is a long coastline in Mozambique and this coastline is vulnerable for tropical cyclones and storm surge and to some extend erosion caused by the rising sea level. The increase in sea level is limited in the period up to 2050, and very little compared to the sea level during storm surge and heavy tropical cyclones. The change in frequency of tropical cyclones and storm surge is very uncertain and most of the infrastructure are prepared for these heavy events or located in safe distance from the costal zone that is most exposed by the heavy events. There fore the sea level rise is not the big concern in relation to roads. The higher general sea level will influence the slope available for the rivers and by that cause a higher water level in the lower part of the rivers especially during max flow.

Much of the coastline of Mozambique is soft, comprising of muddy river sediments and sand, backed by land with low relief and extensive low-lying coastal plains. This is particularly true of the central provinces, which are characterized by major rivers, such as the Zambezi, Save, Buzi and Pungoe, draining the continental interior, and prone to flooding on an annual basis. The coastline has a series of estuaries and deltas, which shift in response to the frequent floods and deposits of large amounts of sediment. Coastal erosion is a problem along the dynamic coastline. People, infrastructure and services in harbor cities such as Beira are in constant need of protection. The numbers of cyclones are too small to draw any significant conclusions regarding trends.

Most of the adaptation measures for reduction of the tread from cyclones and sea level rise will be done for protection of cities and settled areas and not for the roads only. Because of this and the uncertainties and the expected limited change in cyclone events and storm surge/ sea level rise it is chosen not to concentrate on adaptation measures for roads related to the limited change in cyclones and storm surge.

Also the change in temperature is very little and will have a very limited influence on the road structures and the need for operation and maintenance.

The general key figures for the relevant changes in Mozambique until 2050 can be summarized as (for the range in the specific four climate scenarios investigated in this study, see Chapter 2.4):

- The mean temperature increase will range from -1.6 ^{O}C to 2.1 ^{O}C and the number of annual days with heat waves will increase with 0 to 1 days/year. The impact is change in asphalt temperature increase in temperature will cause dust and increased evaporation
- The annual rainfall increase will range from -7% till 28%, most in south and less in north. The impacts is increased runoff, increased river flow, soil moisture, groundwater
- Days with heavy rain will be less frequent and but the design storms for roads etc. will increase with an estimated 19-35% in intensity for a 10-year storm and with 19-37% for a 100 year storm. The impacts are increased frequency of flash floods, erosion, sediment and landslide.

The predicted change in temperature in the 4 scenarios until 2050 is up till around $2^{O}C$ as annual average, which is less than predicted as an average of predictions in the UNDP Climate Change Country Report. An increased temperature influences the general temperature of the roads. Combined with the increase of "hot" days and nights the number of days with high and critical temperature for e.g. the asphalt will increase. Furthermore, higher temperatures will give more frequent occurrence of dust from gravel roads and increased evaporation of rain and moisture in the soil.

The predicted general change in seasonal precipitation as percentage and mm is highest in the season DJF (December - February) and especially in the northern part of the country.

The consequences for roads are based on an estimate of the resulting change in basis discharge in the rivers in the most wet and critical months and the increase in moisture of the soil at slopes and beneath the roads.

There are no forecasts available on very short extreme rainfall. There are estimates of the mean average maximum rainfall in 1-day rainfall. The existing design storms used in the drainage design manuals in nearby countries are based on historical 24-hour rainfalls. These data are used to find design curves for shorter and more intensive storms.

In this study the same calculation method as used in the drainage design manuals in nearby countries is used to establish new design curves for year 2050.

2.4 Climate change for scenarios in this study

The specific analyses in this study are based on 4 climate scenarios for Mozambique representing the span in expected future climate situations from dry to wet according to results from different combinations of emission scenarios (SRES) and GCM models. The scenarios represent a consistent basis between this study and the study “Economics of Adaptation to Climate Change (EACC)"

The climate scenarios chosen by the World Bank are:

	GCM-model	Emission scenario
“Global Wet”:	NCAR-CCSM,	SRES A2
“Global Dry”:	CSIRO-MK3.0	SRES A2
“Mozambique Wet”:	IPSL,	SRES B1
“Mozambique Dry”:	UKMO,	SRES A2

The “UKMO” GCM does not have data for 2046-2065, nor does it contain temperature data. Therefore statistics were not computed for temperature or for the 2046-2065 period for Mozambique.

For these four scenarios data and results have been processed by the University of Colorado[2] especially for this study with focus on precipitation, temperature and run-off for the present climate situation and the future situation in the period around 2050 and around 2100. An introduction to the data base and data processing can be found in the appendix.

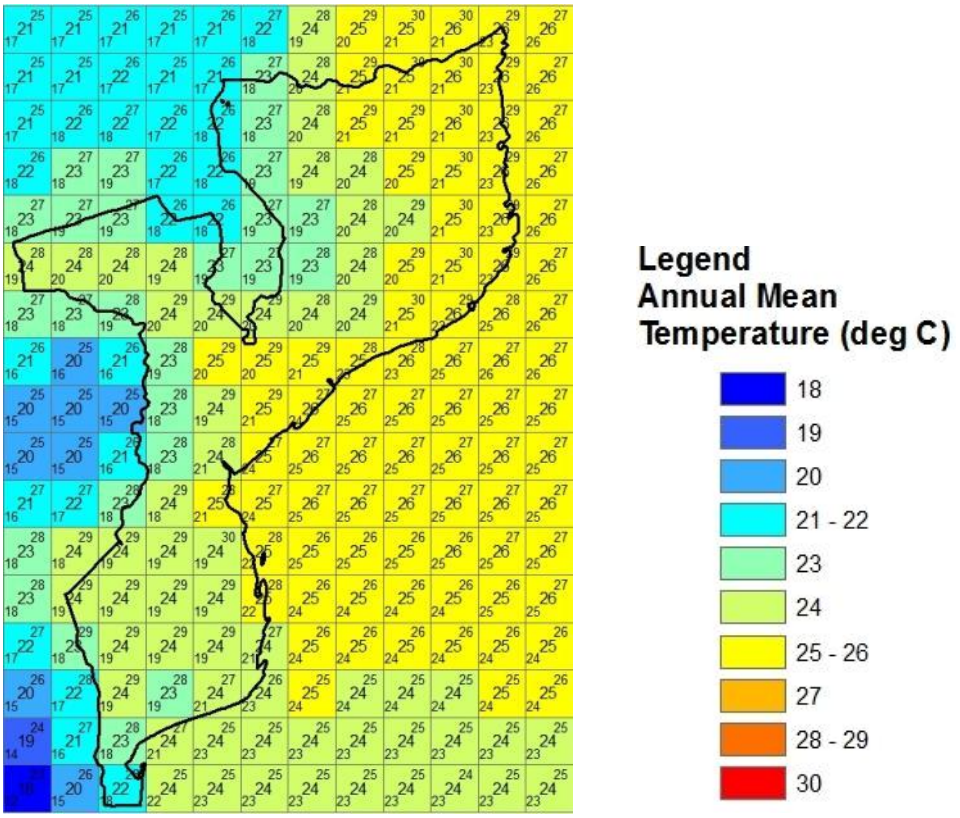
There are no information on cyclones or rising sea level and storm surge available for the four specific chosen climate change scenarios.

2.4.1 Key figures for the climate scenarios

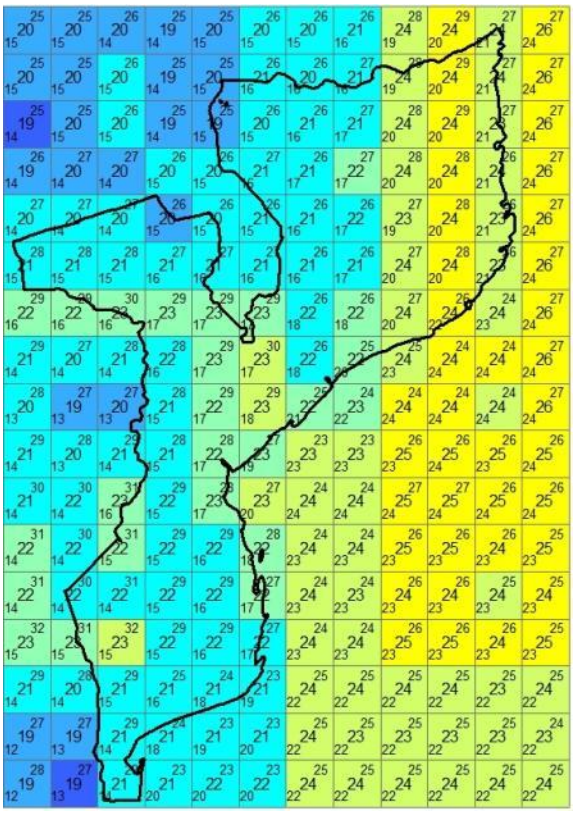
Some of the most essential figures for the received climate information are presented in Figure 2-14 below. The focus is on temperature and precipitation in heavy events.

[2] Processed data delivered by a team from Colorado University:
Len Wright, Ph.D., P.E., D.WRE
Anthony Powell
Chas Fant
Alyssa McCluskey, Ph.D.
Kenneth Strzepek, Ph.D., P.E.

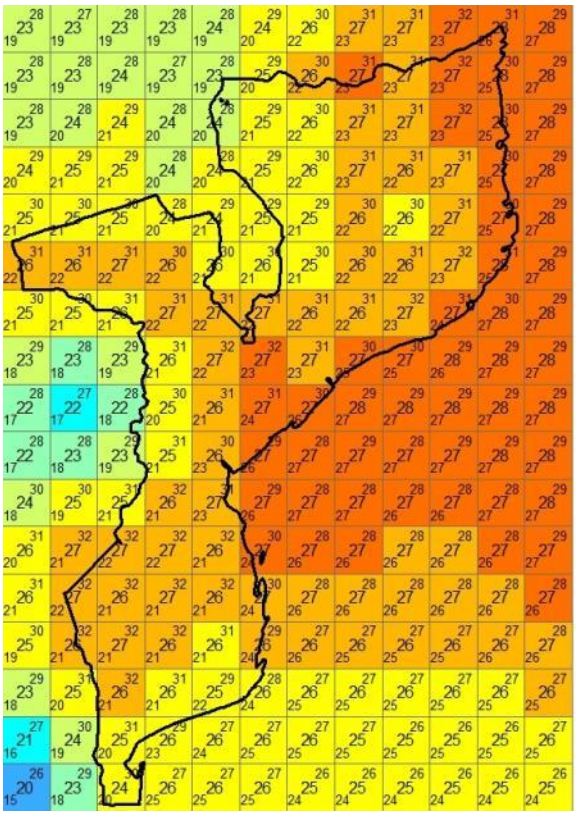
Figure 2-14 Temperature. Annual daily temperature, max, mean and min.



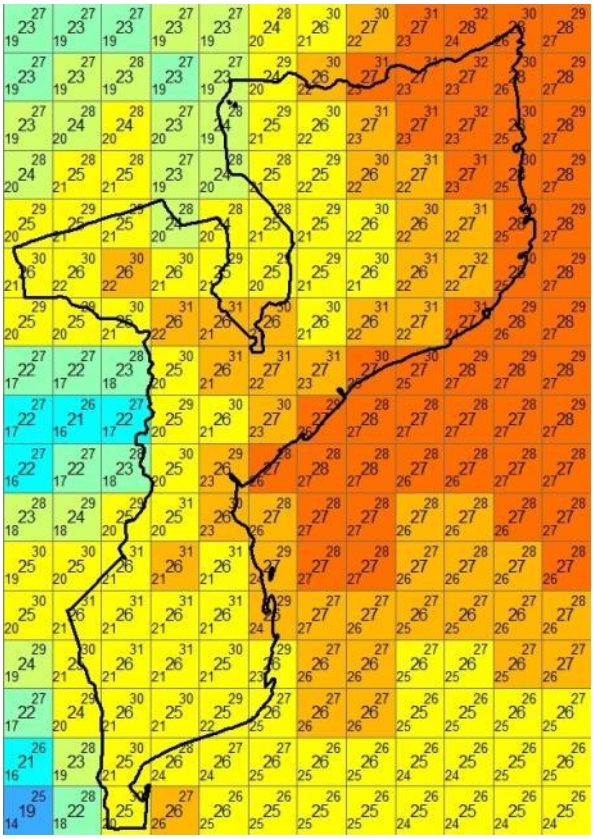
Historical, 1997-2006



"Global Wet": NCAR-CCSM, SRES A2



"Global Dry": CSIRO-MK3.0, SRES A2

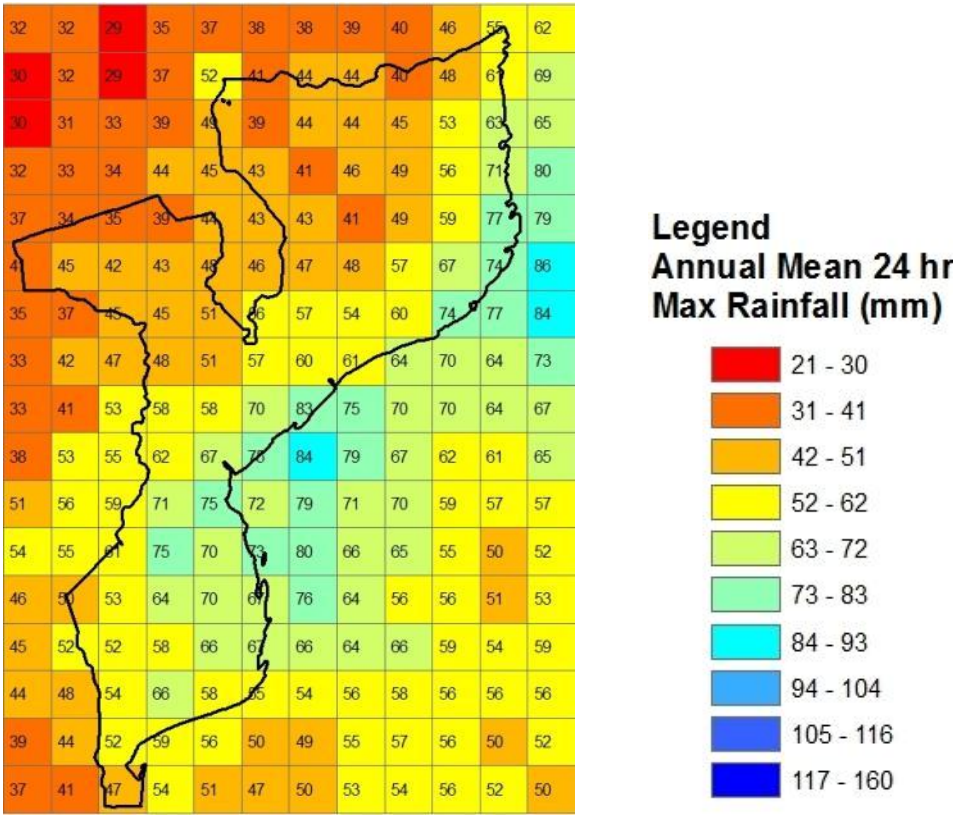


"Mozambique Wet": IPSL-SRES B1

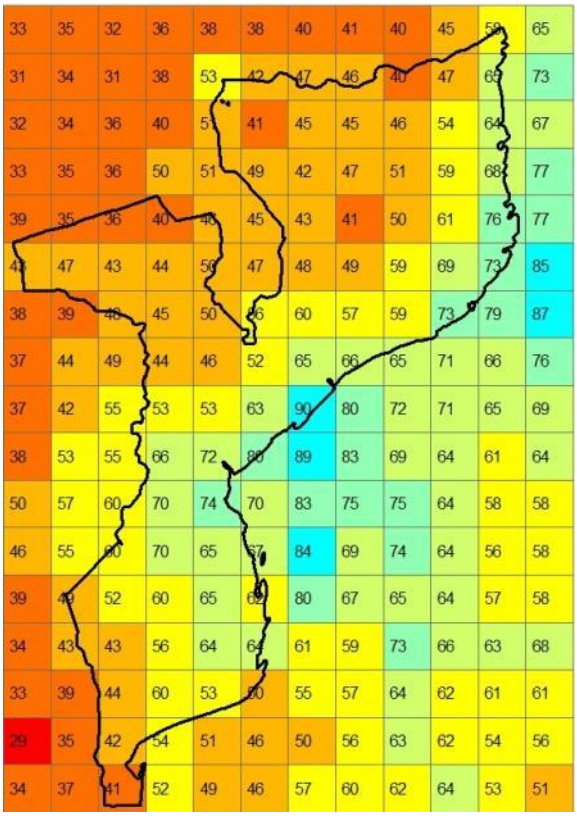
Not available for 2046

"Mozambique Dry": UKMO-SRES A2

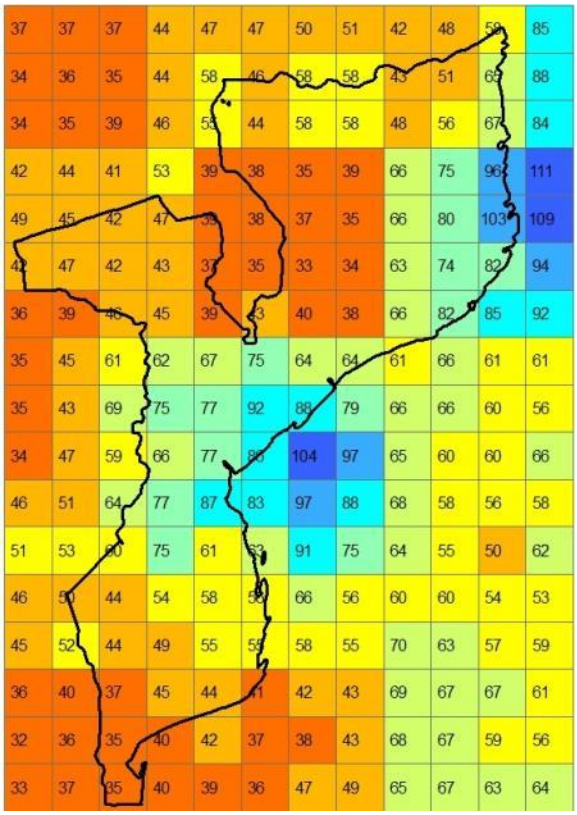
Figure 2-15 Precipitation. Annual 24 hours maximum rainfall (pr year)



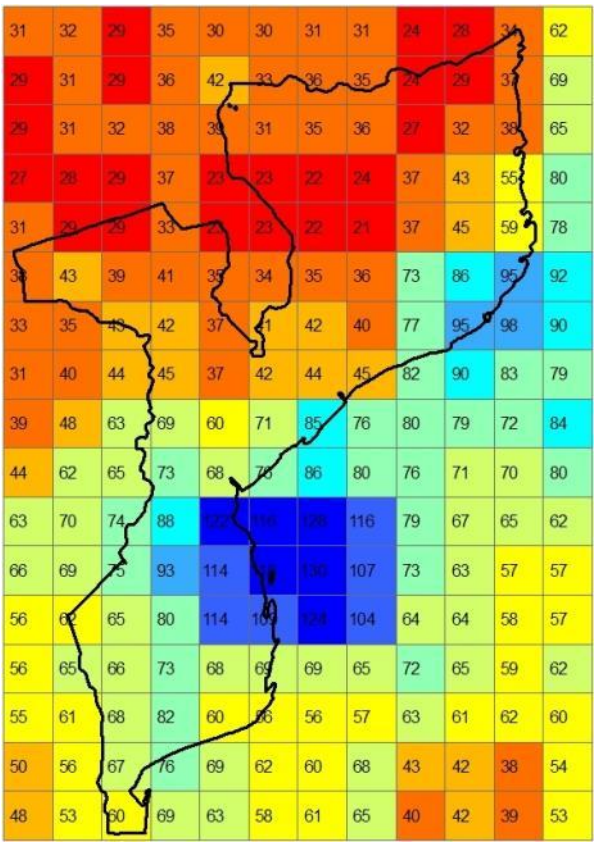
Historical, 1997-2006



"Global Wet": NCAR-CCSM, SRES A2



"Global Dry": CSIRO-MK3.0, SRES A2



"Mozambique Wet": IPSL-SRES B1

Not available for 2046

"Mozambique Dry": UKMO-SRES A2

All received climate data has been processed for the purpose of this study, and in the following datasheets the main climate data relevant for this study are summarized for the different climate scenarios:

Table 2-1 Climate 2050 on average in Mozambique, rain and temperature

Climate 2050 on Average in Mozambique, rain and temperature						
		Hist	GW-NCAR,A2	GD-CSIRO,A2	MW-IPSL,B1	MD-UKMO,A2
Precipitation:						
Annual Mean Rainfall	mm/y	937	1017	970	870	NA
Annual Mean 24 hrs Max. Rainfall	mm/24h	55	59	57	55	NA
Annual Mean 5 days Max. Rainfall	mm/5d	130	142	134	132	NA
Annual days with rainfall	days/y	127	122	109	120	NA
Temperature:						
Annual Mean	deg C	24.2	22.6	26.3	26.1	NA
Annual Min.	deg C	20.0	17.6	22.1	21.9	NA
Annual Max.	deg C	28.5	28.1	30.9	30.2	NA
Annual days with heat waves	days/y	1.6	2.7	1.9	1.8	NA

Table 2-2 Climate 2000-2050 on average in Mozambique

Climate Change 2000->2050 on Average in Mozambique					
Increase from 2000 to 2050		GW-NCAR,A2	GD-CSIRO,A2	MW-IPSL,B1	MD-UKMO,A2
Precipitation:					
Annual Mean Rainfall	mm/y	80	33	-67	NA
Annual Mean 24 hrs Max. Rainfall	mm/24h	4	2	0	NA
Annual Mean 5 days Max. Rainfall	mm/5d	12	4	1	NA
Annual days with rainfall	days/y	-5	-18	-7	NA
Temperature:					
Annual Mean	deg C	-1.6	2.1	1.8	NA
Annual Min.	deg C	-2.4	2.1	1.9	NA
Annual Max.	deg C	-0.4	2.3	1.7	NA
Annual days with heat waves	days/y	1.1	0.3	0.2	NA

Table 2-3 % Climate change 2000-2050 on average in Mozambique

% Climate Change 2000->2050 on Average in Mozambique					
% Increase from 2000 to 2050		GW-NCAR,A2	GD-CSIRO,A2	MW-IPSL,B1	MD-UKMO,A2
Precipitation:					
Annual Mean Rainfall	mm/y	9%	4%	-7%	NA
Annual Mean 24 hrs Max. Rainfall	mm/24h	7%	3%	0%	NA
Annual Mean 5 days Max. Rainfall	mm/5d	9%	3%	1%	NA
Annual days with rainfall	days/y	-4%	-14%	-6%	NA
Temperature:					
Annual Mean	deg C	-7%	9%	8%	NA
Annual Min.	deg C	-12%	11%	9%	NA
Annual Max.	deg C	-1%	8%	6%	NA
Annual days with heat waves	days/y	67%	15%	10%	NA

2.4.2 Design curves for the future climate, 2050

One of the key issues in this study is to find the design storms for the future situation. The existing Drainage Design Manual for Ethiopia and more other countries in the sub Sahara region use design storms based on the 24 hour precipitation for different return periods. In the following tables some of the key results on design curves from these sources are summarized. The results are used to establish curves for the future climate situation in 2050 for the chosen four climate scenarios. The main principle for the curves and calculations are similar to the methods used in the design manual for Ethiopia, as there are no similar design manual specifically for Mozambique.

Curves for the heavy storms with different return periods are established by two methods. First they are calculated directly from the given predicted future climate data for the four climate scenarios and secondly calculated as "smooth" curves based on the same kind of formulas as the present design storm curves, but with slightly revised parameter values. The direct method gives almost smooth curves, but some single values lay unrealistically far from the smooth curve, why it is chosen to use the formula based heavy storm curves for evaluation of the change in return periods. For the same reason the formula based smooth curves are used as basis curves for design of new structures and enlargement or reinforcement of existing roads, culverts, bridges etc.

Using the curve for historical heavy precipitation (based on the climate data set provided with the four scenarios) it can be seen that the present design storm curve for different specific projects are about 50% - 160% higher than the historical precipitation data for a storm with the same return period. This means that present designs of road infrastructure includes a significant "reserve" compared to actual climate.

Instead of making new design curves for each climate scenario, it is chosen to use the % increase in future storms for each of the four climate scenarios compared to the present/historical storm with the same return period. This percen-

tage is used to assess the need for new design, enlargement, reinforcement etc. for roads, culverts, bridges etc. in the future as a result of climate change. This means that the same relative "reserve" is maintained in the curves used for the assessed future current design standard as in the standard today.

It is also calculated how much the return periods will be reduced for the heavy storms. These figures are used to calculate the cost of more frequent damages, blocking of roads, increased repair and maintenance etc. As an example it can be mentioned that the present 100 year storm, will occur once every 21 year in the future (2050), if the predictions for "Global Wet"; NCAR-CCSM, SRES A2, are correct for Mozambique - 5 times more often than today. See Table 2-8.

Table 2-4 24 hour maximum precipitation in mm/24h for different return periods, calculated directly and as smooth curves based on common used formulas for extreme events

24 hour precipitation depth (mm) vs frequency (yrs), Average in Moz. (directly from GCM data):							
mm/24hrs, Return period in years	**1**	**2**	**5**	**10**	**20**	**50**	**100**
Historical	14	35	40	54	60	68	74
"Global Wet"; NCAR-CCSM, SRES A2	17	39	55	65	75	88	98
"Global Dry"; CSIRO-MK3.0, SRES A2	17	39	52	61	69	80	88
"Mozambique Wet"; IPSL, SRES B1	19	43	59	69	79	92	101
"Mozambique Dry"; UKMO, SRES A2	NA	NA	NA	NA	NA	NA	NA

24 hour precipitation depth (mm) vs frequency (yrs), Average in Moz. (based on formula+GCM):							
mm/24hrs, Return period in years	**1**	**2**	**5**	**10**	**20**	**50**	**100**
Historical	26	33	43	50	57	67	74
"Global Wet"; NCAR-CCSM, SRES A2	29	39	53	64	74	88	98
"Global Dry"; CSIRO-MK3.0, SRES A2	31	40	51	60	68	80	89
"Mozambique Wet"; IPSL, SRES B1	34	44	58	68	78	92	102
"Mozambique Dry"; UKMO, SRES A2	NA	NA	NA	NA	NA	NA	NA

Note: formula = "smooth" curves

The increase in 24 hour storms should be used for estimates of the increase in design and for enlargement and reinforcement of roads, culverts, ditches, bridges etc. but as seen in the following Table 2-5 there are some values that seems to be uncertain and not in accordance with the regular pattern for change in precipitation (marked in darker color).

Table 2-5 % change in 24h precipitation for different return periods based on direct data from the GCM

% - Change in 24 hour precipitation depth (mm) vs frequency (yrs), Average in Moz.(directly from GCM data):							
% Change in precipitation based om Climate Change up to 2050 compared to present perecipitation							
(Future-historical)/historical	1	2	5	10	20	50	100
Historical	0%	0%	0%	0%	0%	0%	0%
"Global Wet"; NCAR-CCSM, SRES A2	28%	14%	36%	22%	25%	29%	32%
"Global Dry"; CSIRO-MK3.0, SRES A2	28%	13%	29%	13%	15%	17%	19%
"Mozambique Wet"; IPSL, SRES B1	38%	25%	45%	29%	31%	34%	37%
"Mozambique Dry"; UKMO, SRES A2	NA	NA	NA	NA	NA	NA	NA

Instead of using the direct data from the GCM models, it is chosen to use a smoother pattern for design storms based on formulas for the common pattern for the relations between depth and frequency for heavy storms. The following table is used for increase in design and for enlargement and reinforcement of roads, culverts, ditches, bridges etc.

Table 2-6 % change in 24h precipitation for different return periods based on formulas for smoothing results from the GCM, according to common pattern for precipitation/frequency

% - Change in 24 hour precipitation depth (mm) vs frequency (yrs), Average in Moz. (based on formula+GCM):							
% Change in precipitation based om Climate Change up to 2050 compared to present perecipitation							
(Future-historical)/historical	1	2	5	10	20	50	100
Historical	0%	0%	0%	0%	0%	0%	0%
"Global Wet"; NCAR-CCSM, SRES A2	12%	18%	24%	27%	29%	31%	32%
"Global Dry"; CSIRO-MK3.0, SRES A2	19%	19%	19%	19%	19%	19%	19%
"Mozambique Wet"; IPSL, SRES B1	31%	33%	34%	35%	36%	36%	37%
"Mozambique Dry"; UKMO, SRES A2	NA	NA	NA	NA	NA	NA	NA

Note: formula = "smooth" curves

Table 2-7 Absolute change in precipitation per return period

Change in 24 hour precipitation depth (mm) vs frequency (yrs), Average in Moz. (based on formula+GCM):							
mm/24hrs, Return period in years	1	2	5	10	20	50	100
Historical	0	0	0	0	0	0	0
"Global Wet"; NCAR-CCSM, SRES A2	3	6	10	13	16	21	24
"Global Dry"; CSIRO-MK3.0, SRES A2	5	6	8	10	11	13	14
"Mozambique Wet"; IPSL, SRES B1	8	11	15	18	21	24	27
"Mozambique Dry"; UKMO, SRES A2	NA	NA	NA	NA	NA	NA	NA

Note: formula = "smooth" curves

The changes in frequency or return period for a given historical storm are given in the table below. This table is used for evaluation of increased frequency of damages etc. and increased need for repair and maintenance.

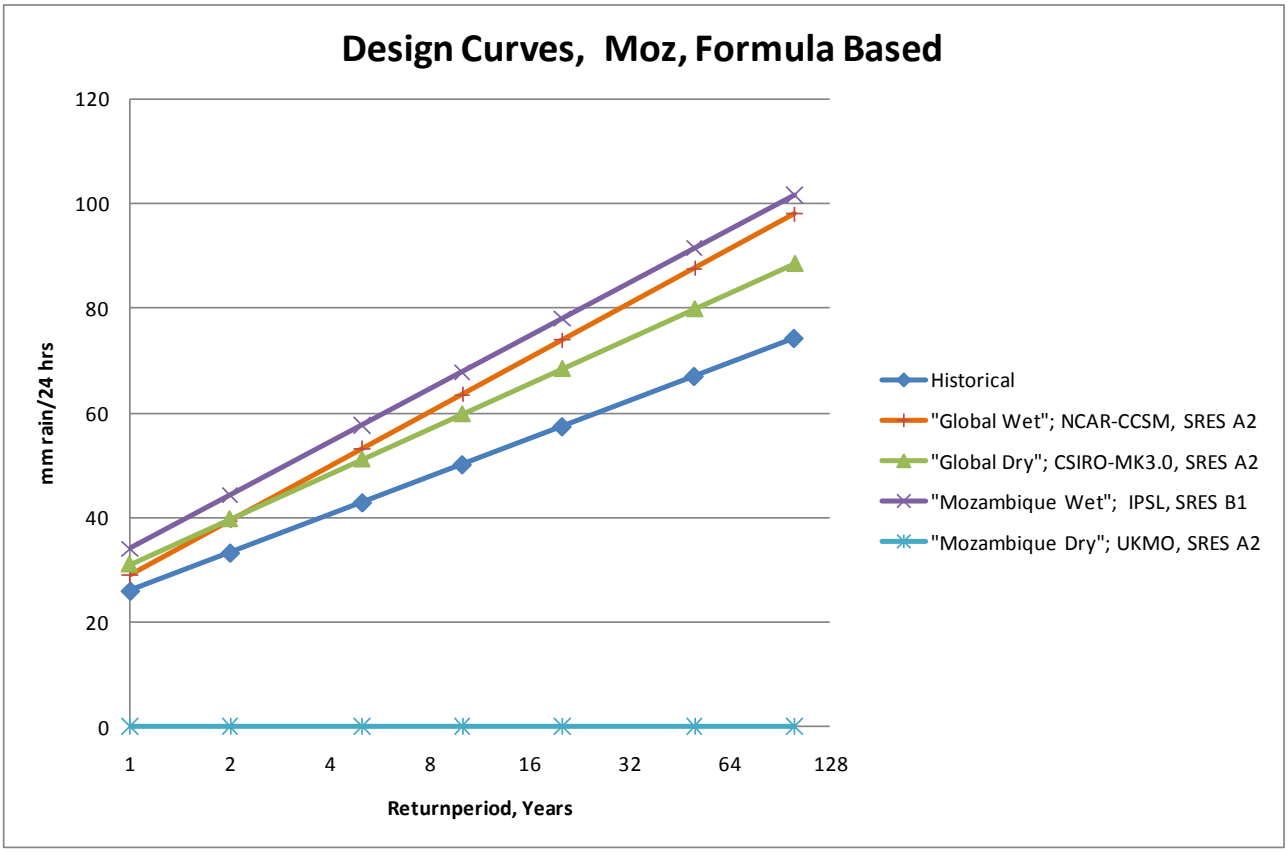
Table 2-8 Future return period in years for present heavy storm with different return periods.

Returnperiod - 24 hour precipitation depth (mm) vs frequency (yrs), Average in Moz. (based on formula+GCM):							
Future returnperiod in years of a present XX year storm							
Return period in years	**1**	**2**	**5**	**10**	**20**	**50**	**100**
Historical returnperiod	1	2	5	10	20	50	100
"Global Wet"; NCAR-CCSM, SRES A2	1	1	3	4	7	13	21
"Global Dry"; CSIRO-MK3.0, SRES A2	1	1	3	5	8	18	32
"Mozambique Wet"; IPSL, SRES B1	1	1	2	3	5	9	16
"Mozambique Dry"; UKMO, SRES A2	NA	NA	NA	NA	NA	NA	NA

Note: formula = "smooth" curves

The figures for present and future 24 hour maximum rainfall are represented in the following graph, Figure 2-16.

Figure 2-16 Calculated design curves for the 24h maximum precipitation in year 2050 and the present 24h maximum precipitation curve



The graph shows that the two "wet" climate scenarios result in relative similar design curves, which can not for any practicable purpose be differentiated. The "Global Dry", CIRO-MK3.0; A2 shows a different pattern as it follows the same pattern as the historical curve, but the values for the future 24 hours precipitation are approximately 19 % higher than the present design curve (as used in other countries) for all return periods. The graph shows curves for the present 24h precipitation and the expected future 24h precipitation under different scenarios, and these curves will be used for assessing the design need, based on the %-increase in 24h precipitation from present to 2050 as seen in Figure 2-16 or Table 2-6.

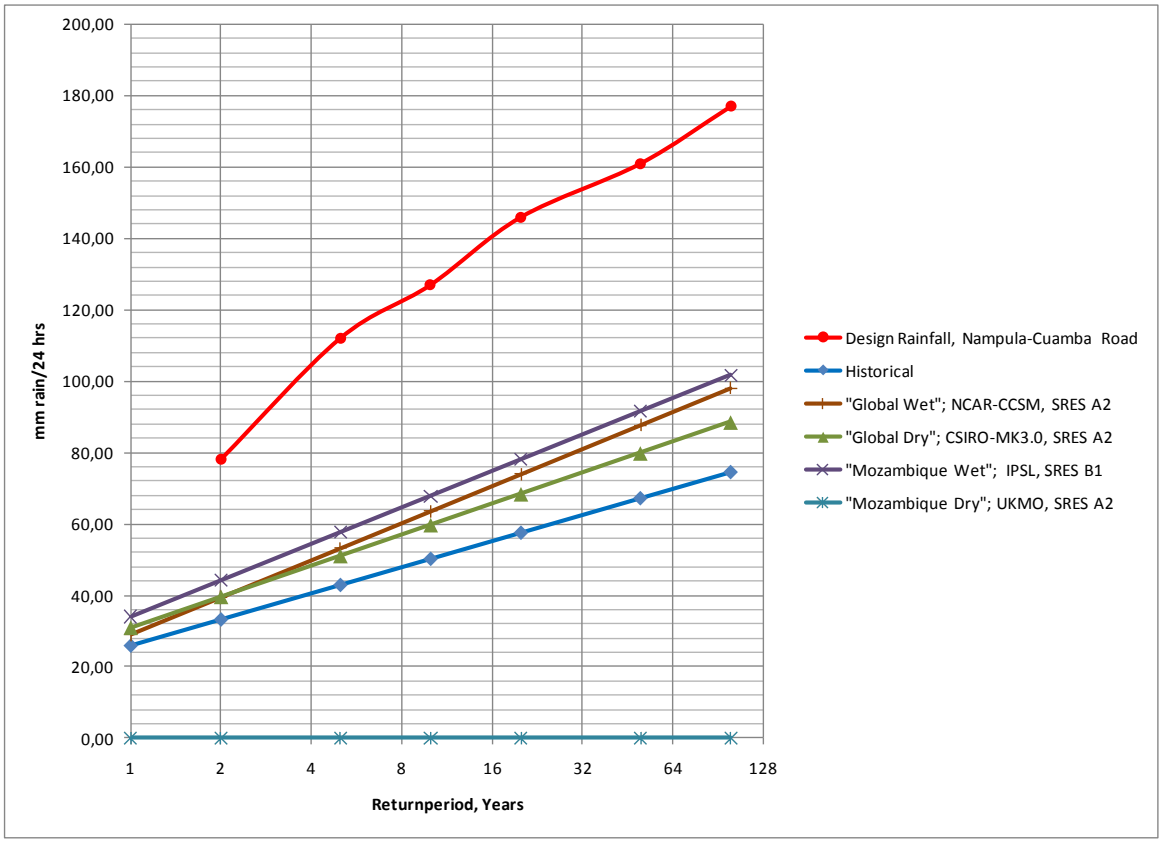
The "current design curve" does not exist for the country as such, as there are no mandatory design standards. Instead individual design curves for different projects and for different regions are left for the designer to decide in the specific project. One of the projects is the Nampula-Cuamba Road where the design curve for 24h precipitation is 130-160% higher than the present historical curve for maximum 24h precipitation in Mozambique as an average; even though the road is located in the part of the country with the lowest 24h rainfall according to Figure 2-15. In the following Table 2-9 and Figure 2-17 the design curve for Nampula-Cuamba Road is compared with the present precipitation and the expected precipitation in 2050.

Table 2-9 Comparison of design storms for Nampula-Cuamba Road and the historical storms and storms in different climate change scenarios

24 hour precipitation depth (mm) vs frequency (yrs), Average in Moz. (based on formula+GCM):						
mm/24h	**2**	**5**	**10**	**20**	**50**	**100**
Design Rainfall, Nampula-Cuamba Road	78	112	127	146	161	177
Historical	**33**	**43**	**50**	**57**	**67**	**74**
"Global Wet"; NCAR-CCSM, SRES A2	39	53	64	74	88	98
"Global Dry"; CSIRO-MK3.0, SRES A2	40	51	60	68	80	89
"Mozambique Wet"; IPSL, SRES B1	44	58	68	78	92	102
"Mozambique Dry"; UKMO, SRES A2	NA	NA	NA	NA	NA	NA

Note: formula = "smooth" curves

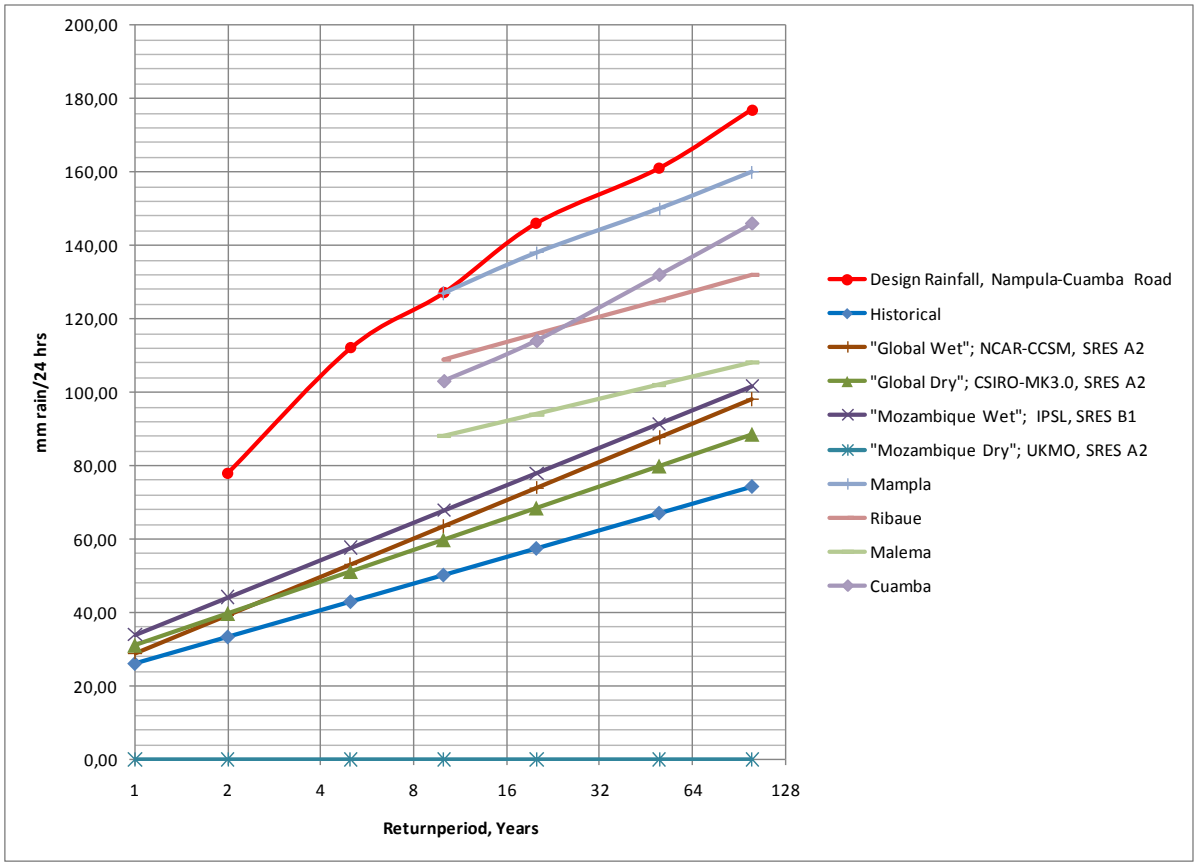
Figure 2-17 Comparison of design storms for Nampula-Cuamba Road and the historical storms and storms in different climate change scenarios



Other design curves from the "Feasibility study N13" are added in Figure 2-18 for illustration of the use of different design curves, depending on the locations and the assumptions. There are only four hydrological stations in the N13 study area, which regularly measure temperature, precipitation, and humidity near the Study road; the data available is considered statistically acceptable and are used

for preliminary design of bridgets and culverts. These stations are located at Nampula, Ribaue, Malema, and Cuamba, which are all major cities and towns on the Study Road. The curves used by the designer are all located higher than the curves for present precipitation and the expected precipitation in 2050 according to the climate change scenarios used in this study. This indicates that current designs for road projects includes a large reserve to deal with climate change.

Figure 2-18 Comparison of design storms for Nampula-Cuamba Road and "Feasibility study N13" with the historical storms and storms in different climate change scenarios



2.4.3 Rising sea level, storm surge and cyclones

There are no data available for these issues for the four specific chosen climate change scenarios. Therefore results from other new studies have been reviewed. The conclusion is that specific calculations of the adaptation consequences for roads can not be included in this study. The main reasons are the large uncertainties, the indicated limited change the next 40 years and that adaptation measures will be initiated for other reasons than for making transportation/roads climate change resilient. Many adaptation measures for disaster risk management are urgently needed for protection of the society and values from damages from the present occurrence of cyclones and storm surge.

The following summarizes results for Mozambique from the INGC study for the mentioned issues that are not specifically addressed in this study as the impacts are small/uncertain and can not be quantified as significant road costs.

Rising sea level
The IPCC and the SRES scenarios represent a Low Sea Level Rise Scenario (Low SLR). A High Sea Level Rise Scenario (High SLR) based polar ice melt is also introduced, and it is very speculative, as the future rates of melting of the polar ice caps are largely unknown. The results of the scenarios are:

	2030	2060	2100
Low Sea Level Rise Scenario	10cm	20cm	30cm
High Sea Level Rise Scenario	10cm	100cm	500cm

Storm surge
The Low SLR Scenario and the High SLR Scenario introduced above are used to generate the future expected extreme sea levels at return periods of 1, 10, 100 and 1,000 years, depending on the location and the particular sea level rise scenario. These scenarios indicate that it is especially after 2060 the large impacts of climate change will be seen.

Nacala	Scenario	1 year	10 years	100 years	1000 years
Present		185cm	234cm	272cm	312cm
2030	All	195cm	244cm	282cm	330cm
2060	Low SLR	205cm	254cm	292cm	349cm
	High SLR	285cm	334cm	372cm	429cm
2100	Low SLR	215cm	264cm	302cm	370cm
	High SLR	585cm	634cm	672cm	740cm

Beira	Scenario	1 year	10 years	100 years	1000 years
Present		346cm	390cm	440cm	490cm
2030	All	361cm	406cm	455cm	517cm
2060	Low SLR	376cm	420cm	470cm	545cm
	High SLR	456cm	500cm	550cm	625cm
2100	Low SLR	391cm	435cm	485cm	576cm
	High SLR	761cm	805cm	855cm	946cm

Maputo	Scenario	1 year	10 years	100 years	1000 years
Present		178cm	225cm	270cm	315cm
2030	All	188cm	235cm	280cm	335cm
2060	Low SLR	198cm	245cm	290cm	355cm
	High SLR	278cm	325cm	370cm	435cm
2100	Low SLR	208cm	255cm	300cm	378cm
	High SLR	678cm	625cm	670cm	748cm

Cyclones

Emanual et al. (2008) describe a technique for downscaling tropical cyclone climatologies from global analyses and models, which aims to avoid the resolution issue. Simulated storms driven by re-analysis of data between 1980 and 2006 concur with the data on observed storms, including their spatial variability and temporal variability on time scales from seasons to decades. The technique is then applied to the output of seven global climate models run in support of the most recent IPCC AR4 report. 2,000 tropical cyclones in each of the 5 ocean basins were simulated using global model data from the last 20 years of

the 20th century, and the 22nd century as simulated by assuming IPCC emission scenario A1b.

The results for the Indian Ocean show that there is an overall tendency toward decreasing frequency of tropical cyclones, consistent with the direct simulations using global climate models, and a general increase in storm intensity, as expected from theory and prior work with regional tropical cyclone models

Thus both recent trends in observations and long term modeling outcomes suggest that climate change will affect the characteristics of tropical cyclones in the South Western Indian Ocean in two distinct ways.

Tropical cyclones in the Mozambique Channel, are likely to become less frequent, but their intensity and associated precipitation is likely to increase.

3 Mozambique road network

3.1 Introduction

During the last decade Mozambique's transportation system has experienced a major restructuring process after getting severely damaged during the civil war. Massive government and foreign efforts have allowed the country to rebuild and expand the system.

ANE (National Road Administration) is a public institution with legal status and administrative autonomy, responsible for development, construction and large repair of the national network. All national and regional classified roads are administrated by ANE, except for urban roads under the jurisdiction of municipal councils. The local authorities are responsible for routine maintenance and construction of low volume roads within their provinces.

The network of classified roads in Mozambique is 30,056 km of which around 20% are paved; in terms of classification they are divided into primary, secondary, tertiary and vicinal as indicated in the table below.

Table 3-1 Mozambique road network

Road Classification	Paved (km)	Unpaved (km)	Total (km)
Primary	4,728	1,243	5,971
Secondary	838	4,078	4,915
Tertiary	667	11,936	12,603
Vicinal	54	6,513	6,567
Total	**6,286**	**23,770**	**30,056**

Source: ANE

Geometric standards for road design depend on the functional requirements of the road network, which therefore is divided into various classes. Such classification is also helpful for administrative purposes.

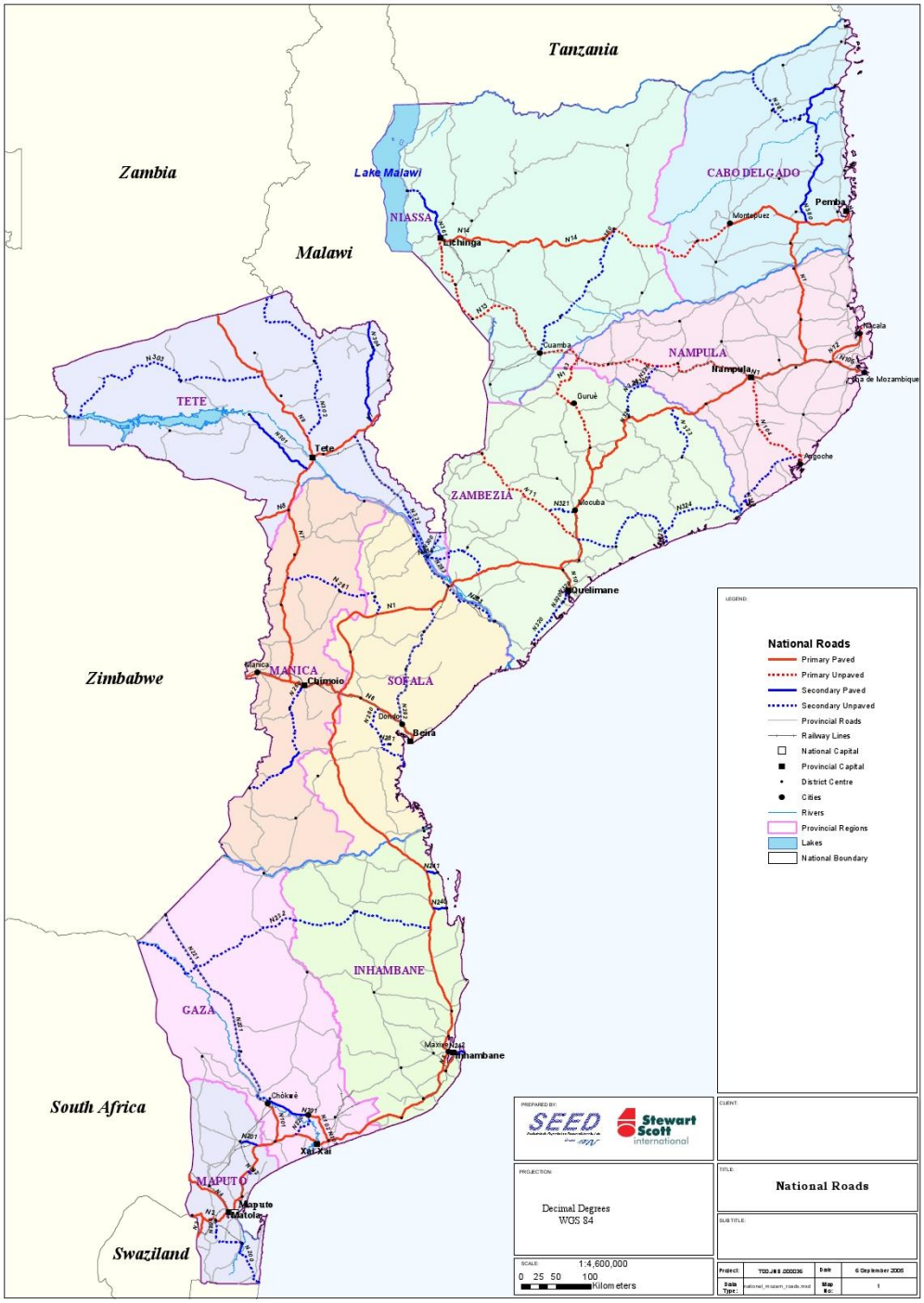
Table 3-2 Classification of the road network in Mozambique

Categoriza-tion	Designation	Functional Definition	Numbering
National Roads	Primary Roads	Form the national trunk road network and link: • Provincial capitals • Provincial capitals and other cities • Provincial capitals and main ports • Provincial capitals and important border posts	(a): N1 to N100 (b): N101 to N199
	Secondary Roads	Form the secondary network complementing the trunk road network and link: • Primary roads • Provincial capitals and sea or river ports • Primary roads and economic poles of high importance • Primary roads and (other) border posts	N200 to N399
Regional Roads	Tertiary Roads	Tertiary roads link: • Secondary roads with primary roads or with other secondary roads • District centers • District centers and administrative posts • District centers and economic poles of high importance	R400 to R799
	Vicinal Roads	Vicinal roads link: • Tertiary roads • Administrative posts • Administrative posts and other population centers	R800 onwards

(a): Roads that constitute major routes (itinerários principais)
(b): Other primary roads

Source: Final Report on "The Reclassification of the Mozambique Road Network", 2003.

Figure 3-1 Mozambique national road network



Source: ANE 2008

To be considered paved, at least a single layer of asphalt is required. Typically gravel roads get no surface dressing, except in areas that have frequent flooding or experience frequent problems. In general, the condition of the paved road network is better than the unpaved network. As of 2006 almost half of the un-

paved roads were in poor condition, and only 57% were fully transitable by normal (non four-wheel drive) traffic.

Table 3-3 Summary road conditions

Condition	Paved Roads	Unpaved Road Network			
			of which		
		Unpaved Total	Fully Tran-sitable	Semi-Transitable	Intransitable
Kilometers					
Good	3,698	4,221	3,648	507	66
Fair	1,302	8,501	6,801	1,432	268
Poor	649	11,596	3,311	5,371	2,914
Total	**5,649**	**24,318**	**13,760**	**7,310**	**3,248**
Percent					
Good	65%	17%	15%	2%	0%
Fair	23%	35%	28%	6%	1%
Poor	11%	48%	14%	22%	12%
Total	**100%**	**100%**	**57%**	**30%**	**13%**

Source: ANE (Road Sector Strategy 2007 - 2011).

In terms of road usage, the paved road network carries the largest share of traffic in terms of estimated vehicle-kilometers, almost 85%. The analysis of road usage indicates that while the unpaved road network is important for accessibility goals, the greatest economic impact of poor road condition is concentrated on the more heavily trafficked paved roads.

Table 3-4 Summary road usage by condition

Condition	Paved Network		Unpaved Network		Total
	Vehicle /km	%	Vehicle /km	%	
Good	1,354	58%	89	4%	1,443
Fair	335	14%	181	8%	516
Poor	266	11%	112	5%	378
Total	**1,955**	**84%**	**381**	**16%**	**2,336**

Source: ANE (Road Sector Strategy 2007 - 2011).

The members of the Southern Africa Transport and Communications Commission (SATCC) comprising Angola, Botswana, Lesotho, Swaziland, Mozambique, Zimbabwe, Zambia, Malawi and Tanzania agreed on harmonizing the standards and specifications for road design, construction and maintenance within the nine member states. The main objective of these recommendations was to develop a set of standards for the regional trunk road network which could be accepted by all member states; the recommendations may therefore be regarded as a compromise between the existing design standards in the regions. ANE uses the SATCC 2001 draft standards for road design and ANE has their own guideline recommendations for hydrology and hydraulic standards. These standards are only guidelines and are not mandatory, so if design consultants have their own guidelines they can choose to use them. The Guidelines used by ANE are in the process of being updated, but this is mostly in relation to the

low volume roads. In 2003, SATCC released an additional guideline focusing on Low Volume Roads.

The design guidelines used in Mozambique for road design include:

- SATCC - Code of Practice for the Design of Road Bridges and Culverts - 2001 Draft
- SATCC - Code of Practice for the Geometric Design of Trunk Roads - 2001 Draft
- SATCC - Code of Practice for the Design of Road Pavements - 2001 Draft
- SATCC - Code of Practice for the Rehabilitation of Road Pavements - 2001 Draft
- SATCC - Standard Specifications for Road and Bridge Works - 2001 Draft
- SATCC - Guideline Low Volume Sealed Roads - 2003
- ANE Design Standards - 2001 Draft

It is inevitable that the recommendations contain gaps in the documentation of certain design variables and layout elements. In addition to these guidelines, other guidelines can be used as references such as the Overseas Road Notes, and other regional road design manuals or South African standards.

Mozambique's transport sector is governed by the following road sector policies and strategies:

- Road Sector Strategy 2007-2011 (RSS)
- Roads and Bridges Management and Maintenance Program (RBMMP)
- PRISE 2007-2009 (PIP)

The RSS presents the main elements of the Government of Mozambique ´s strategy for developing and managing the country's classified road network, establishing the broad goals and priorities. The RSS takes a medium-long -term perspective of the development and management of the classified roads of Mozambique.

The Roads and Bridges Management and Maintenance Program was created to stimulate growth and contribute to poverty reduction through improved road infrastructure, better sector policies, and enhanced roads sector management.

The PRISE Implementation Plan (PIP) generally follows the structure presented in the Strategic Financial Plan contained in the RSS 2007 – 2011 in August 2006, with the addition of several projects and activities. The plan comprises more than $1.0 billion of activities over three years. A substantial portion of the planned civil works is still subject to finalization of feasibility studies, detailed designs and donor commitments. The uses of funds are shown in table below:

Table 3-5 Summary sources and uses of fund, PRISE 2007 -2009 (USD million)

Component	Planned Uses	Funding				Total Funding
		Road Fund	GOM	Sector Budget Support	Donors	
Overhead	$69.6	$29.9		$15.3	$24.4	$69.6
Maintenance	$263.9	$165.1		$98.2	$0.5	$263.9
Rehabilitation and Upgrade	$709.8		$139.1		$570.5	$709.8
Total	$1064	$204.0	$139.1	$113.5	$595.6	$1064

Source: PRISE

3.2 Current road assets in Mozambique

3.2.1 Introduction

A well functioning road is dependent on a number of elements to function correctly. This report has focused on the elements that are most likely to be affected by climate change, and are the most critical to the overall usability of the road network. The main components of the road network considered are: Bridges and Culverts, Pavement Design, Slope Stability, and Surface Drainage.

3.2.2 Bridges and culverts

Mozambique is characterized by climate diversity and a complex hydrological network. No accurate number for the quantity of bridges and culverts exits in Mozambique. In the last decade, ANE initiated a bridge database system, but this was stopped in the last few years due to internal decisions. An estimate from ANE bridge department for the number of bridges in Mozambique is approximately 2000. A bridge in Mozambique is considered longer than 6 meters in length. Of these 2000 bridges, it is estimated that a majority of them are still in good condition with adequate hydraulic capacity.

In the last few years, a number of large bridge projects have been completed or are currently in construction. These include:

- Zambezi Bridge: 2376 m length, approximate cost 85 million EUR
- Unity Bridge: 720 m length, approximate cost 25-40 million USD
- Moamba Bridge: 300 m length, approximate cost 8 million USD

The approximate costs are based on interviews and articles.

From the Hydrologic Study for the Final Report carried out by SRK Consulting for the Study of Upgrading Nampula – Cuamba Road, 37 bridges were found. The main features observed were:

- Road width is narrow (1 lane road)
- The river capacity at the bridge is not enough for smooth discharge
- High water level (HWL) is higher than the surface of the existing bridge
- Temporary bridge is used
- The existing bridge is damaged
- The existing bridge is very old

As a result of the consideration and site inspection of present conditions, the existing 37 bridges were divided into the following three categories based on present conditions:

1) 17 bridges of the existing bridges were well used.
   These bridges had enough road width and the river crossing capacity.
2) 14 small bridges of the existing bridges shall be replaced by box culvert.
   These bridges are short span and have inadequate road width.
3) 6 bridges of the existing bridges have to be reconstructed as new bridges as discussed below:
   These bridges have inadequate road width and/or river crossing capacity is not enough.

The study shows that only 46% of the existing bridges found in the road section can cope with the current climate conditions, 38% have to be replaced and 16% have to be reconstructed as new bridges. This is only the analysis and the considerations for a certain section of the road network of the country, but could give a representative picture of the current situation of the bridges in Mozambique.

Current design practices
For new bridge and culvert construction it is normal to begin with using the design manual; SATCC - Code of Practice for the Design of Road Bridges and Culverts-2001 Draft. Additional design manuals such as AASTHO, British, and South African bridge codes are also often used as references.

Bridges and culverts are designed to withstand a flood return interval based on the discharge of the watercourse they pass over. The design storm return interval is suggested in the ANE Design Standards shown in Table 3-6.

Table 3-6 ANE Return Interval Structures

Flood Discharge 1:20 Year Peak Flow	Return Interval (yrs) High Level Structures	Return Interval (yrs) Culverts and Low Level Structures	Return Interval (yrs) Pipe Culverts
20 $m^3/s > Q$	20	10	5
20 $m^3/s < Q < 250\ m^3/s$	50	20	10
$Q > 250\ m^3/s$	100	30	30

Source: ANE Design Standards-2001.

There are no standard charts or diagrams included in the SATCC manuals regarding hydrology. In order to determine the applicable flows, a hydrologic analysis must be performed. The extent of this analysis is dependent on the size and budget of the project. Typically, it is the consultant's responsibility to perform and attest to the accuracy of the hydrology in the area.

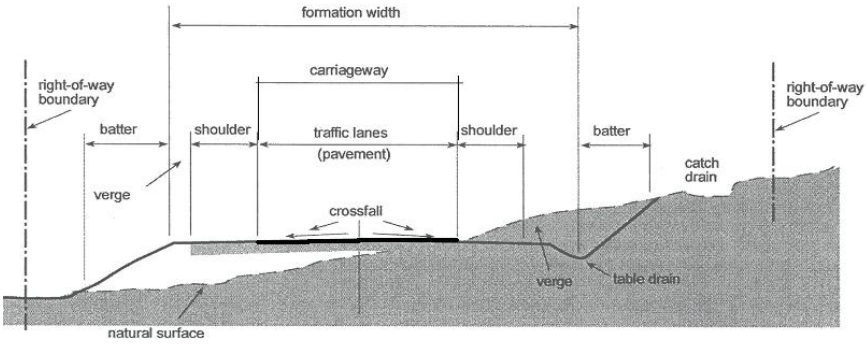
The availability of long term accurate rainfall data is scarce in the country. Many stations were either destroyed, or abandoned during the civil war. It is estimated that there is only 10 to 20 years of recent accurate historical data that can be used for calculations. Reliable data is basic in order to create accurate design standards.

3.2.3 Pavement design

Pavement design covers the design and the structure of the road. This can be broken down into paved or unpaved sections. Paved sections include those roads covered with a bituminous flexible or rigid concrete pavement. The paved roads are typically trunk roads. Unpaved sections typically are covered with a gravel wearing course, or made of an engineered earth surface depending on the design standard. An earth surfaced road is typically made of local materials that are not necessarily graded to specifications or meet any testing standards, most often used on the non-federal community roads.

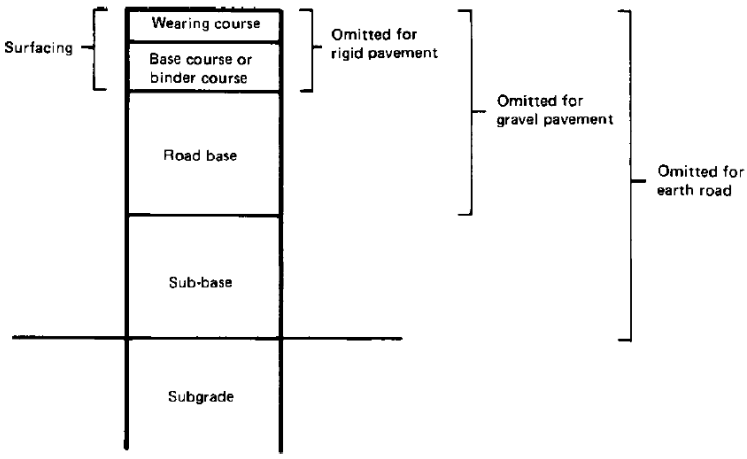
The road section for a paved or gravel road follows more or less a similar structure (see Figure 3-2). The most essential difference is the crossfall, the typical crossfall of an unpaved road being 2.5 % and for an unpaved gravel road 4-6 %. Typically, the structure includes the subgrade, capping layer, the sub base materials and a wearing course. The subbase materials and thicknesses are adjusted or left alone depending on the strength and quality of the subgrade. The weaker the subgrade material is, the stronger the sub base materials need to be. These layers can consist of many different materials, and are typically adjusted to suit local conditions, and meet the requirements set in the design manuals for level of standard for the road.

Figure 3-2 Typical road section



Source: SATCC-Low volume sealed roads

Figure 3-3 Typical elements of paved, gravel, and earth roads



Source: Overseas Road Note, pp 27

Road cross sections typically include shoulders, which are built as an extension of the carriageway. They act as extra accommodation for vehicles and pedestrians. The shoulders are typically made with less structural strength than the carriageway, although they can aid in lateral support of the road layers.

Current design practices

Pavement design follows the design manuals: SATCC Code of Practice for the Design of Road Pavements 1998 and SATCC Low Volume Sealed Roads. In addition Overseas Road Note 31 and TRH4 South African design method are commonly used. The manuals cover design for both paved trunk roads, as well as gravel and community roads.

It is common for a road upgrading project to follow the alignment of the previous road. In these instances, material from the previous road can be reused in the upgrade if it is found to be of good quality and in sufficient supply. Nearly all new road construction that does not follow an old alignment is constructed

as a gravel road. It is the intention to first build a lower cost (lower design standard) road, and pave or seal at a later time if economically feasible.

Soil investigations are done prior to road design using the guidelines explained in the Overseas Road Note. The type of testing and frequency is dependent on the level of standard of the road, as well as the location in Mozambique. In arid regions, a 4 day soaked CBR test would be subject to be decided by the Engineer if necessary. Preliminary soil and material testing and corresponding design for the upper road classifications are of a high level and frequency. The testing and design for the lower level roads is not up to the same standard due to the financial aspects. The lack of testing makes it more difficult to ensure an economically feasible strong design.

In Mozambique, trucks and slow vehicles usually use shoulders as carriageway making easier for faster vehicles to overtake them.

Figure 3-4 Shoulders being used by slow vehicles

Source: Consultant

Surfacing of shoulders is mentioned in the Road Sector Strategy 2007-2011. RSS establishes that paving of shoulder area will be adopted as a standard for high traffic volume roads (>1500 AADT) or where specifically justified by other considerations. Paved shoulders reduce the risk shoulder damage through edge breaking. RSS raises the question of paving shoulders, indicating that the issue should be subjected to tough-minded analysis, with the burden of proof on the case for going beyond the minimum standards. Based on SATCC guidelines, full width surfacing of shoulders will be considered:

- where significant usage by pedestrians and non-motorized traffic occurs
- where shoulders are constructed with materials that are readily erodible, or where the availability of materials for shoulder maintenance is restricted
- in front of guardrails
- where the total gradient exceeds five per cent
- where heavy vehicles would tend to use the shoulder as an auxiliary lane
- in mist belts
- wherever it is economically justified
- in cuttings where concrete side drains are provided

With the purpose of improving surface conditions, traditional watering is generally used in order to increase stability and act as a compaction aid to increase load bearing strength in dry countries with earth roads rich in fine materials. At the same time, the watering process reduces dust in the environment and maintains visibility.

Figure 3-5 Road watering

Source: Consultant

Increased traffic volumes are expected in the medium and long term. In such cases, condition of the surface with increase in air pollution will play an important role in traffic safety. Routine watering during dry season is recommended and should mainly take place in gravel roads with high content of fine materials.

3.2.4 Slope stability

Slope stability refers to the stability of the landscape within the immediate location of the roadway. This includes both slopes above and below the road, some which are directly affected by the construction of the road, and others that are naturally unstable. The main impact of the slope stability to the road network is through landslides which are often caused by saturation causing slip failures. Erosion increases the need for maintenance in the drainage structures by the addition of siltation.

The types of landslides affecting roads range from deep seated failures to shallow slope failures, and is discussed in Overseas Road Note 14. The impact from landslides on roads ranges from temporary partial blockage that can be cleared by maintenance crews, to complete blockages that shut down the road for extended periods of time. A deep seated failure is much more destructive and there is a limited amount of economical engineering solutions for prevention.

There is no information available on the impact of landslides in Mozambique. From discussions with the authorities, landslides are not seen as a major threat for construction or maintenance of roads.

Current design practices
The design of the interaction between the road slopes and the landscape is covered in the Overseas Road Note 31. Slope requirements used in road construction is dependent on the geology, soil conditions, and evidence of past slope instability. A section in Chapter 6 in the SADC Guideline on Low-volume Sealed Roads givers recommendations on slope protection, erosion of culverts and scour checks. SATCC does not deal in detail with slope stability issues, however, it provides a source of comprehensive references which provide additional details and more fully documented examples of local and international experience. Although the Guideline has been produced specifically for the SADC environment, there are many aspects of it which, with sound engineering judgment, could apply in similar environments elsewhere.

3.2.5 Surface conditions

Surface drainage covers the drainage of precipitation from the surface of the road, through the sub base layers in the road section, as well as runoff down hillsides and through road side ditches. Surface drainage elements are some of the assets that are most likely to be exceeded by extreme storm events. Many of these elements are designed for short storm return intervals, and quickly exceeded during a large event. In this report, bridges and culverts are discussed under their own heading, even though they are a vital part of surface drainage. Table 3-6 shows the design storms used for designing the most common drainage elements.

3.2.6 Summary

The road assets in Mozambique vary extremely. The success of these roads relies on similar factors, namely:

- Initial design and construction
- Climate and topography the road passes through
- Traffic loading
- Maintenance

The paved trunk roads are the most vital in the network, and receive a majority of the money used on transportation in Mozambique. They have correspondingly higher design, construction standards, and maintenance programs than the lower standards of roads. It is agreed that there is an overall lack of maintenance available for roads in Mozambique. The explanation for the lack of maintenance is lack of funding and available equipment. The majority of money allocated to maintaining roads in Mozambique is spent on maintaining the trunk roads, leaving the lower standard of roads in need of routine maintenance.

Many of the current problems that are seen in Mozambique are not climate related, but are amplified by the climate. For example, overloading of heavy trucks will have damaging effects on a road regardless of climate; the damage is amplified when the soils and materials beneath are overly saturated. The same can be said about routine maintenance. Maintenance is a requirement on all roads, and without it roads will deteriorate quicker than their design life. An increase in rain will only increase the need for maintenance.

4 Climate change impacts on road assets

4.1 Introduction

In Mozambique, the most influential climate impacts on roads will come from:

- Temperature
- Rain
- Tropical cyclones and sea level raise

Flooding of the infrastructure may have several causes and the impacts and potential adaptation measures are dealt with in two subchapters organized in relation to impacts from rain generally (see especially chapter4.3.2 on floods) and more specifically from cyclones and sea level rise (chapter 4.4.2), which leads to a third subchapter summing up the current soft spots in the road infrastructure (chapter 4.5.2) and conclude with a summary of adaptation measures to deal with climate change impacts (chapters 4.5.4 and 4.5.5) .

4.2 Temperature

4.2.1 Introduction

In Mozambique, the scenario results for change in mean annual temperature go from -2 ^{O}C to 2 ^{O}C. by the 2050. An increase in temperature is expected to have an impact on:

- Bridges
- Bituminous pavements

4.2.2 Bridges

Impact of climate change

A rise of 2° C will possibly mean an increase in the expansion and contraction of the bridge materials. This could cause more strain on the expansion joints.

Climate impact countermeasures

Bridges are already designed with temperature gradients in mind. The temperature changes in Mozambique are not expected to rise so high that they warrant new engineering methods, but it will require the use of best engineering practice and increased maintenance. The most common method of dealing with bridge material expansion is through the use of expansion joints. The biggest drawback of expansion joints is their need for maintenance to function proper-

ly. In order to ensure longevity of the bridge structure, these expansion joints will require increased maintenance, or engineering solutions requiring less maintenance.

Section 4.5 of SATCC-2001 standards for bridges broadly considers the effect on temperature and its changes on the design of bridges. The Guideline analysis daily and seasonal fluctuations in shade air temperature covering the minimum and maximum effective bridge temperatures for different types of construction, the minimum and maximum shade air temperatures, the effects of temperature differences within the superstructure and the adjustment for thickness of surfacing.

Effective bridge temperatures are derived from the isotherms of shade air temperature and the available data from Member States It is already been taken into account that these figures should be updated as and when further data becomes available. In cases where data is not presented, maximum and minimum shade air temperatures should be obtained from appropriate local services. These shade air temperatures are appropriate to mean sea-level in open country and a fifty-year period.

If maintenance is not deemed cost efficient or becomes too costly, then there are bridge designs that do not require expansion joints such as integral bridges. Integral bridges require no expansion joints and are dependent on integral abutment elements which use the surrounding soil in aiding in thermal expansion.

Regarding concrete mixes, there is no available data on the gradient caused by the change of temperature within curing time. The results show that for one scenario there may be an increase of 2 degrees and for another scenario the temperature may decrease by two degrees in a long term period of time. The hardening process of concrete is taking place during the very early ages of a concrete structure compared with its total service life. In the earliest stage of concrete life, when it is freshly placed, concrete is very sensitive and could easily get ruined. The method of curing and the treatment of the concrete structure during these first few days or weeks is very crucial for its final performance and durability. The risk of early-age plastic shrinkage cracks or thermal cracking due to temperature gradients may define the need for curing and protection of the concrete. Furthermore, increase in temperature means increase in 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.

It is not foreseen that special methodology will need to be developed or implemented due to the climate change effects on temperature. These criteria are often stated in the execution specifications for any given project, and there are methods and tools to help the concrete producer to plan and predict the hardening process of a concrete structure under various and changing ambient conditions. Furthermore, there are computer tools that simulate temperatures and early-age stresses within a concrete cross-section during hardening.

Summary
Temperature is an issue that should be dealt with during the design phase. The change in temperature in Mozambique over the next 50 years is not expected to require a change in the methodology of designing bridges. The increase in maintenance required will not be substantially higher than what it should be already.

4.2.3 Pavement design

Impact of climate change
The impact from a 2° C change in temperature over the next 50 years is not expected to have major consequences on pavement design.

The expected service life of a newly constructed road is estimated to be about 10 to 15 years for the upper most asphalt layers. Cracking due to climate change should not be expected, but in case it was necessary to adequate the bitumen to new conditions, the use of modifying additives may improve its properties. Plastic deformation is greatest at high service temperatures, increasing the penetration index of the bitumen significantly improves resistance to deformation. Using the right additives in a hot climate could increase the stiffness and resistance to deformation of asphalt pavements.

Climate impact countermeasures
Any serious increase in temperature is expected to occur on a time scale of 20 to 30 years, so adjustments in pavement design with respect to binder selection can be made at regular service / reconstruction intervals.

Table 4-1 Climate impacts-temperature

Climate variable	Road asset	Current climate impact to road	Current countermeasure	Climate change	Climate change impact to asset	Recommended climate change countermeasure
Average High Temperature	Bridges	Thermal Expansion of materials	Expansion Joints	+2° C Mean Temperature	Increase Expansion	Account for temp increase in Design phase
	Pavement Design	Deformation Surface, Cracking	Proper Asphalt Mix Design		Increase in Surface Deformations	Use current temperatures range during service/ reconstruction intervals
# of very Hot Days	Road Construction/ Maintenance crews working days	Limited working hours during very hot days		Increase in # Hot days	Decreased available working hours	

Source: Consultant

4.3 Rain

4.3.1 Introduction

In Mozambique, climate associated with rainfall has the largest impact on roads and bridges. This chapter covers major elements that are directly impacted by rain either through direct contact from rain, soil moisture, or from streams and rivers that the road must cross.

The majority of these road elements are sized based on different frequency values of a 24 hour storm. Table 4-2 shows the increase in precipitation that can be expected under the different climate scenarios. These new values can then be applied using the current ENA guidelines to determine new sizing requirements, and/or more appropriate engineering solutions. Because the values for Global Wet and Mozambique Wet are short of similar and shows the same trend, the worst wet scenario is used for the analysis, named Mozambique Wet, IPSL, SRES B1.The Mozambique Dry scenario seem to be incoherent, therefore the so-called Global Dry; CSIRO-MK3.0, SRES A2 is taken as representative for the drier climate predictions.

Table 4-2 Increase in design values based on Climate Change up to 2050 compared to present precipitation

% - Change24 hour precipitation depth (mm) vs frequency (yrs), Average in Moz.							
mm/24hrs	1	2	5	10	20	50	100
Historical	0%	0%	0%	0%	0%	0%	0%
"Global Wet"; NCAR-CCSM, SRES A2	12%	18%	24%	27%	29%	31%	32%
"Global Dry"; CSIRO-MK3.0, SRES A2	19%	19%	19%	19%	19%	19%	19%
"Mozambique Wet"; IPSL, SRES B1	31%	33%	34%	35%	36%	36%	37%
"Mozambique Dry"; UKMO, SRES A2	NA	NA	NA	NA	NA	NA	NA

Source: See Table 2-6

Increased rain will have the largest impact on the road network of the expected climate changes. Increases in rain will have an impact on:

- Bridges
- Culverts
- Pavement design
- Slope stability
- Surface drainage
- Sea level rise

4.3.2 Bridges

Impact of climate change

The impact from increased rain will mean more frequent flooding in the rivers and streams. The increased flooding will mean an increase in scour, and increased risk that the hydraulic capacity of the bridge is exceeded.

The majority of bridges are designed to have a hydraulic capacity to withstand a 100 year storm for the future scenarios, but as mentioned before, there may be a big percentage of small and medium sized bridges that already have capacity issues for the current storms. The likelihood for these bridges is that the watershed they were designed for is in fact much larger than originally calculated. Our analyses of current bridge designs indicate that most of these bridges are built with a surplus of hydraulic capacity (see Chapter 2.4).

The available topographic maps, as well as hydrology data have become more accurate since the older bridges were constructed. For bridges that do not have sufficient hydraulic capacity, then there is likelihood that severe damage will occur, most likely in a bridge washout.

Hydraulic investigations are showing that the majority of the bridge structures should be able to withstand future 100 year storms, but experience has shown that this is not always the case. This leads one to believe that the failures are coming either from traffic overloading leading to structural failure from above, or bank or foundation failures due to scour and erosion leading to structural failures from below.

Site investigations have shown that it is not only the hydraulic capacity of the bridge structure that is critical, but also the scour protection for the embankments and footings. If a bridge is designed with scour protection to withstand a 100 year storm, how much protection will then be left after the large flood event? It is unlikely that it is economically feasible to build a bridge that will retain 100% of its scour protection after a large flood event. There is variability on when the most damaging scour events will happen, sometimes it may occur during a peak 100 year flood event, but often times these storms only lead to an increase in flows for a short time period. It may be that the most scour damage comes from higher frequency storms that lead to increased river velocities for a longer period of time. This is dependent on the geology and soil type of the river, as well as the type of bridge foundations used, and accurate results require further research.

Bridge design in the future should take into account the climate prediction models for precipitation as well as the increase in sedimentation due to erosion that is amplified by land use practices and season floods.

Table 4-3 New return period – 24 hour precipitation depth (mm) vs frequency (yrs), average in Mozambique)

Historical return period	1	2	5	10	20	50	100	Year
"Global Wet"; NCAR-CCSM, SRES A2	1	1	3	4	7	13	21	Year
"Global Dry"; CSIRO-MK3.0, SRES A2	1	1	3	5	8	18	32	Year
"Mozambique Wet"; IPSL, SRES B1	1	1	2	3	5	9	16	Year
"Mozambique Dry"; UKMO, SRES A2	NA	NA	NA	NA	NA	NA	NA	Year

Source: See Chapter 2.4

Table 4-3 shows the new return intervals for the different design storms with the new climate scenarios. Under the Mozambique Wet scenario, a storm that is today experienced with a rate of once every 100 years will in 2050 be experienced on average once every 16 years. This means that these current 100 year level design storms will be experienced with an increase in frequency of around 6 times. Discussions with local governments has revealed that storms that are estimated to be around the same levels of a 100 year storm have had devastating consequences to the road network. Although it cannot be said which frequency of design storms has the greatest scour impact, it can be said that the frequency of the storms that do have the greatest impact will increase.

For the Mozambique Wet scenario, it is expected that damaging scour events will increase with a similar increase as that of the increase in frequency of large storms, between 4 and 6 times bigger. It is difficult to estimate how many instances this is, but if a bridge is designed so that it will not require scour maintenance, or serious foundation repair for 20 years, under the Mozambique Wet scenario, maintenance or reconstruction would be required every 5 years.

Floods - the case of Zambezi

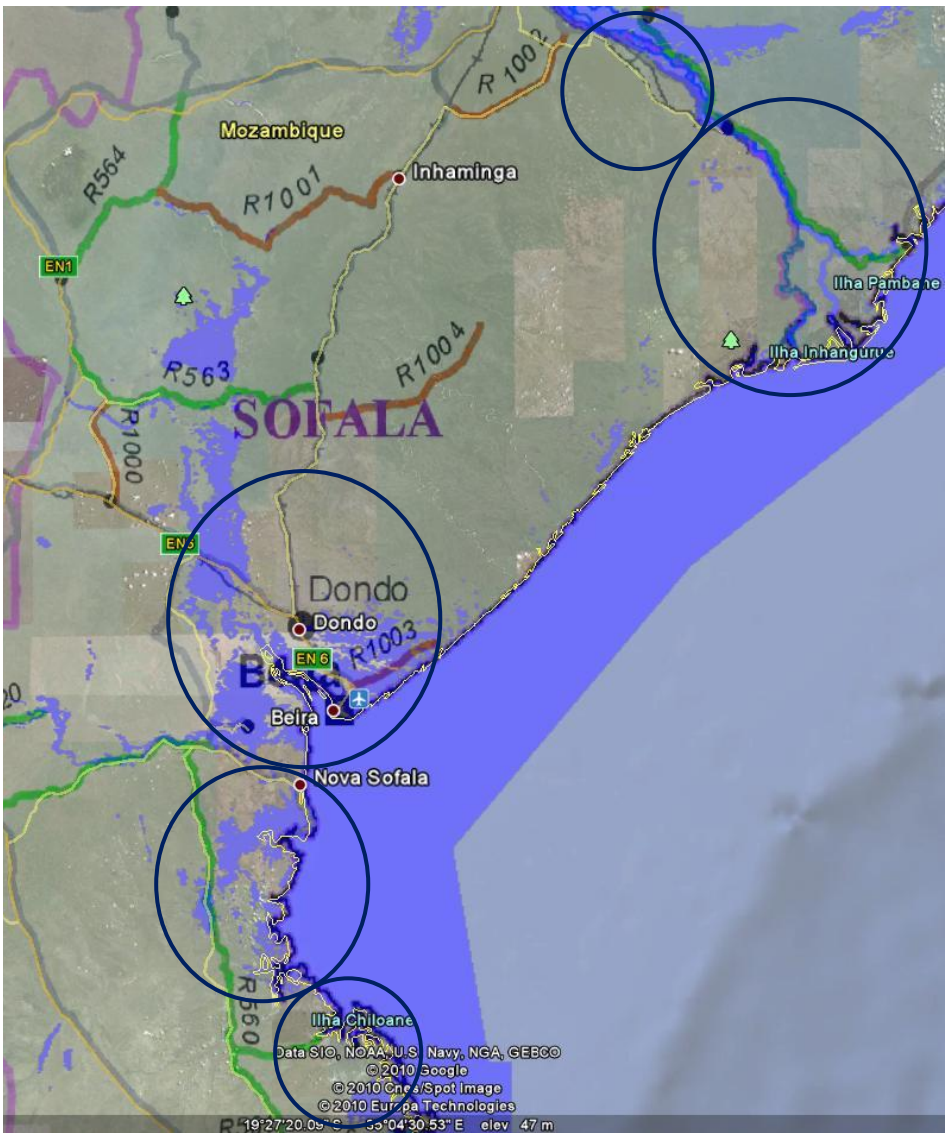
Two types of floods affect the Zambezi delta area. The first and most frequent type of floods is the seasonal flood. This occurs in most years normally in January or February. This is at the peak of the rainfall season. The second and not so frequent one is the cyclone-induced flood, which has become more frequent than before. Several times in the last years, relentless rain has waterlogged fields, destroyed fields and washed out roads and villages in the Zambezi delta area.

In February 2000 and March 2003 cyclones hit the basin bringing with it intense storms. Under these circumstances the most affected areas were towns or villages situated downstream of Cabora Basa or Kariba dams. Extraordinary storms increased the level of water in the dams to a certain level where the water needed to be released from the dams to avoid dam failures leading into floods downstream. In the years of 2000, and 2001, the Limpopo and Zambezi rivers experienced some of their highest floods on record. Return intervals for these storms are not available, but are estimated to be greater than 100 years by the ANE bridge department. This large number of floods has had catastrophic results on a number of roads and bridges. It is very difficult to get accurate

flows or return intervals of these flood events, as many of the monitoring gauges and stations needed were non-existent, or destroyed during the floods

Figure 4-1 shows the extension of the floods in November 2007. Central and South regions suffered the worst impact. The 2007 Mozambican flood began in late December 2006 when the Cahora Bassa Dam overflowed from heavy rains on Southern Africa. It worsened in February 2007 when the Zambezi River broke its banks, flooding the surrounding areas in Mozambique. The Chire and Rivubue rivers also flooded.

Figure 4-1 Primary and secondary roads affected by flooding events (2007)



Source: Google Earth, flooding maps provided by Dartmouth College.

Climate impact countermeasures

Mozambique has experienced a large number of catastrophic failures in the past few decades to their bridges. These failures are from a combination of some

very large floods as well as lack of maintenance and investments during the years of civil war. Detailed reasons for those failures need to be identified.

Wide area (multiple catchment) and severe floods are a major threat for the civil engineering structures in Mozambique, but are not the only reason for the high frequency of destruction or severe damage to bridges and other structures. The frequent failure of structures in Mozambique indicates that the hydrological specifications used by the designers might not be sufficiently conservative. A major problem facing Mozambique bridge design is the estimation of design flows, there is a wide band of uncertainty around all estimates of the flood magnitude-frequency relationship, combined with steep increases in flood magnitude with increase in return periods. In a recent design report done in 2009 for the upgrading of the Nampula-Cuamba Road, estimated design flows used for bridge construction were increased up to 10 times the value as that found in the preliminary report done in 2007. The largest changes came from different calculations of the watershed area. For the design report, access to more accurate maps was used showing a much larger watershed area than previously calculated. Another source of change was due to using different rainfall intensities. Because there are no standard rainfall intensity charts to use for Mozambique, it is up to the Consultant to locate and use the most accurate models they can find. The choice of rainfall data to use is often at the discretion of the Consultant. If the error in watershed area was not found in the design report, the return interval used for the bridge design would have been much less than the actual 100 year return interval.

These uncertainties cannot be satisfactorily accommodated in current design flood estimation procedures, therefore there is an urgent need for a new approach to the estimation of the design flood.

In order for accurate flow predictions to be made, accurate input data must be used. The accuracy of available topography maps should be checked before bridge designs are carried out. The assemblage of hydrological data such as: (IDF curves, Annual rainfall maps, etc.) is needed for Mozambique road design. The use of more standardized rainfall maps and charts will make it easier to design more functional drainage structures. It cannot be expected that every project in Mozambique warrants a large scale hydrologic study, so some better information is needed for the smaller budget projects.

Figure 4-2 Local bridge scour Wukro Agridat Zalambesa road (Ethiopia)

Source: Consultant

A common problem that is found throughout Mozambique's hydraulic structure designs is the use of reliable and accurate hydrology models. A new high standard bridge should be designed for a lifespan of 100 years. This includes the lifespan of the substructure and superstructure as well as the bridges interaction with the hydraulic channel. Estimating these values based on limited historical hydrological data can prove to be difficult because there is less than 100 years of accurate historical data available. Contributing to the error is the increases in debris and sedimentation due to increased erosion upstream.

During the initial bridge design, or design of a replacement bridge, the suitability of the location of the bridge should be thoroughly investigated. Placing a bridge in the midst of an alluvial fan or in an unstable flood plain whose channel is likely to move is not recommended. Investigations should be considered to find if it is more cost beneficial to move a large portion of road, so that the bridge is in a more stable environment.

Standing water on the deck is also an element that needs to be accounted for in the design phase.

Apart from inadequate funding, and hydrological analysis, one of the largest threats to bridges from an increase in precipitation is the increase in floods and associated scour and bank erosion. This issue is related to the use of structural design standards. Although scour may occur at any time, it is usually more significant during high flows when the water is swift and deep. The preferred me-

thod to deal with scour would be to account for it correctly in the design phase and implement sufficient countermeasures to handle the expected scour. Scour is a common problem with bridges around the world, and not just isolated to bridges in Mozambique. There is ongoing research on the best engineering methods to implement scour prevention. Potential scour can be a significant factor in the analysis of a stream crossing system, which should involve an acceptable balance between a waterway opening that will not suffer undue damage from scour and a crossing profile sufficiently high to provide the required traffic service.

Some preventive measures for scour are discussed in the draft of ANE's design standards, pointing out that anticipated depth of scour should be included in cases where foundations conditions are complicated.

The SATCC Standard regulates the maximum flow velocity for the prevention of scouring as follows. See Appendix for further explanation.

Scour potential is also analyzed according to TRH25 – (South African Guidelines for the Hydraulic design and Maintenance of River Crossings) . The soil cover for the piers and abutments are designed to prevent the erosion of the river bed. The protections for the erosion are recommended the suitable gabion and stone pitching.

Riprap is the most commonly applied material for protection of bridge piers against local scour. However riprap is not a permanent solution, as it is susceptible to being washed out after floods. Different methods of riprap placement can be used as scour protection. The easiest, cheapest and least effective is the placing of loose fill material (graded rock) around the piers and abutments. This is the most susceptible to being washed away during floods given the loose individual pieces. The preferred method is the use of riprap gabions. The gabion fencing keeps the riprap together as one unit giving it more weight and resilience to be being washed away during floods. A stronger more permanent solution should be investigated if it is found to be cost effective. In some locations, riprap may be unavailable, costly, or physically untenable for installation. There are alternatives to riprap as scour prevention methods around bridge piers such as the use of mats, grout bags, footings, or tetrapods.

As a new alternative countermeasure to riprap for scour protection around bridge piers, wire gabions were investigated experimentally for failure mechanisms, effects of significant parameters on failure and its sizing in a clear-water condition. The dominating failure mechanism was found to be a shear failure. Based on the experimental data, the controlling factors for the stability of wire gabions as a scour countermeasure at the pier are flow depth relative to pier diameter, length to thickness ratio, coverage, alignment and placement depth of wire gabions. An equation for sizing of a wire gabion is proposed in terms of Froude number and factors reflecting both the effect and limit of significant parameters. Comparison of the equation with those of ripraps shows that smaller wire gabions than ripraps provide an equivalent protection implying cost effective and improved stability.

Regular maintenance before the rainy season and after high water events is required to ensure that there is still some protection left around the bridge substructure. A lapse in scour maintenance between high water events may be enough to permanently damage the bridge.

Increased protection should be ensured along the banks upstream and downstream of the bridge. Large scale bank erosion can work its way towards the bridge abutments from a far distance. If the banks become unstable, the stability of the abutments is compromised and the superstructure becomes in danger. A potential method of bank stabilization is the use of coir fabric, or other bio-engineering methods. These methods have been proven to be effective in re-establishing bank vegetation and stabilization, although may be ineffective in drought prone areas.

In areas with unstable flood plains, there needs to be an increase in upstream river training to ensure that the channel is directed under the bridge span, and not allowed to meander or braid into different paths. This potentially requires large scale river training, through the use of bio-engineered bank stabilization, gabions, or other suitable methods. River training using these methods is only expected to last 4-5 years, and their maintenance and repair is critical to allow them to direct the river correctly.

Figure 4-3 Large scale river works effort using rock gabions Mekele-Adwa (Ethiopia)

Source: Consultant

In areas where there are multiple channels, such as alluvial fans, it may be cost beneficial to raise the road embankment and use a series of culverts, rather than invest in a limited number of large bridges. The culverts will be cheaper to replace if washed out, and a high number of culverts will help alleviate the flooding problem if the main channel changes course, or if the flood plain experiences sever flooding.

Another consequence of floods will be the sediment deposits left behind near the bridges. This deposit will also need to be removed to ensure the hydraulic capacity of the channel. The ANE guidelines in the National Roads Strategy propose a return period appropriate to the design discharge. The return periods for major transversal structures are basically proposed to be selected in the following way:

Table 4-4 Design return period for crossing structure

Flood Discharge	Recurrence Interval (yrs)
20 $m^3/s > Q$	20
20 $m^3/s < Q < 250$ m^3/s	50
$Q > 250$ m^3/s	100

Source: ANE

Regarding flood clearance ANE applies TRH25 – Guidelines for the Hydraulic Design and Maintenance of River Crossings. As a result, the bridges are designed 1.0 m freeboard below the bridge soffit for 100-year flood.

The flood action on the bridge elements are calculated according to section 3.9 of SATCC. The action of flowing water on bridge structures over rivers or estuaries shall be derived in accordance with the principles of modern theory of hydraulics based on the best data available for the site. The design flood shall be determined in consultation with the responsible authority preferably based on sensitivity studies and risk analysis and the partial load factors.

As previously mentioned, according to the hydraulic study carried out for the Study of Upgrading Nampula-Cuamba Road, 6 of the existing 37 bridges linking the road should be reconstructed as new bridges due to inadequate river crossing capacity, and other 14 small bridges should be replaced by box culverts due to inadequate road width.

4-4 Lurio bridge in Mozambique

4-5 Nomola bridge in Mozambique

Source: Final Report November 2007; The Study on Upgrading of Nampula – Cuamba Road in the Republic of Mozambique (Japan International Cooperation Agency).

Increased rainfall would increase river flow and therefore river capacity problems for smooth discharge as well as increase in HWL (High Water Level). If for that study and under current climate effects, in 7 out of 37 bridges the bridge deck level needs to be raised by heights that vary from 1.416m to 4.846m, it is very likely that the amount of bridges with insufficient crossing capacity will rise rapidly.

A well designed bridge will still require maintenance to meet its 50 to100 year design life. With an increase in precipitation, it can be expected that the maintenance required will also need to be increased. It would be nearly impossible from an economic point of view to design and build a bridge to be able to withstand 100 years of flooding events without maintenance. The current Strategic Plan in Mozambique warrants having rigorous maintenance which will need to be kept and likely improve in order to cope with the severe increases in precipitation. With an increase in precipitation, the most vital factor for bridges survival is maintenance. Any future Strategic Maintenance Program will have to be flexible and robust, otherwise there is little chance that these bridges will meet their design lives under the future climate scenarios.

Summary

The success of the bridge is dependent on its hydraulic capacity, the stability of the channel and its interaction with the bridge substructure. Bridge design needs to take into account the increased flows expected as well as the increase of sedimentation. It is recommended to review the design standards for river and stream crossing as well as drainage including increases in high intensity rainfall and potential future floods hazard. Designs with more culverts may reduce the risk of creating "dam effects" of roads across riverbeds.

Upstream river training is needed in unstable flood plains where the river has the opportunity to change its course. The suitability of the bridges location for future flows needs to be considered.

There needs to be a greater investment into scour protection during initial construction. Maintenance needs to be increased in not only the protection of the substructure from scour, but also ensuring the hydraulic capacity of the channel by removal of sediment and debris. If maintenance cannot be assured, then it is

recommended to invest in more permanent bank and scour protection, or design bridges with larger capacity to handle the sedimentation.

Information from previous bridge failures and collapses due to floods should be used to ensure permanent control measures and facilities should be used for scour protection of all disturbed areas ensuring that the bearing capacity is met under any conditions that the bridge was design for.

As recommended in TRH25 – Guidelines for the Hydraulic design and Maintenance of River Crossings-, improved theoretical models for the prediction of floods magnitudes and probability of these floods should be used to re-assess the risk on strategically important existing structures so that preventive measures can be taken in good time. Models should be updated with latest forecasts from climate change scenarios data.

The selection of the return period for bridge or culvert design has a large impact on the size of the structures. The adoption of a higher return period would decrease the probability of flooding on the road, damages to the road and other facilities as well as result in a more reliable road connection for the road users. However, this could also cause a substantial increase in the initial capital and future maintenance costs.

It is highly recommended to increase efforts for creating a reliable bridge inventory with the most relevant information collected by on site investigations, historical records, topographical surveys and interviews to local people living nearby the bridges. It would be beneficial to incorporate flood record information including the flood HWL.

4.3.3 Culverts

Impact of climate change

Some of the factors that usually influence blockage of culverts are size, material type, land use, stream slope, catchment area, number of culverts upstream and blockage of upstream culverts. Especially important factors are the size and stream slope. Generally culverts placed in locations with steep stream slope tend to have more blockages due to the greater ability of steep streams to mobilize debris, and the more mobile nature of the debris type (sediment and vegetation) in the upper parts of the catchments.

Experience has shown that increasing only the culvert size will not automatically make for a more climate resilient culvert. If the culvert capacity is large enough to handle the expected increase in flows, but still fails, then it can be concluded that the failure is coming from another factor such as insufficient inlet control, outlet control, lack of maintenance, underestimation of rainfall runoff, or a combination of all these factors. Like bridges, many of the culvert failures that are experienced are directly related to scour events. If the inlet or outlet control is not designed to handle scour correctly, the culvert itself will be undermined leading to failure of the both the culvert and the roadway section.

Earth drains tend to fail due to accumulated earth and soil and eroded road surfaces. These problems are particularly notable on sections with steep gradient, in “cut and fill” and those that are lower than the surrounding ground level. On such sections, an appropriate drainage system should be designed. Furthermore, drainage structures should be connected and discharged through suitable and regular outlets.

According to ANE´s design standards, the internal channel maximum slope depends on the material and the ratio Hw:D varies from 1:1 to the maximum 1:3. If the inlet or outlet control is not designed to handle scour correctly, the culvert itself will be undermined leading to failure of the both the culvert and the roadway section. With a Hw:D >1, ponding of water can be expected at the inlet. A larger Hw:D ratio will lead to deeper ponding at the culvert inlet increasing the chance for erosion around the roadway structure. More ponding at the inlet will also increase the velocities of the water coming out of the culvert increasing the scour potential on the downstream side of the roadway section. A culvert with inlet control that has a Hw:D ratio of 1.3 will have a much higher capacity than a culvert with a Hw:D ratio of 1, however if the inlet or outlet control is not designed to handle the increased velocities from the higher flows, then failure is likely to occur. Scour damages are expected to increase in similar ratios to those that are experienced by bridges, 400-650% for the Mozambique Wet scenario, and 200-350% for the Global Dry scenario.

The Consultant did not have access to any culvert´s data base, therefore a detailed analysis could not be assessed. However, it is very likely that with the scenarios used for this study Mozambique’s culvert system would be stressed by increase precipitation.

Climate impact countermeasures

Maintenance is one of the most important aspects of a well functioning culvert. The investment in culverts will not be met if they are allowed to fill with debris reducing hydraulic capacity. Maintenance needs to be increased on culverts before the rainy season ensuring that the culverts will have clear conduits. This can be difficult on smaller culverts where access is limited.

Culverts have the potential to be blocked very quickly; maintenance before and during the rainy season is required to clean out accumulated debris. Currently, the minimum size culvert allowed is 600 mm diameter for gradient > 2% and 900mm for gradient < 2%. If experience shows that this sizing is too small to allow routine labor based maintenance, it may be necessary to increase minimum sizing to 900 mm diameter.

Culverts should be designed and constructed so that in case of a flood, the least amount of damage to the road and the surrounding landscape occurs. As shown in Table 3-6 reinforced culverts are not designed to have capacity for large scale floods greater than 30 year return interval, but they should be designed so that the road they are covered by is not washed out during large floods. For the Global Dry scenario, the 50 years return period would become the 18 years return period, and the 20 years return period would become the 8 years return period. For the Wet Mozambique scenario, the 50 years return period would be-

come the 9 years return period, and the 5 years return period would become the 8 years return period. The easiest approach is to cope with increased flow would be to increase the culvert size, or raise the road embankment, but this may not be economically feasible and experience has shown that it will not automatically make a culvert climate resilient. Culvert sizes should be increased in areas where the potential for damage is greatest, such as in areas with large fills and high risk of floods. These are the areas with the greatest potential for damage from floods, because the flood water has no escape, and will erode the road section until it can pass through to the other side. The investment and design in culvert sizing should take into account the cost of potential failure.

Where a culvert is not sized to handle large floods, there needs to be insurance that the flood waters are able to easily overtop the road near the culvert and re-enter the stream on the other side of the road causing only local damage to the road fill. Preferably the culvert should be at a low point in the vertical profile of the road ensuring all flood water is directed back into the channel, and not allowed to run down the drainage ditches. The culvert needs to be placed near a low point of a sag curve with the top of the culvert headwall equal to the top of the road in nearby location.

Figure 4-6 Eroded culvert outlet protection Mekele-Adwa km 39+038, Ethiopia

Source: Consultant

For low class roads, a drainage swale should be included that runs across the road to direct the flow back into its original channel. This method keeps flood water in the original channel if the capacity of the culvert is exceeded, which is a likely occurrence if using only a 5 year design storm for pipe culverts as required for pipe culverts and low road class. A drainage swale is only suitable where it is acceptable to have a speed barrier. It is most suitable for low class roads. There is difficulty in using this method on a high speed road, making it

more critical to use a sufficiently sized culvert on the high speed roads. Although this does not prevent damage to the road, it keeps the damage localized rather than allowing the flows to travel alongside the roadways as seen in Figure 4-7.

The investment in culverts will not be met if they are allowed to fill with debris reducing hydraulic capacity. Maintenance needs to be increased on culverts before the rainy season ensuring that the culverts will have clear conduits. This can be difficult on smaller culverts where access is limited.

Figure 4-7 Diversion potential through gravel road Mekele-Adwa km 165+946, Ethiopia

Source: Consultant

Debris at the culvert will attract more debris and sediment increasing the rate of plugging of the culvert. In remote areas where maintenance is limited, or in places that are hard to reach, culverts should be oversized and provided with appropriated gradient to allow for hydraulic capacity and to prevent silting up.

Figure 4-8 Road shoulder erosion caused from overtopping culvert, Tanzania Ethiopia

Source: Consultant

According to the Road Sector Strategy, when applied to maintenance planning and investment prioritization, transitability requires flexibility in addressing designs and interventions may not be uniform over the length of the road. Transitability maintenance interventions may call for localized repairs and spot improvements such as the construction of culverts or other drainage structures.
It is recommended to make a more thorough analysis of the current situation of the culverts of the road network and establish a more detailed plan for interventions in order to monitor and maintain the culvert system. It would be beneficial to budget an inspection plan for scour in culverts.

Figure 4-9 Increased culvert outlet protection Mekele-Adwa km 68+722, Ethiopia

Source: Consultant

Summary
Culvert design needs to take into account expected increases in rain and design storms as well as the increases in precipitation. Culverts should be designed so that in a flood, there is limited damage to the road and limited erosion to the surrounding area. Culvert entrances need to be designed as an extension of the natural channel. More outfall protection will be required on the downstream side of culverts. Higher flows will increase the potential for downstream scour and erosion. Culvert sizing should be designed taking into account the cost to repair a failure. Maintenance needs to be increased for all culverts especially in high risk areas. It is recommended that culvert design use revised rainfall charts based on the predicted climate models and it would be beneficial the creation of a drainage risk mapping with existing and expected data from floods and droughts. Problems with some type of pipes especially in coastal regions should be made known to prevent maintenance problems due to rusting of materials or collapse.

According to the Road Sector Strategy (RSS) 2007 – 2011, the significant maintenance problems that erosion causes can and should be reduced through proper design and planning. The life of many roads is reduced because they are located at the same or even lower level as the surrounding ground. The raising of the road surface should always be considered during design.

4.3.4 Pavement design

Impact of climate change
All of the climate scenarios are showing significant increases in precipitation. It is difficult to quantify the difference in impact the different scenarios will

have, as many of the impacts of rain are dependent on the design and amount of maintenance performed.

The Mozambique Wet scenario is showing large increases in the intensity of storms and overall yearly rainfall, while the Global Dry scenario is showing increases to a lesser degree but still high compared to the current climate conditions. The largest impacts come from; loss of gravel, or other wearing courses and saturation of the base materials either through the surface, or from below. See Appendix for further explanation of impacts of rain on pavement design.

Pavement design encompasses all the materials that comprise of the road that vehicles drive on. Rain will affect all parts of the road section, namely the subgrade, capping layers, sub base layers, and wearing course, whether it be gravel, paved, or an earth surface.

Figure 4-10 Damaged road by flooding in Mopeia, in the Zambezi River basin in Mozambique

Source: USAID (Photo by Tresja Denysenko)

Design of pavement structures is based on the methods given by the "SATCC Practice for the Design of Road Pavements". In addition to the SATCC standard, other design methods such as "Road Notes 31" and "TRH4 of the South Africa" could also be considered.

Climate impact countermeasures

(1) Subgrade

With an increase in precipitation, it can be expected there will be a rise in groundwater levels and soil moisture. It follows that the number of sites with expansive and other problem soils that are detrimentally affected by high moisture content will increase. There is mitigation measures covered in SATCC design manual, 2003. The need to use these mitigation measures will increase as the soil moisture content increases.

One of the key mitigations is to avoid these soils in the first place, but often due to other constraints, this is impossible. There is likelihood that in low-lying areas or areas near rivers or streams the water table will rise. It is worth investigating where an increase in water table in the future is likely to affect the structural strength of the soils in the roadway alignment. 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 that would need to be removed in order to reach it.

The use of geo-textiles and geo-net is briefly discussed in other design manuals from the African region. These are currently an expensive solution to problem soils, however, they have proven to be successful in many applications, and their use may be deemed warranted with increases in precipitation and water table levels.

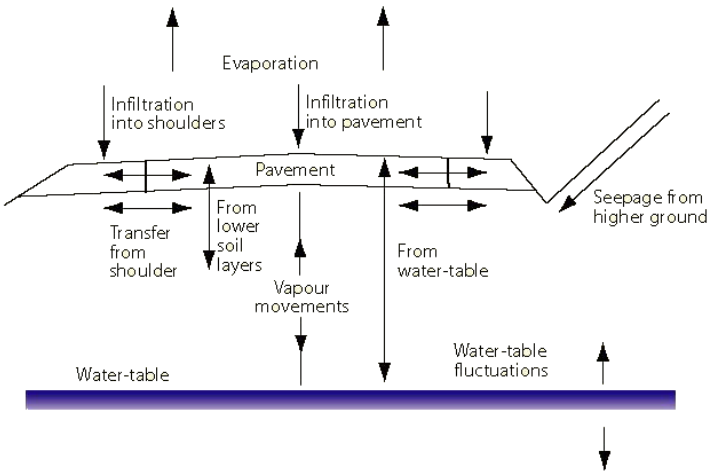
The use of chemical stabilizers has been proven to be an effective mode at strengthening the subgrade materials which helps to maintain the paving investment. Their initial cost is less than having to repair a paved road section later on. The use of stabilizers is discussed in the SATCC design manuals.

It is recommended to always use a 4 day soaked CBR test for the testing of subgrade materials. It is currently practice in Mozambique that it is at the engineer's discretion to classify the environment and the subsequently CBR test procedure for design CBR. The CBR testing requirements and design parameters is divided in three categories: Wet (use of 4 days soaked CBR), Medium (no use of soaked CBR), Dry (no use of soaked CBR, and dried back CBR value to in-situ conditions used for design). Thus the 4 day soaked test is not required in areas that currently do not have high water tables or flooding problems. Using a 4 day soaked CBR test will give some increased insurance in case the water tables do rise or more moisture is encountered in the future.

Raising the road surface using a capping layer can be a cost effective method of raising the roadway out of flood prone areas, or areas with high water tables. Raising the road also helps promote positive drainage away from the road surface.

High levels of saturation (80% – 100%) could cause distress which will usually result from pore pressure effects under wheel loads and mobilization of plasticity in the fine fractions. To avoid this saturation in wet areas where high levels of saturation is likely to occur, use of low permeability selected lower sub-base and sealed shoulders could be used to protect the subgrade from moisture movements.

4-11 Moisture movements in pavements and subgrades (NAASRA,1987)



Source: SATCC

Increases in precipitation and soil measure is expected to require additional use of the following construction techniques:

- Increased subsurface drainage
- Geo-textiles and Geo-net
- Increased use of chemical stabilizers
- Use of 4 day soaked CBR test
- Raise road using capping layer
- Sealing shoulders

(2) Sub-base and unbound base layers

There are technical methods discussed in the SATCC design manuals in keeping the sub-base layers within their optimum moisture content. An important factor in maintaining the paved wearing course is to insure a waterproof layer preventing water from infiltrating into the base layers. This requires routine maintenance patching, repairing cracking, repairing potholes, etc. There is also a need to maintain internal drainage of the layers. Water must be allowed to freely move through the section and exit into a well functioning surface drainage system.

When permeable base materials are used particular attention must be given to the drainage of the sub-base layer. Ideally, the base and subbase should extend right across the shoulders to the drainage ditches. Under no circumstances

should a 'trench' type of cross-section be used in which the pavement layers are confined between continuous impervious shoulders.

If the water table is high, raising the road level with the use of large amounts of capping material may be necessary to move the section above poor draining soils and ensure a well draining section.

In order to maintain functioning sub base layers with increased precipitation, there is a need for:

- Increased maintenance
- Raising road elevation
- Securing drainage (i.e. digging out a ditch and filling it in with high permeable material through shoulder)

(3) Wearing course

Regardless of the wearing course that is used on the road, the key elements to ensure climate resilient roads are adequate drainage, strong subgrade, and proper maintenance.

(a) Paved surface

Increase in precipitation will require an increase in pavement maintenance and repair. It is inevitable that some water penetrates the lower levels. The more water that infiltrates the sub base layers, the greater the chance of damage to the paved surface. Routine maintenance sealing, patching cracks, is essential, preferably in the dry seasons to prepare the surfaces for the upcoming rainy seasons. Improved paving or sealing of the shoulders is discussed in the SATCC design manuals and in the Road Strategic Plan and will help in maintaining dry base layers. Improved strength of the shoulders may also help in maintaining the paved road. Shoulders are often used as an extension of the road by overloaded vehicles, but are usually only designed to withstand minor loadings. Overloading of the shoulders leads to asphalt edge breaking, which will increase the rate of infiltration of water into the sub base and subgrade layers. A method helping to increase the waterproofing properties of the paved surface being used in Tanzania is to place a layer of geo-textile on top of the sub base materials before paving. This aids in waterproofing the lower sub base layers.

The paved surface is the final step in the road. In order to maintain the paving investment, there must be a well functioning subgrade, sufficient drainage, and routine maintenance.

The following list may be needed in areas that experience higher than normal rainfall amounts:

- Increased maintenance
- Geo-textiles
- Increase in shoulder design strength
- Improved drainage

When a pavement is nearing the end of its design life or has been prematurely damaged, it is usually to strengthen it by adding an overlay. Strengthening is not discussed, neither in the SATCC guide nor in the Road Note 31, however it is straightforward to use the guide for design of overlays on existing pavements.

(b) Gravel Surface

Extensive research in Vietnam (RRGAP) has shown that unbound gravel surfaces should not be used in areas with high gradients or high precipitation due to the levels of gravel loss. Gravel surfaces can also be harmful to health in very dry areas due to high levels of dust. The current practice in Cambodia, Laos, and Vietnam, countries with high precipitation and hilly terrain is to move away from using gravel as a wearing course and in stead to use materials that are locally available in plentiful supplies, or upgrade to sealed roads. In these countries, the maintenance required and amount of quality material has not been able to be supplied in sufficient quantities. Large areas of Mozambique suffer of the same lack of sufficient gravel material, but in local areas where gravel is available, road usage is low and the roads are regularly maintained, gravel roads could be a possible and good design solution.

In areas where gravel roads are suitable, those with lower gradients, less rainfall, and suitable amounts of available gravel for maintenance, a climate resilient gravel surfaced road needs to meet similar requirements as a paved road to meet its design life. It must have a well functioning subgrade, sufficient drainage, and routine maintenance.

During the rainy season, many roads suffer from erosion by heavy rainfall and uncontrolled surface run off. The erosion makes driving conditions difficult. The erosion issue is a result of various problems such as the road being lower than the surrounding area, steep gradients, improper or defected drainage, and the use of road materials with high Plasticity Index (PI)..In addition, during the dry season, the road surface is corrugated as a result of substandard material characteristics and car driving forces. Driving on corrugated road is very uncomfortable for drivers and passengers. Longitudinal drainage should be installed in all sloping sections with cutting, velocities should be properly assessed for the given gradients, raising profile for the road should be considered as well as the choice of materials for both the road and the drainage.

In areas where earth roads are suitable, gravel loss must be replaced before the depth is too low to act as protection for the underlying layers. If the thickness of gravel wearing course is allowed to be less than 50 - 100 mm (according to ANE´s standards for subgrade CBR>5% and road category III and IV), the gravel pavement ceases to function, no longer offering protection to the base materials and subgrade below, and the road becomes at risk of serious degrading requiring reconstruction. Gravel roads are estimated to need re-gravelling at least every 5 years, and are dependent on a plentiful source of quality material.

According to ANE´s standards, the Structural Design Period of Unpaved Roads will be dictated by the quality of the material to be used, the traffic and the road

category. If erodible materials are to be used (no funds for cement or bitumen treatment or for transporting material of a better quality), a shorter structural design period should be adopted, resulting in a higher rehabilitation (reworking, regravelling and compaction) frequency. Gravel roads are estimated to need re-gravelling at least every 5 years, and are dependent on a plentiful source of quality material. In the RSS periodic maintenance for unpaved roads is planned every five years, while rehabilitation is schedule every eight years.

In ANE´s standards the minimum thickness "t" is as defined in the Draft TRH20:1999 as the first term of the following equation:

$$T = t + (1 + Ct/100) \times (GLp \times Ld)$$

where,

t	=	minimum thickness required for subgrade protection (mm),
Ct	=	traffic induced compaction,
GLp	=	predicted annual gravel loss (mm)
Ld	=	design life of road or regravelling frequency (years)

The terms Ld and GLp in the equation will be directly influenced by the increase of rainfall. The amount of gravel lost in an unpaved road is very dependent on the slope and the materials of the road, therefore needs to be locally addressed because each road has its own features, but regardless of the details depending on the characteristics of each road, increases in precipitation will lead to increases in gravel loss.

The type of material used as wearing course will influence the annual material loss and may result inadequate for the design period chosen. If sandy material is used and the material loss due to rainfall, traffic or wind is expected to be high, the sandy material to be used in the wearing course has to be treated with bituminous products (prime coat, emulsion) or cement (50 mm depth minimum). The butter-slopes shall be protected with cohesive materials where possible and grassed.

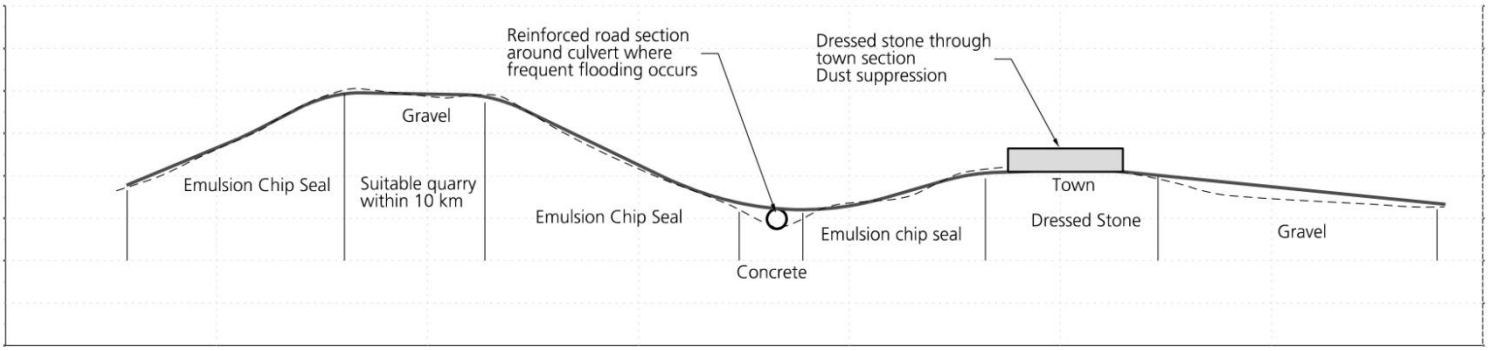
In areas with higher precipitation and/or gradients, alternative methods of road construction should be used. This includes paving, stabilization, and the use of sealants as improvements in the areas most likely to be damaged. Spot improvements include updating the drainage, sealing or stabilizing the road with cement or lime only in certain sections of the road. The use of spot improvements allows the total cost of the road to be kept lower, while still giving increased protection in key areas.

Where it is decided to upgrade a gravel road to a sealed road, no sealing investment will be met unless the road system as a whole is in good working order. This requires a strong subgrade, good drainage, and maintenance.

A lower budget climate resilient road that is not completely paved should consist of different wearing course materials, depending on the vehicle loading, terrain, climate, and availability of materials both for construction and mainten-

ance. A typical stretch of road could consist of: a gravel wearing course stretch in flatter areas with lower precipitation, an emulsion sealed section in areas with higher gradients and more precipitation, reinforced concrete around drainage structures where flooding can be expected.

Figure 4-12 Climate resilient gravel road



Source: Consultant

An increase in rain will most likely require an increase in the following:

- Increased maintenance
- Increased frequency of re-gravelling
- Use of alternative materials and sealing options
- Spot Improvements
- Improved drainage

(c) Earth surfaces

In high precipitation areas, or those with high gradients, community earth surfaced roads are a prime candidate for using the alternative paving methods and spot improvements. Community roads have a narrower carriageway making them more suitable to methods such as cobble stones or engineered bricks. An engineered earth surface can be suitable with proper materials and adequate drainage, if the terrain allows it. The most critical factor of an engineered surface is draining the surface and underlying materials quickly. Soils lose their bearing capacity when saturated, and can be quickly destroyed by loaded vehicles if they are not drained rapidly.

In steeper areas, some sort of paving method is needed to ensure accessibility during the rainy season. A cost effective mode of paving for community roads is to only pave the wheel tracks. Increases in precipitation will require an increase in maintenance as well as more investment into the subgrade to ensure a strong foundation year round.

Like a climate resilient gravel road, a climate resilient earth surfaced road will be constructed of different elements depending on the terrain and high risk areas. A community road could consist of an engineered earth surface with proper drainage along flatter areas or ridges, concrete paved wheel tracks in the steeper gradients, heavily stoned reinforcements around drainage structures, and cobble stoning through the town areas.

Figure 4-13 Poorly draining earth surface road, Uganda

Source: Consultant

All of these methods for a community or lower standard gravel road can be built using labor-based methods. If the roads are built using labor-based methods, then it follows that they should be able to be maintained using labor-based methods. An adherence to guidelines as well as the following list will help to improve the likelihood of success for a community road.

- Increased maintenance
- Engineered earth surfaces
- Alternative materials
- Increased drainage

Summary

The conditions of unpaved roads are fairly good in dry season, however, in rainy season, they significantly deteriorate by heavy rains. Road surface erosion is frequently observed which causes problems to traffic. Maintenance plays a vital role for securing a smooth traffic flow. Increased gravel loss due to in-

creased in precipitation and suitability of materials should be determinant factors for choosing wearing course structures.

The design requirements for the new paved roads are on a high level. The problems seen today in the national network roads are the result of a combination of different factors such as lack of maintenance, poor drainage, and design that cannot accommodate the overloaded traffic.

Where plentiful supplies of gravel are not available, alternatives for gravel wearing course should begin to be used. Gravel is not a sustainable material and the maintenance required is frequent and expensive. Spot improvements should be used around areas that are likely to fail. Non-paved road design should be designed in smaller length increments using a variety of materials depending on which is most suitable depending on climate, topography, and availability. More effort should be spent on investigation on the subgrade materials for community roads, as well as drainage of the road section. Maintenance becomes critical with increased rain, paved roads would then be a cheaper and better long term solution for a greater specter of roads, also low traffic roads, because of the relatively cheap (and possibly labor-based) maintenance, compared to the expensive maintenance required by gravel roads. It is recommended to introduce risk assessment and life cycle cost reports into the selection of pavement type.

The design life of a road can have a large impact on the design specifications of its pavement structure and it is therefore important to decide on an appropriate period. Usually, a 10-, 15-, or 20-year period is adopted, with the selection of an appropriate design life being dependent on the unique circumstances of the individual project. Availability of reliable traffic data is a problem because of lack of historical record, which can create significant errors when forecasting long-term traffic demands. This last issue and the significant changes in precipitation should be taken into consideration for the decision of the design life of a road.

4.3.5 Slope stability

Impact of climate change

Research has shown that heavy amounts of rainfall increases the likelihood of landslides. All climate scenarios are showing increases in heavy rainfall events. Roads located in coastal areas close to the shore will be significantly affected by erosion due to sea level rise.

There is high likelihood that the large increases in rainfall seen in the Mozambique Wet scenario will have severe consequences for landslides and erosion. The frequency of large storms is expected to increase over 600%. There is not available data on landslides in Mozambique to accurately predict the increase in slide activities but it is very likely that areas which are now slide prone will experience slides more often with the future scenarios. The increase in slide activity holds true for the Global Dry scenario to a lesser degree.

Unstable geology, new road construction, and or poor land use leading to deforestation will all amplify the negative impacts of the increased rainfall and sea level rise on slope stability.

Figure 4-14 Small slip landslide Mekele-Abi Adi-Adwa km 115+800, Ethiopia

Source: Consultant

Climate impact countermeasures

Topographically the backbone of the country is the mountain chain which forms the eastern escarpment of the continental plateau. It does not present a uniformly abrupt descent to the plains, but in places, as in the lower Zambezi district, slopes gradually to the coast. It is, however, only along the Zambezi and north of that river that Mozambique's territory reaches to the continental plateau. The plateau lands west of the escarpment are of moderate elevation - perhaps averaging 610 to 762 m.

It is usually not cost-beneficial or technically possible to build a road in a mountainous region that is not affected by slope failures. Even though there are mountainous areas in Mozambique, the vast majority of the country is fairly flat. Damage to the road should be expected from slope failures in geologically unstable areas and in roads located too close to the shore that can be affected by sea level rise. There are best practices during construction and remediation that can help to minimize the occurrence of slope failure. There are slope stabilization techniques that can be used to aid in stopping deep landslide movements, and slope protection techniques that can be used to limit slope erosion and shallow slope failures less than 0.5m.

Slope failures should be viewed as a consequence to road construction in unstable locations. Landslide incidents may increase with greater precipitation and bigger impact of sea level rise. Areas that are suitable now are suitable for road construction, might need additional retaining walls if it became unstable due to the changes in precipitation, or areas that today are still far away from the shore might be overtaken by the water in some years, therefore the suitability of the location of the road plays a determinant role for the slope stability factor.

The level of slope stabilization used should be based on how critical the road is and the rate of road damage that is acceptable. The road should be designed so that it can be built and maintained at an acceptable cost. There is no data for the costs of maintenance related to landslide damages for Mozambique, but for Ethiopia they were found to be costs of maintenance of landslide damages in unstable areas have been found to be in the long term, comparable to 10% of the costs of construction. For Mozambique these costs should be expected to be lower due to the flatter topography of the country. The costs of repair works become proportionately higher depending on the design standard of the road; however, high design standards do not necessarily insure that the risk of slope failures is lessened. In very unstable areas where frequent damages occur, it is advisable to design a lower standard of road. A lower standard road will be both cheaper to build and cheaper to repair and maintain when slope failures take place.

Figure 4-15 Rockfall protection retaining wall Mekele-Abi Adi-Adwa km 52+3, Ethiopia

Source: Consultant

The cost spent on slope failure preventions should be proportionate to the effort spent investigating the site. There is a risk that high investment slope stabiliza-

tion projects will not be the correct solution if the required geo-technical information is not known beforehand. If geo-technical investigations find high probability of a significant deep seated landslide, the costs of preventing it is most likely not cost effective, and a new alignment should be investigated. Along new trunk alignments and higher class roads, a more intensive geo-technical investigation is needed in order to quantify the likelihood of slope failures, as the investment and repair of these roads is very high. If the likelihood of the cost of maintaining this road due to slope failures becomes too high, an alternative alignment, or a lower level of standard should be considered. The cost of an intensive geotechnical investigation is maybe not cost effective on the lower class roads, and using current techniques covered in SATCC design manuals to estimate the stability of the landscape is sufficient.
Slope stabilization can be a costly investment with limited benefits depending on the geology of the area. At a minimum, proper drainage of the slopes should be provided. Drainage of the slopes is covered briefly in the manuals. Drainage measures have been shown to lessen the movement of slopes when they work correctly; however, if they are allowed to deteriorate due to natural causes, bad design or lack of maintenance, their presence can accelerate the slope movement. Their use and installation should be done with care.

Toe-retaining structures are a common form of stabilization of soil slopes. Their success depends on adequacy, design, construction, and drainage. With any retaining wall system, proper drainage must be provided. On above road cut slopes, the use of toe retaining structures should be based on their long term maintenance savings. Based on the likelihood of slope failures and the associated costs to repair them, the capital investment could be spent better elsewhere in areas like drainage improvements. Toe-retaining structures on below road slopes are a different matter. The damage to the road from a below road slope failure is typically much greater and more expensive to repair than an above road failure.

Below road failures can be minimized using some best practices such as not dumping spoils onto already heavily loaded slopes. The excess weight of the soil can increase the likelihood of slope failures. Proper drainage of shoulders will slow down the rate of erosion of the slopes below. Increased scour protection along floodplains or rivers may be needed to provide slope stability. Preventing the toe of the slope from being undercut is crucial in maintaining the road section.

Figure 4-16 Gabions used as bank protection Mekele-Abi Adi- Adwa km 83, Ethiopia

Source: Consultant

Toe-retaining structures can be built from a variety of different materials and the selection should be chosen based on the cost, factor of safety required, and availability of materials. Low cost slope stabilization methods being trialed in Lao PDR include bio-engineered retaining walls, masonry and brick retaining walls, and hand-applied reinforced concrete surfacing.

Slope protection measures which aid in lessening the rate of erosion are a worthwhile investment that lessen the amount of maintenance and repair later on. Bio-engineering is one of the most cost efficient methods of slope protection. Some form of vegetation should be used on all roadway slopes that will accept plant growth. The vegetation helps to root the soil, preventing excess erosion that will later need to be removed from the drainage system. Eucalyptus trees were planted in some coast strips in Mozambique to fight erosion due to sea level rise, but in most cases they were swept by the water.

On roads built in flood plains, there needs to be more effort on bank stabilization projects. The photo of the bank erosion on an Ethiopian road in Dire Dawa, Figure 4-17 shows the results of a large flood with high erosive forces. The bank stabilization required to prevent this would be a large investment, most likely requiring retaining walls either constructed of gabions as seen in Figure 4-16 or concrete retaining walls. Maputo City is bordered by an extensive slope which separates the upper part of the town (up to 60 m height) from the downtown area (almost at sea level). Slope instability plays a significant role

throughout the city problems reported on roads, buildings and other infrastructures.

Figure 4-17 Roadside erosion Dire Dawa Region

Source: ERA Network Management

On the trunk road shown in Figure 4-18 from aerial photo investigations it is found that over 2 km of bank protection would be needed to prevent this type of road destruction. The alternative to bank protection measures is to realign the road higher up out of the floodplain. Although it is easier to design a road that runs through a river valley, the costs associated with flooding may warrant moving the road up along the ridge or higher up out of the floodplain. It is worth delineating the 100 year flood, and determining the impacts of the flood on the roadway. If the road is at high risk from damage due to floods, it may be necessary to relocate the roadway.

Figure 4-18 Alternative roadway alignment out of flood limits

Source: Google Earth

There are a number of slope stability measures and techniques that are being currently used with positive results in Mozambique. It is recommended to continue using these methods and build them flexible to slowly adapt newer techniques and climate change conditions.

Summary

The stability of slopes will be adversely affected by an increase in precipitation and increase in sea level rise. The investment spent on preventing landslides is only cost beneficial if it is a vital link. It is better to carry out a careful analysis of the most suitable location of the road as well as invest in slope protection measures and use best practices during construction for the lower class roads. Landslides are a natural occurrence and the road design needs to have the least amount of impact to the surrounding environment to lessen its chances of failure. Large cuts and fills will only accentuate the opportunities for slope failures. Proper road drainage is needed to reduce erosion. Road location becomes more important with increased flooding and sea level rise; the suitability of building roads in river valleys and coastal areas at risk need to be investigated. Slope re-vegetation should be required on all impacted slopes to aid in slowing erosion. Cut and fill slope grades should be adjusted depending on materials. In areas bordering a stream that will be covered by stream waters at a flood stage, careful analysis should be done for choosing the most suitable location and alignment of the road and for calculating the maximum bankfull depth alternatives in the prone areas.

4.3.6 Surface drainage

Impact of climate change

The Mozambique Wet and Global Dry scenarios are showing that the intensity of design storms for 2 to 10 year storms will increase by 19% to 35%. These values alone should not overstress the current drainage system. What is more important is that the frequency of these design storms can increase up to 333%. This implies that these drainage elements will need to be monitored and cleaned more frequently to insure that there is capacity for these average sized storms.

The main impacts from the increase in rain will be in lack of capacity of the drainage elements. Roadside ditches and inlets may be undersized for the increase in precipitation leading to increased events of flooding on the roads both in cities and rural areas. Water velocities will be higher than designed for leading to increased scour damage of roadside drainage.

The measures to deal with surface draining from a road sector point of view both inside and outside cities are principally the same. The drainage systems have to be designed with a capacity which reflects the expected change in intensity of rain with a clear view to balance construction costs with the economic risks and costs to the society of not having sufficient drainage capacity. And the requirements to maintenance may also be similar. The road authority is normally in full control of designs outside cities but in cities designs may have to be integrated with other types of planning and it has to be ensured that surface drainage in urban areas is designed to meet drainage requirements from both roads and other uses of space. Handling the increase of water in urban areas generally needs to be the responsibility of the relevant city authorities.

Climate impact countermeasures

According to the Road Sector Strategy (RSS) 2007 – 2011, drainage must be a major aspect of future road and rehabilitation designs. Maintenance to the existing drainage network becomes all the more important with increases in high intensity storms. Routine maintenance, before, during and after the rainy season will help to alleviate total failures requiring replacement. Investments in drainage systems will be quickly lost if they are left to deteriorate or fill up with sediment. Maintenance should be prioritized in the areas most likely to experience flooding.

4-19 Poor maintenance in roadside ditch

Source: Consultant

Drainage systems should be updated in areas that have historically experienced flooding. Investigations should be done to find if it is cost beneficial to upgrade the drainage systems in these areas before a drainage failure occurs, or afterwards during repair or reconstruction. The risk of waiting to update the drainage system until after a failure is that during a large storm, the risk of multiple failures occurring at the same time increases. There are drainage systems that have additional storage capacity which could be needed in high risk areas.

The use of storm water drainage systems that require difficult cleaning methods should be questioned. If routine maintenance using specialized machinery cannot be ensured, then it is better to use an initially less effective, but less maintenance craving drainage system.

The design storms should be updated using the information from the climate prediction models.

Summary

Increased maintenance should be prioritized in areas that are likely to experience flooding and drainage failures. Investigations should be conducted in areas where flooding is likely to occur and determine if it is cost beneficial to increase the drainage system before or wait until after a drainage failure. Research is needed in the accuracy of the design parameters in predicting sedimentation in the rapidly changing landscape in Mozambique. The design storm parameters should be adjusted to reflect the anticipated climate changes.

Table 4-5 Climate change impacts-rain

Climate Variable	Road Asset	Climate Change	Climate Change Impact to Asset	Recommended Climate Change Countermeasure
Flooding	Bridges	+19% to 37% increase in intensity of extreme events	Increase in: Scouring, Capacity exceeded, River meandering, Siltation	Update Design Parameters; Increased scour protection during design phase; Large scale river training efforts; Detailed investigations in suitability of site location based on climate change predictions; Increase maintenance (scour protection, siltation removal)
	Culverts		Increased outlet velocities and scouring; Increase of overtopping events; Loss of gravel around culverts due to flooding; Increased siltation	Update Design Parameters; Increased outlet scour protection; Pave areas where frequent flooding occurs; Raise embankment; Increase maintenance (scour protection, siltation removal)
	Pavement Design		More frequent flooding events; Loss of gravel surfaces	Raise roadway; increases in paving gravel roads, other spot improvements
	Surface Drainage		More frequent flooding events, damage to road and drainage systems	Preemptive maintenance; Use storm water systems that can accommodate more siltation, and require less maintenance
Average annual Precipitation; Groundwater levels	Pavement Design	Up to 88 mm increase in 24h precipitation for the annual rainfall, possible increase groundwater levels	Increased saturation of subgrade materials; Gravel loss; Impassable earth surfaced roads; Weakened subgrade materials	Require 4 day soaked CBR testing in all regions; Increased use of chemical stabilizers, geo-textiles; Sealing of gravel roads; Paving of shoulders; Increased maintenance
	Slope Stability		Increases in Landslides, Erosion	Detailed investigations in suitability of site location based on climate change predictions; Increase in slope protection.
	Surface Drainage		Increased siltation leading to increased flooding of the drainage systems	Preemptive maintenance; Storm water systems that can accommodate more siltation, and require less maintenance

Source: Consultant

4.4 Cyclones and sea level raise

4.4.1 Introduction

Cyclones have not been solely considered in the analysis of data, but the increase in rainfall has been calculated taking into account the effect of cyclones.

4.4.2 Infrastructures

Impact of climate change

Intensive tropical cyclones produce destructive winds, coastal storm surges, torrential rains and severe floods. Mozambique has a coastline of about 2,700 km. More than 60% of its population lives in coastal areas, which in many places consist of lowlands with rural roads connecting villages and giving access to the beaches, but most of highways are placed inland.

The global sea level has risen over the past century. As the earth temperature increases, the sea level expands. Melting glaciers and ice caps contribute to the rise in sea level, but local climate change factors also affect relative sea level rise. According to the Sea Level Rise and Cyclone Analysis from the INGC Climate Change Report, global climate models have shown that there is a wide variation in the results, with a tendency toward decreasing frequency of tropical cyclones, but an increase in their intensity and associated precipitation, as in the study by Bengtsson (2007). Other reports from the Intergovernmental Panel on Climate Change (IPCC) agree describing that 'it is likely that future tropical cyclones (typhoons and hurricanes) will become more intense, with larger peak wind speeds and heavier precipitation'.

Ocean tides in Mozambique are the largest natural forcing affecting sea water intrusion into river systems. This intrusion is already occurring now. Sea level rise and storm surge appear to be much smaller in magnitude than the ocean tides. In terms of area impacted, the Zambezi is the largest but the Save river could become more serious affected because of its long annual period of low river flows. In terms of distance inland, the Limpopo is the worst affected followed by the Incomati and Zambezi.

The two climate scenarios pictured from the data received from the Colorado University show a substantial increase in average for the 24h precipitation in Mozambique, such an increase in precipitation, combined with strong winds and ocean tides could create a devastating scenario.

A low lying coastal strip, from the Marginal to the Costa do Sol, is in need of protection as it is subject to coastal erosion with mainly urban roads, ports and railways under threat from extreme sea level events.

Erosion caused by rising sea levels could increase the risk of landslides near the shore. Recent studies (NAPA) revealed that the average erosion in the southern coastal region of Mozambique rated to 0.11 m/year (1971-1975) for protected beaches, and 1.10 m/year (1999-2004) for beaches exposed to ocean waves. Anthropogenic factors have been dominant in the processes, including urban expansion, ports, and more recently disordered expansion of tourism infrastructure.

Climate impact countermeasures

Seawall and river locks are the main engineering solutions provided to contain sea level rise and to prevent sea water intrusion into the rivers.

Knowledge on cyclone behavior, including areas of landfall and possible future changes are needed in order to undertake countermeasures, and they are so difficult to predict in medium-long term perspective that water-level design standards for seawalls could only be determined on a project-by-project basis, with a short year span.

The extreme sea levels at Maputo need to be adjusted upwards to take account of sea level rise and the likely increase in intensity of the most intense tropical cyclones. The coastal defenses would also need to be raised as the sea level rises over the coming years. At a minimum the coastal defenses need to be raised to protect against 100 years returns events under the at least the "dry" scenario given. On the top of the difficulties for forecasting size and frequency of these extreme events, data records are inconsistent.

There are very few sea level data available from 1960 to 2001, of the quality needed for sea level rise analysis, and nothing in recent years. Thus recent past trends in global rates of sea level rise can be cautiously used for the coast of Mozambique, as reflecting the best estimates available. A long and representative observational record of sea level has not as yet been assembled to test whether or not the acceleration will be sustained into the future, however, with changing emissions and increased temperatures, there is likely to be further acceleration of sea level rise through the links to climate change processes.

With this perspective, the most reasonable solution to face the sea level threat seems to be gradual relocation of coastal developments from the coast to avoid building settlements and infrastructures in areas at risk.

Summary

The sea level is generally inferred from sea-level data of sufficient length and accurate bench marks, obtained from observation stations in the coast. The quality of the Mozambique sea-level data is poor due to gaps in the records, making it inadequate for sea-level trend estimates.
Predictions of future sea level rise in Mozambique may be adopted from globally modeled studies. Investment on data collection is recommended.

With the current climate change scenarios, the central and south coastal areas will be more vulnerable than the North, it is expected that Maputo and especially Beira will be affected by sea level rise.

The majority of Mozambique's highway system is currently inland enough where the affect of sea rise on erosion and road construction will not have that large of an impact. It is thought that the largest affect of sea rise will occur in the larger cities that are near the sea, such as Beira and Tete, where the impact on roads would be serious but minor compared to the human impact. Nevertheless, there are some small sections of EN1 that are close to the sea, but the

roads that are most seriously threatened by coastal resection are the paved and gravel roads used to connect the beach from fish settlements which were built a long time ago are now, as well as the urban roads of the cities located in areas at risk.

The approach of making infrastructure climate resilient has a different dimension when considering sea level rise. The implications of a considerable increase in sea level would be rather devastating on humans than on infrastructures. Regardless of the standards, techniques or materials being used, if the water took over urbanized land sides, the infrastructures located in those areas would be severely damaged, there would be broken links for the infrastructures affected, and the area would be unutilized by population. If such a scenario took place, it would not be reasonable to replace the infrastructure but rather to find safer locations for the population to settle and for the infrastructures to be built, therefore reconstruction should be avoided. Nevertheless, it is recommended to protect the existing urbanized areas at risk with coastal defenses.

Roads should not be constructed in risky areas. The direct approached solution to this problem is to monitor land use, because the decision on where to build infrastructure is driven by the locations that the road has to connect. It should be avoided to build more dwellings in areas at risk.

4.5 Nature and extent of climate impacts

4.5.1 Introduction

The climate predictions results show important increases in precipitation for the two scenarios considered. The climate is unpredictable in Mozambique, an estimate of the impacts of natural disasters between 1956 and 2008 is given in Table 4-6:

Table 4-6 Summary of the impacts of natural disasters between1956 and 2008

Disaster Type	# Events	Total killed	Total affected
Drought	10	100,200	16,444,000
Flood	20	1,921	9,039,251
Tropical cyclone	13	697	2,997,300
Epidemic	18	2,446	314,056
Windstorm	5	20	5,100
Earthquake	1	4	1,440

Source: Queface (2008)

Climate change effects are very difficult to predict. There is a big uncertainty on foreseeing the frequency and size of natural disasters in Mozambique. The conclusion is that there will be increases in precipitation, but not enough to warrant a complete change to the methodology of designing and constructing roads in Mozambique. Regardless of climate change in the future, Mozambique has issues with climate now that need to be solved.

4.5.2 Current soft spots in the road infrastructure

The term "soft spots" is used to describe areas in the current Mozambique road network that are frequent problem areas with large disruptions to the traffic flow.

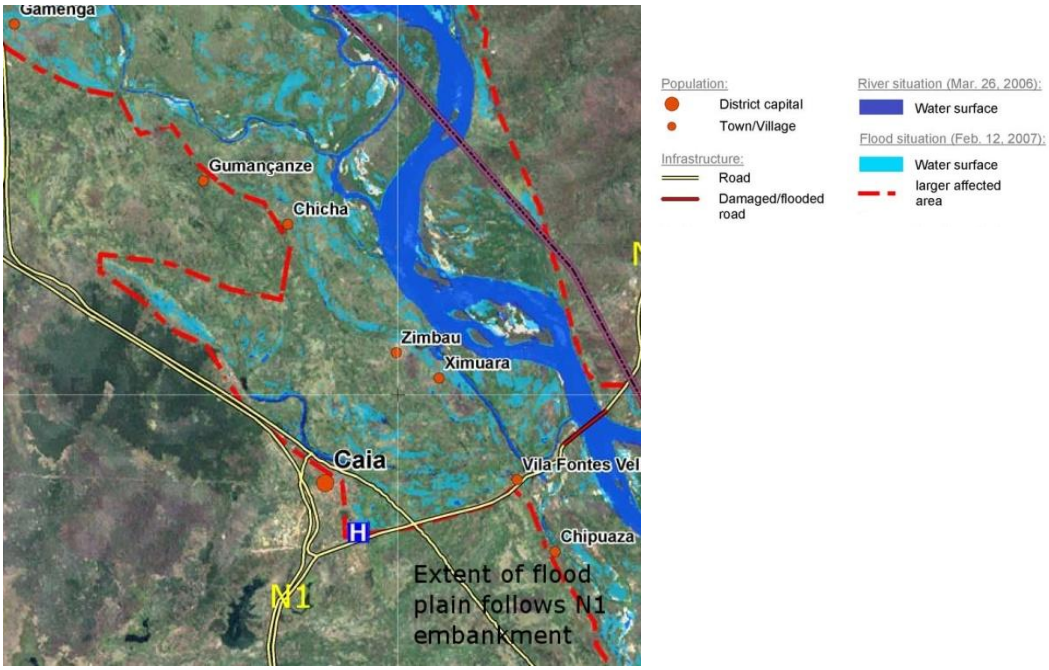
It is difficult to get a detailed overview of all the problems and locations in the Mozambique road network without some sort of study on each kilometer of road. Based on conversations with ANE, desktop research, and some site visits in the country, it is possible to narrow down some areas which frequently experience problems.

In the past, Mozambique has experienced large scale flooding that has had devastating effects on the road network. The 2000/2001 floods left sections of the N1 road closed for up to a month, and destroyed a number of bridges. Floods on this level are a rare occurrence, but there have been a number of large floods over the last decade. The loss of a vital bridge or culvert link has obvious traffic delay implications, and repair can take from days to months, depending on the size, location and importance of the road affected.

Figure 4-20 shows the impact that the N1 road embankment has on the Zambezi River floodplain near the town of Caia. This picture is from a flood event in 2007, and the ferry today is replaced by a new bridge, but the high road em-

bankment is still being used. Figure 4-20 clearly shows how the flood plain boundary has been narrowed by more than twice its original width due to the road embankment.

Figure 4-20 Zambezi floodplain N1 near Zambezi Bridge

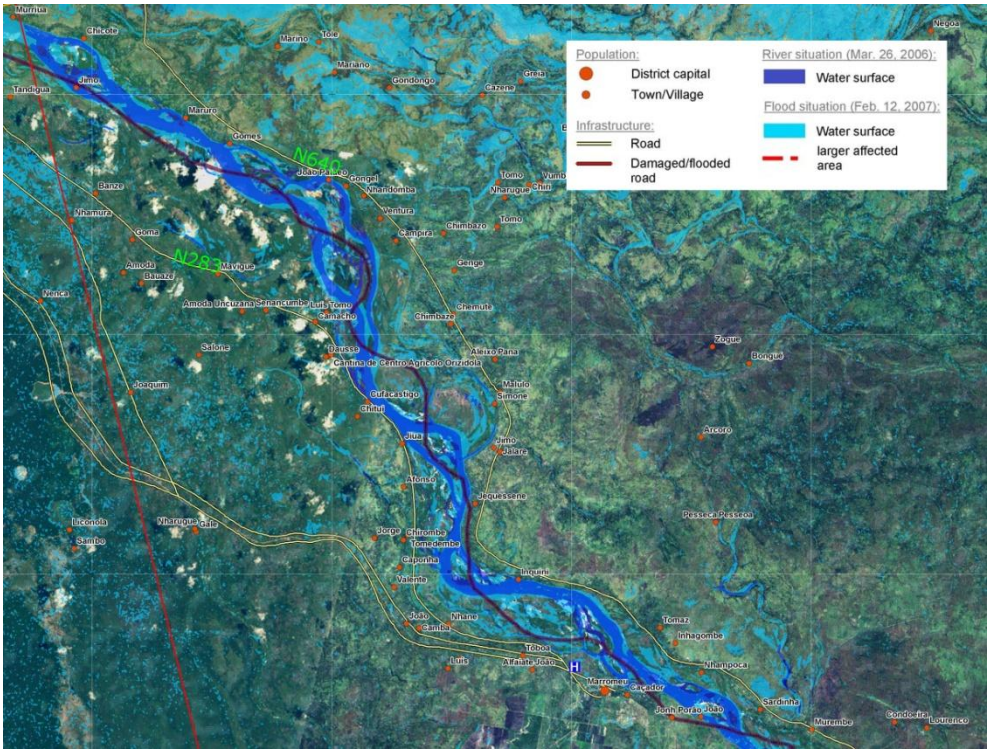


Source: RESPOND,UNOSAT, DLR

The road embankment serves as a large flood levy, and its construction needs to be at the same level as a flood levy requires for it to withstand large floods. The narrowing of the floodplain also acts to increase the flood velocity underneath the bridge area which will increase the scour potential and downstream damage in the vicinity of the embankment.

Another challenge is finding suitable locations to build roads in the flatter coastal areas of Mozambique. Figure 4-21 shows the extent of the water surface during a flood in February 2007. Both roads N283 (secondary unpaved road) and N640 (tertiary provincial road) pass through the midst of large sections of flooded areas. Many sections of these roads are found to be at or slightly above the elevation of normal Zambezi river levels.

Figure 4-21 extent of the water surface during a flood in February 2007



Source: RESPOND,UNOSAT, DLR

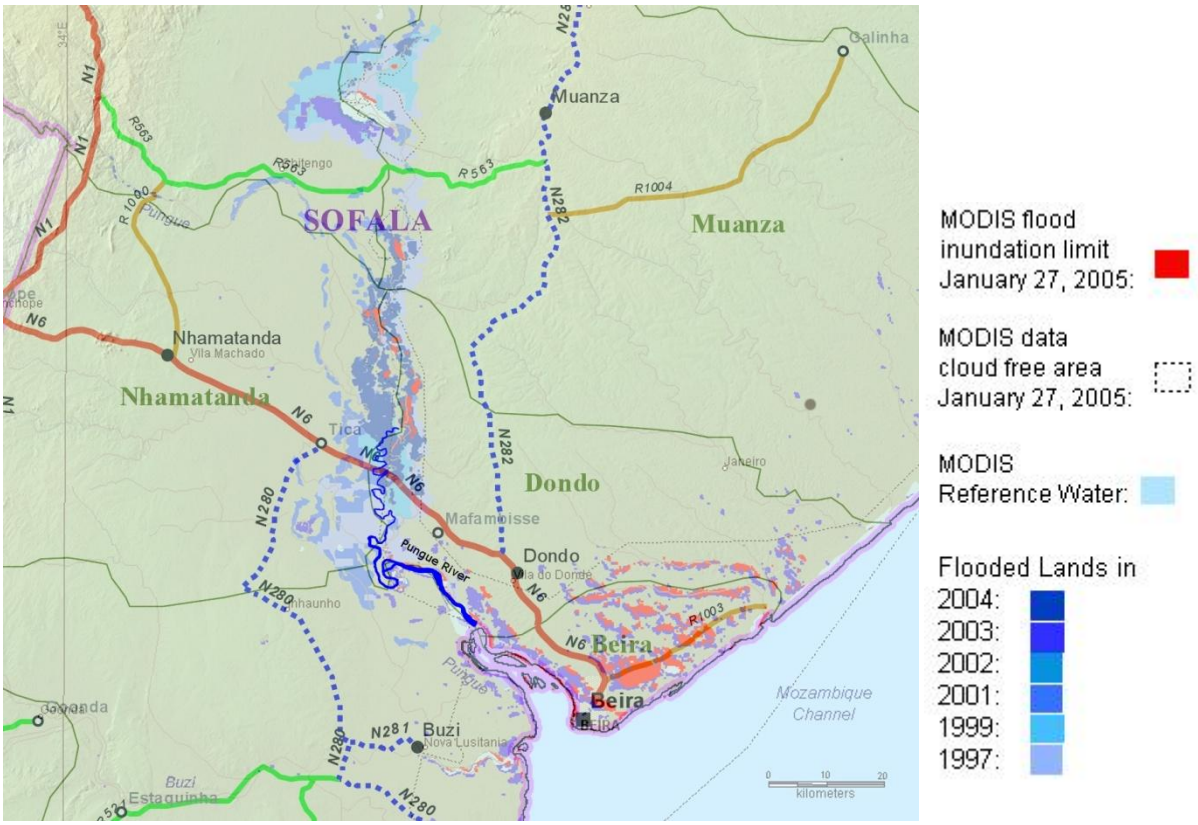
It would not take large floods to inundate or destroy sections of these roads. The roads built in these areas must balance the need to stay dry during the wet season as well as not contributing to downstream flooding by acting as unwanted flood levies. If their intention is to be used as flood levies, then their construction needs to be of a very high (expensive) standard, associated with frequent adequate maintenance.

The inundation extent is also associated with rising sea levels in the estuaries of the river basins. Most of the Mozambican coast is protected by sand dunes formed through the deposition of sand as a result of wind and wave action. The river estuaries are low points in the band of protection through which sea water can easily propagate inland. These estuaries are vulnerable to the combined effects of chronic sea level rise, tidal wave action and acute events such as tropical storms and cyclones.

At present time, ocean tides are the largest natural forcing affecting sea water intrusion into river systems. Sea level rise and storm surge appear to be much smaller in magnitude. In terms of area impacted, the Zambezi delta is the largest in size, but the threat for the Save river could become more serious because of its long annual period of low river flows. In terms of distance inland, the Limpopo is the worst affected followed by the Incomati and Zambezi.

Figure 4-22 shows areas that have been flooded around the city of Beira from the years between 1997-2005. In the area between Tica and Mafambisse there is currently a bridge over 200 m which spans the Pungue River. This area is very flat, and the bridge spans a large meander. There is good likelihood that the river could easily change its course during a large flood and make the current bridge location obsolete. The flood plain in this area is around 15km wide and river training to keep the river in its current location is most likely unfeasible.

Figure 4-22 Pungue River Floodplain



Source: ANE, Dartmouth Flood Observatory

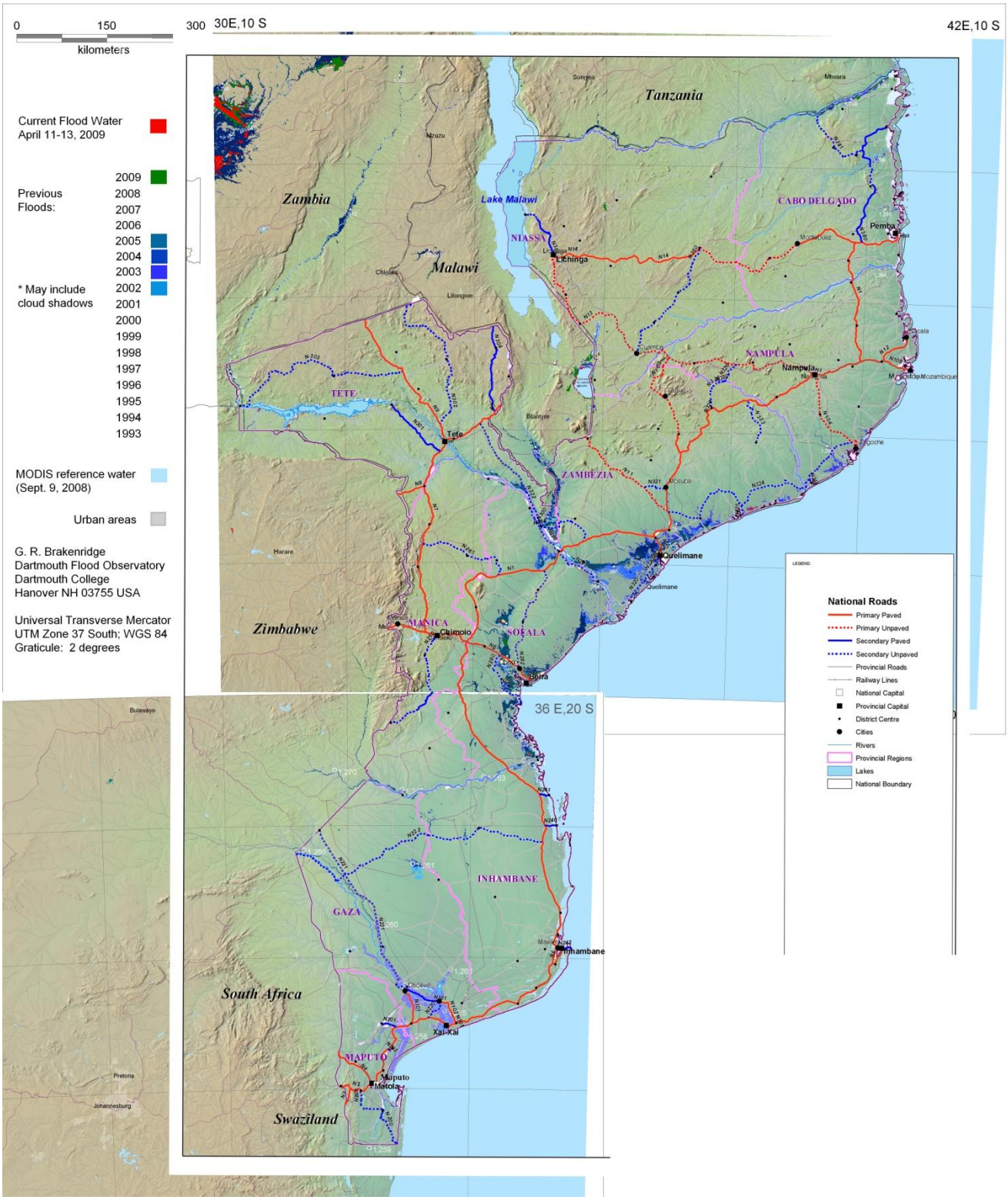
Figure 4-23 shows a map of the current Mozambique road network imposed over a map of areas that have experienced severe flooding between the years 2000 and 2009. The most severe flooding occurs on rivers with watersheds that encompass areas outside of Mozambique's political borders. These rivers include the Incomati, Limpopo, Save, Zambezi, Shire, and Rovuma.

Rivers with origins inside the countries borders also have the potential to cause large damage during large storms. Many of the roads in the coastal plains are currently placed in or near the highest spots in the landscape. These high spots may however only be a few meters above river elevation. The landscape in the coastal plains is so flat that the only way to ensure a road stays dry throughout the year is to build the road up on high embankments. Again, this can be a dangerous method if road embankments are constructed poorly. Road em-

bankments have the potential to decrease the size of the floodplain increasing flooding potential in other areas.

From measurements using maps supplied from ANE as well as flood maps from DFO (Dartmouth Flood Observatory), estimations in the lengths of roads in the network currently in flood affected areas can be estimated. For N1, there is an estimated 100 km that passes through areas that have been flooded in the last decade. Approximately 40 km of N6 pass through severely flooded areas, mostly between Nhamatanda and Dondo. The majority of N101 and N221 are only a few meters above the Limpopo river elevation and at severe risk of being flooded. A much larger percentage of the smaller provincial roads that connect smaller villages pass through areas at high risk for flooding. Typically these roads are built with lower budgets and less flood resistant materials than the national roads.

Figure 4-23 Flooding maps (2009)



Source: Dartmouth Flood Observatory

A problem facing Mozambique roads which is not climate related is the source of plentiful supplies of usable materials. A layer of granite rock underlies most of northern and west-central Mozambique, whereas the soils of the southern and east-central regions are sedimentary. Mozambique's soils are diverse in quality and type, but the northern and central provinces have generally more water-retentive soils than does the south, where sandy soils prevail. The northern soils, have a higher content of red clay. In contrast, the central region has a broad expanse of rich alluvial soils along the Zambezi delta. In general, Southern African countries natural gravel and soil road materials are mostly residual soils, residual weathered rocks or pedocretes which are poor quality for road construction.

Over large areas of the country, finding suitable construction materials for road building is a big issue due to widespread occurrence of sands and decomposed granites with high plasticity. Although they can be used to affect substantial savings in costs, the conditions under which marginal and non standard materials can be successfully used should be accurately defined. Greater political and engineering acceptance of appropriate standards and risk would probably enable more unpaved roads to be surfaced that looking into a medium-long term perspective could provide significant returns in future maintenance savings.

Much of the soils and materials found in the coastal plains are of a poor quality for road construction. The material is high in fines and low in coarse material. Figure 4-24 shows a typical borrow pit for material in the rehabilitation of a tertiary gravel road in the Maputo province. There is essentially no coarse material in the pit, and the material is subject to being quickly washed away during heavy rain events, and localized flooding. As a result of materials being washed away, coarse material would be susceptible to erosion or abrasion.

Figure 4-24 Borrow Pit Road R811

Source : Consultant

Suitable gravel for a wearing course may be hundreds of kilometers away, and their use quickly becomes one of the most expensive pay items. This adds additional challenges during required re-gravelling, and the use of alternative materials should be thoroughly investigated prior to construction. The material found for use as crushed rock is clearly of marginal quality and material should be carefully selected when used as crushed rock in both concrete work as well

as bituminous surfacing. If used in the base, all material is acceptable since it will be used as a source to obtain base material of G4 quality at least.

It is already a problem with about 80% of the total network consisting of unpaved roads, whereas in 2006 almost half of the unpaved roads were in poor condition, and only 57% were fully transitable by normal (non four-wheel drive) traffic. Deterioration of these roads will come much earlier and progress more rapidly if the materials used are of marginal quality and the precipitation increases. Some of the problems come from past decisions when road projects focused on providing access for as many people as possible, and where the number of kilometers of completed network was more important than the quality of those roads, which failed to take into account long term consequences.

Due to lack of good quality materials for road construction, sometimes roads were built using local marginal materials. Low quality of subgrade and increasing traffic loads lead into fast deterioration, a process that in some cases does not even reach the life span that they have been designed for. The procedures for the application and approval of wearing course materials are more stringent than those of the subgrade. For instance, the required thickness of the wearing course takes into account the need for adequate bearing capacity to carry the traffic and general wear due to traffic and erosion. Uniformity and consistence of the wearing course layer in terms of material properties, layer thickness and compaction are of great importance. It follows therefore that the approval method should endeavor to minimize inadequacies in these aspects.

According to ANE´s Design Standards, unpaved roads for categories II, III, and IV should have a structural design period of 5 years for both new constructions and rehabilitation, but it is stated that the structural design period of Unpaved Roads will be dictated by the quality of the material to be used, the traffic and the road category. If erodible materials are to be used (no funds for cement or bitumen treatment or for transporting material of a better quality), a shorter structural design period should be adopted, resulting in a higher rehabilitation (reworking, regravelling and compaction) frequency

Supplies of suitable gravel for road construction and repairs are running out in certain areas, with increasing costs of transport of materials. Increase in precipitation will make that circumstance more vulnerable, washing away pits under heavy rain episodes. In these circumstances, the temptation to use any available material may be strong, but this would only accelerate the problems. If any savings come from using cheaper lower quality materials which could not meet the required standards and therefore could not fit for the purpose, there would be a subsequent offset in maintenance demands.

It is obvious that in order to reduce transportation costs, the preferable materials to use are the ones found locally, therefore the emphasis and stress is on how to adjust guidelines, specifications and construction techniques to suit the quality constraints for the given traffic volumes..
The absence of sound material investigation data contributes significantly to the high cost of rehabilitation and periodic maintenance by creating an area of high risk in what could be technically determinable area with great impact on overall

pricing by bidders. According to RSS 2007-2011, currently there are plans to determine an inventory of road building materials linked to a database, and there is a pavement design research program using accelerated pavement testing, and experimenting with ETBs (Emulsion Treated Base). It is highly recommended to continue investing on new pavement solutions and on the creation of a database for road building materials.

4.5.3 Future climate impacts on the road infrastructure

The climate models are predicting an increase in the severity of heavy events, for the year 2050. The large increase in precipitation means that it will not become any easier to deal with climate problems in the future, if the strategies towards technical adaptation, design and maintenance are not flexible enough to adapt and accommodate to the future changes.

Flooding can be expected to increase in the areas that have historically experienced heavy flooding and have high flooding risk, mainly in the central and south areas including the big floodplains. These areas will require more robust designs to withstand the heavy flooding that they are likely to encounter.

4.5.4 Summary of climate change adaptation measures related to sea level rise and cyclones

Increasing sea levels and the large variation in ocean tides is a big challenge for infrastructure and cities located in low areas near the ocean. Basically, the choice is either to protect existing road infrastructure by investing in protective coastal defenses, e.g. sea walls, or gradually relocate the infrastructure (and the population) to more stable areas that are typically farther inland and at higher elevations.

Areas that are at low elevation above sea level, or just above river levels are at the greatest risk. No major construction of infrastructure should be built within the high water limits of a 100 year storm, large cyclone event, or high water limit from ocean storm surges.

The obvious measure is not to rebuild in areas that will be destroyed from the next cyclone, or design protection so that the effect of next cyclone is diverted around important areas. This could involve large engineering infrastructure in the form of concrete sea walls that would divert incoming surges.

The current quality of sea level data is rather poor due to many data gaps which make the data inadequate for sea level trend estimation. The alternative is to use prediction from global models. In any case current specific information on sea level rise which can be used for specific investment decisions is very uncertain and there is a need to improve and standardize data collection and handling to create a base for important future investment decisions. This will require monitoring stations, as well as the scientific knowledge to accurately decipher the data.

4.5.5 Summary of climate change adaptation measures related to river basins and coastal flood plains

Hydrological specifications used by designers are often based on very uncertain information, especially calculations of watershed areas, so there is an urgent need for investment in a new approach to estimation of design floods based on standardized hydrological data (e.g. rain fall maps) and models, which can be used as a default standard for designers.

During initial investigations for a new or reconstructed bridge/road or replacement of an existing infrastructure the location should be thoroughly investigated. It should be tested if the bridge or road could be placed in a more stable environment and if additional constructions costs over time are likely to be more than covered by savings from a smaller risk of flooding. An important element to be considered is the possibility of upstream river training potentially including permanent bank protection to ensure that the river channel is directed under the bridge span which can reduce the risk of flooding of the infrastructure. However, river training is only feasible on the smaller tributaries to the larger rivers. River training will most likely not work on the large rivers such as the Zambezi. These areas would require massive engineering works such as large flood levies.

Designing economically feasible roads and highways that cross floodplains is a challenging task with no simple solutions. For future floodplain crossings, road and bridge adaptation measures should take into account the successes or failures of the existing and new road construction that is currently being built in Mozambique. There is a large amount of road and bridge construction in Mozambique whose performance in flood prone areas should be monitored to aid in future design. A section of the N1 Highway near Xai Xai has been designed with a series of smaller bridges in order to accommodate frequent flooding. This sections performance over the next years should be evaluated and if proven successful, can be used a basis for new flood plain design in other parts of the country.

Increased precipitation and flooding also leads to more scour and bank erosion, which is an important threat to bridges. The most cost-efficient way of dealing with scour is to account for it in the design phase and take structural counter measures. For existing bridges various methods exists for placing different types of materials to protect bridge piers, but this solution requires regular preventive maintenance to ensure that protection is maintained over time. If this cannot be guaranteed, structural solutions and permanent bank protection may be the only realistic solution.

If roads cannot be located in relatively stable environments they may have to be constructed on high embankments to ensure a long lifetime of the road, but sufficient drainage e.g. in form of culverts may have to be ensured so the road will not function as unwanted flood levies with a high risk of a major wash away or increase the threat of flooding in other areas.

4.6 National design standards in Mozambique

4.6.1 Introduction

SATCC design manuals were created for the SADC region, which is itself a diverse one, on the top of that, Mozambique has its own specific and concrete characteristics depending on the area of the country. Other manuals than SATCC such as the Overseas Road Notes or other South African standards are commonly used. It would be impractical and inappropriate to provide recipe solutions for specific situations in the general Guidelines. Instead, emphasis should rather be placed on guiding the practitioner towards evaluating alternative options and considering their pros and cons as a basis for decision making and application to country-specific situations. As considered in the RSS 2007 – 2009, design guidelines must sensitize the designer to the practical realities prevailing in Mozambique. In particular the designs must be builder friendly, taking into account the plant, materials and skill levels that are available in the region. Design guidelines must emphasize boldly the importance of material investigations; life-cycle assessments of

As already taken into account in the RSS 2007 – 2011, given the limited availability of resources for both maintenance and for road rehabilitation and upgrade, it is essential that the design of projects strive for the most efficient and economical solutions. This entails carefully scrutiny of the technical (e.g., engineering), economic (e.g., traffic) and social (e.g., safety) requirements for all rehabilitation and upgrade designs so as to minimize life-cycle costs and maximize the impact of scarce resources as well as climate change effects. Mozambique can hardly afford to design and construct roads that provide higher levels of service than the bare minimum required for the conditions. Where traffic is very low (i.e., normally less than 200-300 vehicles per day with relatively few heavies), gravel roads should normally prevail. Where either traffic justifies the paving of a road, or where maintenance considerations dictate paved surfaces, widths will be kept to the minimum consistent with traffic and environment. The question of paving shoulders will be subjected to deeper analysis. One area where design standards should not be compromised is in the area of road safety. The provision of appropriate, consistent, vertical and horizontal curvatures, site distance and road marking and signing for safety should not be compromised. Similarly, the volume and nature of non-motorized traffic will be taken into account when designing roads for width and shoulder treatments.

The engineering solutions needed to make a climate resilient road can be found spread throughout these manuals. Solutions to hydraulic related problems such as scour and sedimentation are found in the Bridge and Drainage design manuals. Solutions to problem soils and subgrade problems are found in the Pavement design manuals. Slope stability and surface drainage solutions can also be found spread throughout the manuals.

4.6.2 Recommendations to the manuals

The largest problems facing the Mozambique's road network are climate related.

There is a small section in Chapter 5 of the SADC Guideline on Low-volume Sealed Roads, where it is mentioned the influence of climate on road building materials in Southern African countries. It is suggested to put more emphasis on organizing the manuals so that the climate related issues and solutions are presented clearly in an additional chapter. A chapter could be added to the manuals focusing on environmental conditions; similar to what Tanzania Ministry of Works has done with their Pavement and Materials Design Manual. Having a chapter dedicated to the environmental impacts on the road would make it easier for the designer to choose quickly and efficiently which engineering solutions would be best for the terrain, soil conditions and climate where the road is located.

It is recommended to review the Drainage Design Manual and Design Manuals for river and stream crossing with the updated drainage charts included in this report. Review and if needed update bridge standards using data collected from latest bridge failures to figure out why and where the problems occurred.

It is recommended to adjust the requirements for testing of subgrade materials to always use a 4 day soak, even in dry conditions or when saturation is unlikely, (SATCC – Code of Practice for the Design of Road Pavements , Section 3.3 Classifying Design Subgrade Strength Table 3.2: Method for classifying subgrade design CBR).

Effort should be put on updating the manuals with more low cost engineering solutions and in continue in the same line proposed by the Sector Plan Reports (RSS and PRISE).

4.7 Maintenance

A big effort has been made in Mozambique in order to develop a proper maintenance strategy. Maintenance and road management chapter on the SADC Guideline on Low-volume Sealed Roads, but especially the Program Implementation Plan for Roads (PIP) and the Road Sector Strategy (RSS) present a thorough and positive analysis on what has to be done in the present and in a short term perspective. Development of strategies should work in the same direction.

The recommendation of the Consultant is summarized below.

4.7.1 Climate change and road maintenance

Strictly speaking road maintenance is not an adaptation measure as the purpose of maintenance is not a function of climate change but applies irrespective of the conditions for the road infrastructure, hereunder impact by climate.

The purpose of maintenance is to ensure the longevity and functionality of the infrastructure investment. The scope of maintenance is therefore a function of all parameters which affect the longevity and functionality of the infrastructure. This includes i.a. geometric, pavement and drainage design, traffic impact and climate. Therefore the local climate shall be taken into consideration when planning and implementing maintenance. It follows that climate change may

trigger new requirements and demands to maintenance in order to prevent deterioration of the infrastructure.

Our basis for the following is a postulate that the optimal measure to adapt to climate will be to maintain the roads so that they always are in a (near) perfect condition meaning that their resilience to climate impact is at all times (near) maximum.

- Roads/road sections which, under such maintenance attention, are able to tolerate the climate impact and maintain their longevity and functionality, shall not be strengthened.
- Roads/road sections which, in spite of optimal maintenance, can not tolerate the climate, but suffers from reduced longevity and functionality, should be designated for relevant reconstruction and strengthening

The proposed adaptation strategy is therefore to maintain the road network as best possible and only when this is insufficient in view of the climate impact, to reconstruct and strengthen the road in appropriate ways.

It follows that maintenance will have a key role in the adaption to climate changes. It will not be possible or even necessary to change or reconstruct the bulk of the road network, primary or secondary, in order to cope with climate changes. Reconstruction of roads may of course be the only solution at certain sites if e.g. there are serious risks of flooding ("soft spots"), mudslides or whatever, but should only be applied when the possibilities for making the roads climate resilient through maintenance is exhausted or there are other reasons like e.g. changes in traffic patterns which will make upgrading of the roads beneficial.

4.7.2 Road sector strategy 2007-2011

Mozambique has developed a strategy for the road sector: Road sector strategy 2007-2011. We refer to the Final Report of August 2006 ((http://www.ane.gov.mz/pdf/study/rss/RSS%202006%20Final%20Report%20Eng.pdf). This strategy includes a detailed and comprehensive approach to road maintenance (See Chapter 3: Strategic Plan).

We consider the strategic plan is essential for the road administration in handling the maintenance in general and climate adaptation in particular. We highlight a few of the principles adopted in the strategy:

- On maintenance strategic it is stated (p. 18: Maintenance Strategy): "In principle, standard maintenance will be applied so as to preserve as much of the network in good and fair condition as possible".

  This is very much in line with our recommended strategy in relation to climate adaptation measures.

- It is further stated that (page 21, clause 3.2): "The principle of sustainability dictates that new investments (rehabilitation, upgrading and new construction) will only be undertaken where there is a demonstrated capacity to maintain those investments."

  This underlines the intention of keeping maintenance at a high level.
- Page 16: *"Wherever possible, labor-based intervention methods will be utilized."* This is completely in line with the consultants recommendations.
- We notice that contracting of maintenance works is part of the strategy, which we endorse as an important means to optimize the cost/benefit in road maintenance.
- We also note that it is planned to develop a road database for central management and monitoring of maintenance activities and planning. See below our proposal on Road Database

All together we find the Road Sector Strategy 2007-2011 to be excellent and highly suitable as basis for high quality and economic road maintenance. Further we believe that the Road Sector Strategy contains many of the right approaches to secure optimal adaptation to climate change - because high quality road maintenance in itself is an important adaptation measure..

4.7.3 Climate change adaptation strategy

We summarize the basic strategy as:[3]

a) In general the existing road network should remain as is unless changes in traffic patterns make reconstructions beneficial and necessary and unless climate impact is above the design resilience sections of the roads.

b) The strategy is to maintain the roads all the time to a high quality[4]. Only if this is insufficient in relation to the climate impact, reconstruction should be considered.[5]

c) Maintenance measures shall be planned to cope with existing climate while reconstructions (strengthening) or upgrading of roads and road sections (soft spots) shall be designed to cope with future climate.

It shall be understood in the following that climate change in practical terms refers to an increase of the climate impact. Climate changes with leads to less impact are not considered directly[6].

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[3] Although traffic impact is not considered in the following it shall not be forgotten that traffic impact and traffic impact changes in parallel to climate impact plays an important role in the planning of maintenance and reconstruction activities . It means that traffic projections and development plans should be taken into account.

[4] It should be noted, that this strategy applies at all times and not in particular in relation to climate change.

[5] It follows that the alternative strategy - which assumes that roads are reconstructed to increase their design resilience while maintenance is kept sub-standard, is considered inappropriate and uneconomic.

4.7.4 Economy

It should be realized that present road maintenance performance does not meet the proposed strategy: optimizing maintenance so that the roads are always in a very good condition. Implementing the strategy, even under the assumption that climate impact is not increasing, indicates that maintenance costs are bound to increase.

This view is too simplistic however. In the present maintenance regime, there may be amble possibilities for improving efficiency - by improving the decision basis, by adjusting the maintenance organization and/or by changing the technological methods in maintenance.

Basically it will be central for successful adaptation to climate change, that the costs of maintenance are minimized in respect of performance. In other words, economic considerations should have a central role in forming the maintenance strategy. This is even more important as maintenance activities are foreseen to increase for - at least - part of the road network as result of the expected climate changes.

In the following we consider means and measures which may lead to a more efficient maintenance organization. It is also realized that external support in funding of adaptation measures may be focusing on the increase of maintenance costs as result of climate change. We therefore propose a model for how maintenance activities (and subsequent costs) can be linked in a transparent and verifiable way to climate changes (road database).

4.7.5 Overview

Maintenance categories

We consider three principal maintenance approaches:

- Routine maintenance
- Corrective maintenance
- Conditional maintenance

Routine maintenance is performed according to a predetermined plan, independently of actual road condition. Routine maintenance should be the foundation for the maintenance activities and will if planned correctly in respect of known impact from climate and traffic, ensure that the road is for a large part of the time in good condition. Since routine maintenance is executed before road failure takes place, it will usually be possible to minimize traffic problems as result of the maintenance activities.

Corrective maintenance is performed in response to actual road condition. Corrective maintenance should only be necessary in case of unusual events (flood, mudslides, accidents) but will if routine maintenance is insufficient or absent,

[6] In case of climate changes leading to less impact, strengthening of the roads may not be relevant and to keep the roads in a permanent good condition maintenance activities may even be reduced.

often be the common maintenance activity. That is when the road organization only responds to serious failure (closures or difficult pass ability) of the road.

Conditional maintenance is between the other types of maintenance and should apply when the roads is observed to suffer damage, but is still fully functional. Conditional maintenance therefore relevant when routine maintenance is inadequate and will prevent application of corrective maintenance.

Maintenance centers
Maintenance organization may be central or decentralized. It will be normal that major equipment and maintenance activities originates in large centers with facilities for transport of heavy materials and equipment while small and light maintenance activities originates in small decentralized units.

Execution
We further consider two principal modes of maintenance execution:

- Force account
- Contracting

In force account the road maintenance organization (the Employer) is his own contractor and manages staff and equipment to perform the maintenance.

In contracting the employer tender for services by private contractor in open completion.

In both cases the Employer is responsible for specifying the work to be done.

Methodologies
Finally we consider two principal technical methodologies:

- Equipment based technology
- Labor-based technology

It should be noted that the optimal approach will depend on the type of roads as well as the type of work to be done. Labor-based technology may be economical for some work/roads but not for other.

We summarize the options in Table 4-7.

Table 4-7 Maintenance management-Gravel Roads (sample)

	Category			Organization					
	Rou-tine	**Cond-itional**	**Cor-rective**	**Cen-tralized**	**De-cen-tralized**	**Equip-ment-based**	**Labor-based**	**Force ac-count**	**Con-tract-ing**
Grading	x	x		x		x		x	x
Spot main-tenance			x		x		x		x
Shoulders	x	x		x		X		x	x
Ditches		x	x		x		x		x
Culverts (cleaning)	x	x	x		x		x		x
Culverts (repair)		x	x	x		X	x	x	x
Bridge abutments		x	x	x	x		x		x

Before we discuss the issues above we will however consider the application of a basic planning and decision-making tool for

4.7.6 Organization of road maintenance

Overall the organization of road maintenance should be designed to achieve its objectives in the most economical way - in order to maximize returns at any given input - and to meet external political objectives relevant for the activities.

We suggest that the road organizations develop a central database (se also Road sector Strategy - Integrated Road Management System, IRMS), holding relevant information for central and decentralized decision making and analysis of activities. Further we suggest that the road organizations are analyzed with regard to two issues: Force account versus contracting and equipment based versus labor-based maintenance methodologies.

Road database

Management of the road infrastructure should be based on proper and relevant information as basis for planning, budgeting and decisions. Establishment of a comprehensive centralized road database will be a logical and helpful tool.

The Bridge Management System can be used as an example and built upon to include information such as:

- Road ID
- Road location
- Road category (primary, secondary, bound, unbound surface etc.)
- Traffic data
- Weather data (weather station data, local observations)
- Road condition and pass ability correlated with milestones/GPS coordinates
- Specific temporary problems (flooding, mud slides) correlated with milestones/GPS coordinates
- Identification of soft spots (requiring extensive maintenance and attention) correlated with milestones/GPS coordinates
- Maintenance activities for each road section (planned, required, done)
- Maintenance cost data (actual and standard) broken down in equipment, labors and materials cost
- Technology applied in maintenance activities (labor-based, equipment based (specification))

The database should be dynamic, that is under continuous update. Data should be assembled through e.g. mobile-internet[7] means by links to centralized server. The capacity of today's technology makes it possible to preserve all historic data and make them subject to automatic analysis. Of particular interest will be to monitor changing maintenance requirements with respect to changing climate over medium to long periods and subsequent register developments in budget requirements with respect to climate changes.

The purpose of the database is to enable management optimize resource allocation, plan activities and identify urgency of interventions (soft spots). The database will be a tool for planning of budget, staff and equipment requirements and serve as a means for prioritization of activities in case of budgeting restraints.

The establishment of the database will make transparent management possible. It should be considered that decentralized road organizations as well as the public in general shall have access to the database or parts of it to provide all stakeholders with a thorough understanding of the situation. The hope of decentralizing road maintenance on rural roads is that it will enable development of smaller local based maintenance operations. The operations may be com-

[7] Internet services based on mobile phones are already widely used in Africa and plays a much stronger role here that most places elsewhere. Collection and submission of data via mobile phones to central serves is a very fast, efficient and cheap way of compiling data and could be ideal for maintaining the database with up-to-date and reliable data.

munity based, and aid in the development of labor based maintenance methods, with the maintenance of roads acting as a source of local income.

Execution

Road construction and maintenance is usually performed either on basis of force account where the employer (the government owned maintenance organization) is its own contractor or by contracting where private contractors are competing for contracts with the employer. In order to optimize work output compared with budgets it should be relevant to consider which setup is the most economical.

Force account is common in many countries but experience shows that it is not very economical and performance is typically poor. Since the employer is on "both sides of the contract", there are no contractual means whereupon he can enforce the performance by the contractor (i.e. him self). This tends to lower performance compared with a private contractor who is obliged to perform in order to be paid.

The force account concept tends to create a very rigid situation with little means for improvement and with no means to make use of the services from the private market and exploit the benefits this may offer.

A benefit of contracting the work out is that the Employer can avoid the double responsibility of also being a contractor. In particular he will have no burden of also being equipment and equipment maintenance manager. Further contracting will, if executed transparently and fair, promote efficiency and high performance by the contractor who in this can maximize his profit.

It must also be recognized that contracting the maintenance work to private firms depends on the availability of skilled contractors in sufficient capacity to undertake the works. This may be hard in an environment where contractors are already scarce and it may take some time before a fleet of competent contractors are available for offering their services.

Methodologies

The technology applied in maintenance is also critical for the economical performance. The key to optimize the choice of technology is economy. Assuming a free market (contracting) and design specifications being open for different technologies to reach the same result, economic considerations will naturally filter out the less economic technologies and promote the more economical technologies.

Equipment based technologies (EBT) means the application of heavy, labor-saving equipment, that is on the balance much equipment and little labors. Labor-based technologies (LBT) also uses equipment, but with more weight on manual work and less on equipment based work. So both technologies employ equipment as well as labor, but the balance is different.

In Mozambique the wages are much lower that in the industrialized countries. The economical optimal balance between equipment and labor input will there-

fore also be different. Equipment is used in the rich countries when it is economical beneficial, not because it is fancy. The same should apply in Africa.

However, much road maintenance in Africa is done by application of heavy equipment which is characteristic for work methods in the rich countries[8]. The result is that available cheap labor in Africa are not getting jobs they could have performed economically while labor in the rich countries are being employed in the production of the equipment.

Therefore we suggest that the work activities in road maintenance are analyzed with respect to suitability of labor or equipment based methods. In particular for gravel roads, many work procedures may be economically optimal by application of LBT.

Apart from being economically beneficial for the private investor (the contractor) making him more competitive and therefore also more beneficial to the road organizations, LBT creates cash flow in the small communities who provides the labor. Other considerations can be that LBT is much more robust in respect of equipment maintenance (tractors are much easier to maintain than heavy, hydraulic equipment) and the contractor is therefore not so vulnerable in case of mechanical failures. Dissemination of LBT on a large scale may also create a basis for local industry producing construction equipment for LBT.

Extensive experience from a number of African countries on LBT should be studied to identify work areas where it can be applied to the benefit of society.

[8] This may to some extent be attributed to the influence by donors who historically has encouraged EBT, perhaps out of interest in supporting their own equipment industries.

5 Costs of climate change

5.1 Introduction

For new construction, rehabilitation, or upgrading, the major work items are as follows:

- General
- Site clearance
- Drainage
- Earthworks
- Subbase, road base and gravel wearing course
- Bituminous surfacing and road bases
- Structures
- Ancillary works

5.2 Current costs

For construction of roads, upgrading and rehabilitation, the costs per kilometer have been retrieved from ANE (Prise 2007 – 2009) as listed in the following table.

Table 5-1 Average cost/km for contracts awarded by ANE

Construction Type	Cost / Km USD
Regional Roads Investment Program (construction of secondary, tertiary and vicinal roads)	49,000
National Roads Rehabilitation Program (mainly primary roads)	180,000
National Roads Upgrade Program (mainly upgrading to paved primary roads)	274,000
Paved Road Periodic Maintenance (mainly reseal and light rehabilitation in primary roads)	113,000

Source: ANE (RSS and PRISE)

Table 5-2 shows how big the difference in construction price there is between small-medium sized and major bridges. For investment of small bridges in Zambezia, the price estimate per bridge is $3.0. million Examples of construction of major bridges are the Zambezi bridge, the Unity bridge, the Moamba bridge and the Guijá Bridge. Mozambique Island Bridge was constructed in 1969, and due to the lack of maintenance, the traffic over the bridge was restricted only to vehicles with maximum weight of 1.5 tonnes and which are not wider than 193 cm., the expenditure for rehabilitation from PRISE is $4.0 million. The existing Tete Bridge has been undergoing excessive traffic, not envisaged when the bridge was built in the early 1970s, which has led to cables breaking and other problems. It has been undergoing rehabilitation and is subject to severe speed and weight restrictions. An alternative is upgoing, there will be a new bridge designed to be 1350m long, with an estimate cost of $109, which is the lion's share of 137 million dollars to be spent on improving the 250

kilometer long highway from Zimbabwe to Malawi which goes through the middle of Tete province.

Table 5-2 Bridge Rehabilitation and Construction Program (2007 -2009, USD million)

Name	Link	Province	Road no	Length	Est. project	PRISE (2007-09)
Zambezie Bridge	Caia - Chimuara	Sofa-la/Zambezia	N1	2,400	$ 85.6	$ 66.5
Guijá Bridge (Limpopo)	Guijá - Chokwé	Gaza	N221 - R856	500	$12.8	$7.7
Mozambique Is. Bridge	Mozambi-que Is. – Monapo	Nampula	N105	3,340	$2.5	$4.0
Meluli Bridge	Angoche – Moma	Nampula	N324	300	$3.3	$1.3
Unity Bridge (Rovuma)	Negomane - Mtam-baswala	Cabo Delgado	R1251	730	$12.3	$8.6
Moamba Bridge	Moamba – Sabie	Maputo	R409 / R811	300	$5.0	$3.5
Lugela Bridge	Mocuba - Lugela	Zambezia	R653	200	$6.0	$3.0
Tete Bridge	Tete City	Tete	N7	720	$7.0	$3.5
Zambezia Prov Bridges (EU)	Various	Zambezia			$5.2	$5.2
Licungo (2 bridges)	Malei – Maganja	Zambezia	N324		$6.0	$6.0
Cuacua (2 bridges)	Mopeia – Luabo	Zambezia	R640		$6.0	$6.0
Chueza River	Mutarara Corridor	Tete	N222		$3.0	$3.0
Rio Muíra Bridge	Mungari – Buzua	Manica	R950	240	$5.0	$5.0
Rio Mussapa Bridge	Dombe – Gogoi	Manica	N260	80	$2.0	$2.0
Rio Lucite Bridge	Dombe – Gogoi	Manica	N260	120	$3.0	$3.0
Rio Nhamu-cuarara Bridge	Mavonde - Zimbabwe border	Manica		80	$2.0	$2.0
Total					$166.7	$130.3

Source: ANE ("PRISE Implementation Plan 2007 – 2009: Final Summary")

Prices provided in these tables seem to be low compared to prices found from other sources and prices compared to other countries actual construction's costs. Many factors could have influenced the differences in prices, i.e. currency exchange rate, labor rate conversion factor, local fuel rate, local mechanic rate, material rates, etc.

Table 5-3 shows associated cost/km taken from the average cost/km of upgrading from a gravel road to a paved DBST (Double Bituminous Surface Treatment) supported by a granular base-course and sub-base, DS3standard. The unit prices were obtained on the basis of comparison and analysis of real market prices of similar projects previously implemented in Mozambique. The cost item percentages were made on the basis of the result of the preliminary design, the quantity of each work item, and the construction planning of the Project. The results are summarized in the following table:

Table 5-3 Cost item percentages for upgrading from gravel to paved road

Description	Percentage	Cost/km USD
Preliminary and general	28.7%	95,672
Earthworks	10.9%	36,508
Subbase, Road Base and Gravel Wearing Course Bituminous Surfacings and Road Bases	36.1%	120,435
Drainage	13.1%	43,555
Road furniture	0.6%	1,855
Miscellaneous	0.5%	1,738
Structures	7.2%	24,137
Dayworks	2.9%	9,700
Total	100%	333,600

Source: Final Report November 2007; The Study on Upgrading of Nampula – Cuamba Road in the Republic of Mozambique (Japan International Cooperation Agency)

5.3 Climate impact

Rainfall will have the most significant cost impact on the Mozambique's road network. Temperature and wind will have minor cost implications that should be dealt with during the design phase, and will not have an overall large influence on the cost of a climate resilient road. For this economic analysis, only the influence of increased rain is investigated.

From the climate change predictions, the data used corresponds to the largest change in 24 hour storm precipitation which is expected to be around 37% for the 100 years storm for the Mozambique Wet scenario and 19% for the Global Dry scenario.

5.4 Costs increases for construction of a climate resilient road

5.4.1 Preliminary and general

The costs associated with the General work item are not expected to increase for a climate resilient road in the future. This work item generally includes costing for accommodation, office space, AIDS prevention, and various other items generally unrelated to climate.

5.4.2 Earthworks

The cost item Earthworks include all the initial excavation and compacted fill, up to top of subgrade level, as well as the disposal of surplus soil. The increased rainfall may lead to increased ground water levels, which may have a negative impact on expansive soils. This will either require the increased removal of problem soils, increased use of chemical stabilizers in the native material such as lime or cement, or increasing the fill embankment height to raise the road surface. It is impossible to estimate the quantities that will be required in the future based on the limited information we have now.

As development in the country increases, more soils problems will be encountered requiring more use of these options.

Price of using chemical stabilization is unknown for the project, but based on average estimated prices for Ethiopia, for a road section requiring chemical stabilization, the increased costs associated are approximately 41,000 USD/km. Raising the roadway one meter for a 2 lanes and 10 meters carriageway cost between 10,000 and 40,000 USD/km. These solutions are not applicable every where and it is at the discretion of the engineer to decide when and where they should be used.

Many of these problem soils areas will be able to be determined before a problem is experienced if a 4 day soaked CBR test is used, and are not dependent on increase in rain but on the type of materials the road is built upon. For this reason, it is difficult to predict the cost increases associated with this item due to climate change. It is expected on average that the Mozambique Wet scenario will require between10% to 20% more investment in earthwork stabilization due to climate change. The Global dry scenario will require approximately 5% to 10%. These are increases associated with climate change; many areas that will experience flooding in the future most likely require some sort of stabilization now.

5.4.3 Subbase, road base and gravel wearing course and bituminous surfacings

This cost item includes all the sub items related to the pavement design. The costs associated with this work item vary extremely depending on the pavement design and surface dressing chosen. Most often, a gravel wearing course is in most cases the cheapest to construct but at the same time the least climate resilient solution.

In areas with high rainfall, it may be beneficial to seal the roads with a waterproof bitumen, rather than use a gravel wearing course in order to protect the investments to the subgrade stabilization and subbase materials. Gravel wearing course requires high maintenance and re-gravelling in order to maintain a road surface that sheds water quickly and is smooth to drive. The cost increases associated with this item will be directly dependent on the materials and the slope of the road, therefore there will be big differences on costs. Alternatives should be investigated. There is a large threat to gravel roads from allowing them to deteriorate to the point where they will need to be reconstructed. Cost beneficial analysis should continue to be used to determine the economic benefit of sealing the roads.

The pavement composition has a significant impact on the initial investment cost and future maintenance cost. Bituminous surfacing is the most expensive cost item of road and typically account for 20 to 50% of the total cost. It is unreasonable to suggest sealing every road. It is more cost feasible to seal areas that are most likely to fail, those with high gradients and high amounts of rain, or susceptibility to flooding. Research from Vietnam suggests sealing roads with gradients higher than 6% that receive more than 1000 mm of rain per year. ANE has developed a Paved Road Management Program (PRMP) as a new key element of the Strategic Maintenance Plan (SMP), as well as the Regional Roads Investment Program which focuses on tertiary and vicinal roads that has less funding and suffer in a higher degree the effect of the rainy season and lack of maintenance.

The cost difference between a bituminous paved road, and a high standard gravel road and an asphalt concrete road vary significantly depending on type of sealant used and unit prices of materials. There are substantial differences in haulage distances depending on the locations between the construction sections and the material sources. For the aforementioned project, a standard 200mm granular base course would cost around 50% of the price of a Double Bituminous Surface Treatment (DBST); and at the same time a DBST would represent 50% of the price of choosing an AC (50mm) and around 25% of an AC (100mm).

Paved shoulders serve a dual purpose of keeping pedestrians on the shoulder, (rather than walking on the more comfortable paved carriageway) and helping to keep the subbase materials dry. Having paved shoulders is a more expensive solution, but helps minimize maintenance and prolong the life of the roadway.

The cost increase of paved shoulders between 1.5 and 3 m wide is around 16,000 USD/km. Paving shoulders is expected to cost an additional 13% for this work item.

The decision on type of sealant used and the option to pave shoulders is a political one based on road use, importance, and economics. It is expected that these will continue to be the driving factors in the future.

As mentioned in the Road Sector Strategy 2007 – 2011, finding stock of suitable construction materials is a big problem over large areas of Mozambique

implying an enormous cost for the projects with no access to a full inventory of road materials. Granular materials represent the cheapest sub item of the price for building the subbase, road base and wearing course of a road, but big amounts of the material are required. It is expected that because of the increased rainfall, gravel roads will require more frequent maintenance and regravelling than under current climate conditions, therefore more material will be required. At the same time, lack of sound material may increase due to major climate events. The source for obtaining crushed stones shall be selected based on the distance between the construction site and the quarry. Distances would become higher and prices too. Therefore there may be increase in the cost of paving materials associated with increased rainfall, due to an increase on the amounts used if decided to pave shoulders or sections of gravel roads and increase of regravelling and at the same time, unit costs may become higher because of higher haulage distances.

If climate change becomes a driving factor, then for a more climate resilient road, it is expected that the cost of pavement design should an increase between 10% and 25% under the Mozambique Wet scenario and between 5% and 15% for the Global Dry scenario.

5.4.4 Drainage

The cost item Drainage includes: cross and box culverts, unlined side ditches, concrete lined side ditch as well as U-shaped ditches (open and covered).

In the hydrologic assessment conducted for the Study on Upgrading of Nampula – Cuamba Road, it was appreciated that the road was generally lower than the surrounding ground and had an earth/gravel surface with a poorly defined open drainage system. The side drains discharged surface water through irregularly positioned miter-drains. Crossing culverts on the road were observed at reasonably regular intervals. Some new culverts were recently constructed, and other culverts had headwalls repaired. Existing culverts and their inlets and outlets are generally in a good condition. However the width between culvert headwalls varies according to the existing road width, ground terrain conditions, etc. Furthermore, not all existing culverts can be extended due to their inadequate strength. Therefore, it was proposed that all existing culverts were replaced by new “Concrete Box Culverts” with sufficient capacity and strength.

In average for the aforementioned project, the cost of replacing a box culvert 1.0*1.0 is 8,700USD and a box culvert 2.0*2.0 is 27,300USD. So each box culverts represents 0,05 % and 0,2 % of the total cost of drainage of the project.

The hydrological assessment is conducted assuming that the culverts are free of debris and capable of handling full flow. Often times there is debris and siltation reducing the capacity of the culverts. Further studies should be done investigating using larger culverts, which may be easier to clean, and can hold more siltation while still allowing hydraulic capacity.

The minimum culvert size recommended by ANE is 600 mm for gradient > 2% and 900mm for a gradient < 2%..Table 5-4 shows the relationship between cul-

vert sizing and cost increases for standard sizes and for a road study in Ethiopia.

Table 5-4 Reinforced concrete culvert capacity and cost

Diameter mm	Cost/m USD	Capacity increase	Cost increase
900	400		
		30%	25%
1000	500		
		27%	20%
1100	600		
		24%	15%
1200	750		

Source: COWI 2008 for the Wukro-Agridat-Zalambesa Road Study in Ethiopia

Using data from a recent project on the Wukro-Agridat-Zalambesa Road in Ethiopia, the cost of increasing the sizing of all of the reinforced concrete pipes can be found. To increase the hydraulic capacity by a minimum of 27% namely 900mm to 1000mm and 1000mm to 1100mm, as well as their respective headwalls and outlets would cost an additional 10% to the drainage item, but only an additional 1% to the total cost of the project, an additional 5,000 USD/km.

The remaining drainage items such as ditches and drains are relatively low cost items, but their costs can be expected to increase relative to the increase in costs of culverts, namely 10%.

For a completely new road where minimum sized culverts and drainage elements are used for all crossings, cost is expected to increase comparable to the 25 year storm, 36% for the Mozambique Wet, and 19% for the Global Dry scenarios. For road upgrading projects, it is assumed that many of the structures will still have the hydraulic capacity for the new design storms.

5.4.5 Road furniture and miscellaneous

This item includes guardrails, signage and marking and concrete kerbs.

In Mozambique a program to update and replace road signs to reflect the new classification system is expected to be budgeted and implemented. Within the Road Sector Strategy, it has been accounted to replace or correct all signs within a year. There will not be additional costs associated to climate change.

5.4.6 Structures

The costs of structures is the result of the cost estimate carried out considering the foundation, substructure, superstructure, drainage, riprap protection, expansion joints and construction of temporary road.

For the study of upgrading the Nampula – Cuamba road, the estimated cost of building bridge structures accounted for 7,2% of the total cost of the project, whereas only the construction of the temporary road amounted 2,9% of this construction item. In this road project, 5 rivers and 37 waterways were considered along the 348km road part of the EN8 road. Because of the characteristics of the road and the existing structures, this study could be taken as a good representation of the state of the roads and structures of the country. In this study, it was found that small and medium sized bridges (with up to 60m in length) are most common, and it is assumed that small bridges with narrow widths would have been constructed during the 1930s-40s, while the medium sized bridges with 2-lane carriageways would have been built in the 1960s-70s. The bridges constructed with Japanese funds were completed in either 1998 or 2002, these bridges where the only ones built under international standard life loads.

Regarding the condition of the existing bridges, most of the bridges have been kept in good conditions for both superstructure and substructure. Significant damages were not observed but surface cracks, abrasion of the deck surface and missing railings were found in some existing structures. However, the study shows that only 46% of the existing 37 bridges found in the road section could cope with the current climate conditions, whereas 38% had to be replaced and 16% had to be reconstructed as new bridges. It is estimated that there are around 2000 bridges in Mozambique. If most of the small and medium sized bridges were built around 50 years ago, without using international standard life loads and possibly without accurate hydrologic data, it is very likely that the majority of those bridges would fail if a major event with a big increase in precipitation took place.

The cost difference of constructing a bridge or box culvert that has capacity for a 50 year storm compared to one that only has capacity for a 25 year storm is on the order of 36% more expensive for the Mozambique Wet scenario, and 19% higher for the Global Dry scenario. This follows that the IDF curves for a 50 year storm are on the order of 36% higher than the IDF curves for a 25 year curve (Mozambique Wet), and the bridge must be a minimum 36% larger in size to accommodate the capacity. For new bridge construction, the expected costs increases of bridges in order to accommodate expected flows in 2050 is expected to in the order of 36% for the Mozambique Wet scenario, and 19% for the Global Dry. However, much of the new road construction is upgrading existing alignments, and in these situations as much of the existing infrastructure is reused as possible. It is often found that the existing bridges were built based on the optimal river crossing, which often gives flow capacity larger than the design storm. Some of the existing bridges will have the hydraulic capacity for the design storms using the new climate predictions. However, just because a bridge has the capacity, does not automatically mean that it will have the scour protection needed.

Currently practice is to use gabions or other countermeasures after a problem is observed. The goal is to direct the river back to its original course under the bridge. The justification for waiting till after the problem has occurred is one knows bests where to apply the countermeasures. It is suggested to armor

banks that are prone to erosion during the construction phase, to help ensure the rivers stays in its original channel. By waiting till after a problem develops, it may be too late to successfully retrain the river. The increase in costs for initial bank and scour protection is expected to be around 300% for the Mozambique Wet scenario and 150% for the Global Dry. Typically scour protection is around 5-6% of the total cost of the bridge.

The cost increases associated with retaining walls may increase associated to an increase in erosion due to sea level rise and increase in rainfall. At the same time, slopes that appear to be unstable now will be more unstable in the future with increased rain, and should be avoided in the roadway alignment. If these areas cannot be avoided, it is not recommended to increase the investment of retaining walls and slope protection from their current levels as high investment slope stabilization efforts are often not successful.

Roads that follow rivers or are set in flood plains are subject to similar issues as those set in areas with unstable slopes. There is expected to be increases in flooding events, and the largest cost savings will come from not building roads in areas subject to large flooding events. If there are no other alternatives, then it is expected that there will be some need for increases in the effort of roadside river bank protection. The amount is impossible to calculate as it is completely dependent on the location of the road, which varies for each road.

The cost for a completely new road with all new bridges and structures is expected to increase in cost comparable with the increase in precipitation for a 100 year storm, 37% for the Mozambique Wet, and 19% for the Global Dry scenarios. For road upgrading projects, it is assumed that some of the structures will still have the hydraulic capacity for the new design storms, and the cost would be associated in replacing the structures that do not have hydraulic capacity, as well as increasing the scour and bank protection; however, according to the results from the Nampula-Cuamba road project, it could be expected that the majority of bridges would have to replaced..

5.4.7 Dayworks

Dayworks covering effective working rates and considering non-working days (i.e. rainy days, Sundays and holidays) has a significant impact on the construction schedule and therefore on the project cost estimate. Climate change may play a determinant role on the planning schedule of any construction project. It is impossible to determine in which degree the total cost would be influenced by an increase of temperature and precipitation, but in an attempt to include the extra cost associated to the climate change impacts, the Consultant recommendation is to increase by 2% the cost for the Global Dry scenario and by 5% for the Mozambique wet scenario.

5.4.8 Maintenance

Maintenance is not a work item for most cost estimates of new road construction, even though maintenance is the most important activity that will ensure the longevity and functionality of the construction investment. No climate

proofing investments, let alone road investments will be met without sufficient maintenance.

Increased rainfall and associated flooding will put more pressure on all of the road assets discussed above. A large portion of the maintenance required can be done using labor based methods. A climate resilient road will require full time maintenance, rather than annual or biannual maintenance.

The cost of maintenance is expected to climb drastically under the new climate scenarios. The frequency of large storm events is expected to increase by up to six times in the Mozambique wet scenario. Maintenance budgets, monitoring and repair for drainage structures is expected to need to be increased on a similar ratio in order to ensure that the existing drainage infrastructure is able to accommodate such an increase. Maintenance related to non drainage structures is expected to increase proportionately to the annual increase in rain, around 37% and 19% for the Mozambique Wet and Global Dry scenarios respectively.

Drainage
The benefit of using larger culverts is that they are easily cleaned using unskilled labor and small tools. Ditches can be cleaned in a similar fashion with the use of small tools and supervision.

Bituminous pavement repairs
Small patching of cracks should be done regularly, and can be easily done manually by unskilled labor with some supervision. If the small cracks are repaired early enough on using manual labor, it may not be necessary to bring out the larger paving machines later for a large repair.

Ancillary works
Gabions and scour protection can be repaired by hand with supervision. Landscaping and slope protection vegetation needs to be tended during the first years to ensure that the vegetation roots itself into the soils.

5.5 Summary of cost increase

For a high standard road, the cost increases for upgrading to paved standard taking into account the climate change scenario in 2050 are summarized in Table 5-5.

Table 5-5 Summary of cost increases to paved road DBST

Description	Current cost/km USD	Global Dry Scenario cost/km USD	Increase cost Percentage Global Dry	Mozambique Wet Scenario cost/km USD	Increase cost percentage Mozambique Wet
Preliminary and general	95,672	95,672	0%	95,672	0%
Earthworks	36,508	38,350 40,200	5-10%	40,200 43,800	10-20%
Subbase, Road Base and Gravel Wearing Course Bituminous Surfacings and Road Bases	120,435	126,500 138,500	5-15%	132,500 150,550	10-25%
Drainage	43,555	51,830	19%	59,235	36%
Road Furniture	1,855	1,855	0%	1,855	0%
Miscellaneous	1,738	1,738	0%	1,738	0%
Structures	24,137	28,723	19%	33,067	37%
Dayworks	5,615	5,730	2%	5,900	5%
Social Issues	4,085	4,085	0%	4,085	0%
Total Cost Increase Percentage	333,600	354,483-368,333 **6,3% -10,4%**		374,252-395,902 **12,2%-18,7%**	

Source: COWI

The values listed in Table 5-5 discuss the likely costs in adapting construction to make a climate resilient road taking into account the climate models for 2050. The values may be misleadingly low for the true cost of climate change as they only show the anticipated cost of building or upgrading a road to meet the minimum requirements as stated in the manuals recommended by ANE. The true cost would need to account for the increase in maintenance associated with the increase in precipitation, as well as the increased risk on existing structures. This is further explained in the Economic assessment.

All new paved road construction can be expected to require similar increases in cost. There is a large variability and uncertainty on the results due to the changeability in the landscape and likely conditions that are expected to be found. It is clear to show how an increase in precipitation will require an increase in drainage structure sizing, but it becomes more difficult to quantify it due to the lack of data from the country. Realistic costs of increases to earthworks and subgrade stabilization are completely dependent on what is found during the site investigations for each different project, therefore they are only possible to estimate on a project-by-project basis.

It is not expected that climate changes in the near future will require large changes to the methodology of high standard roads in Mozambique. The standards that they are designed for and should be built at are at a high level. Climate adaptation methods such as soil stabilization and paved shoulders are not guarantees that the road will function without a good drainage system and the required maintenance of patching, cleaning drainage structures, etc.

High standard gravel roads are expected to require cost increases in the same areas as paved roads, plus the additional cost of sealing in areas with high gradients and high rainfall. .

5.5.1 Methodology and base for broad costs

These cost increases are found using cost items information from the Upgrading of the Nampula – Cuamba Road in the Republic of Mozambique. The average costs per kilometer were calculated for one of the alternatives, with a total length of 347.63km and design speed=80Km/h, 2007 prices (applying an annual price inflation factor of 109.81% per year, average of 1996 – 2005 by INE). Contingency Costs (10% of total construction and non-construction costs) and Engineering Cost (8% of construction, non-construction and contingency costs) have to be added, as well as VAT (17%) and Compensation to obtain the market costs.

The estimated cost for the pavement item for a DBST (Double Bituminous Surface Treatment) assumes that it is supported by a granular base-course and sub-base. Unit prices of granular materials are on the base of findings suitable aggregates for road construction in quarries located close to the road project. Higher transport coefficients could in some parts of the country be relevant depending on availability of materials.

5.6 Economic costs of climate related incidents

5.6.1 Approach and methodology

In a traditional analysis the costs and benefits (in the remaining of this chapter we use *costs* for *costs and benefits*[9]) of a project are compared to a basis scenario (or 0-alternative) where the project is not carried through. If the costs of a project are lower than the costs in the basis scenario, the project is economically feasible and should be carried through.

Although climate changes are not a decision the same framework can be used assessing the costs of climate changes. Thus, the costs of climate changes can be estimated as the difference between the costs in a scenario *with* climate changes compared to the costs and benefits in a scenario *without* climate changes (or "basis scenario").

In order to make this comparison as accurate as possible it is necessary to have a clear understanding of what the situation is without climate changes, and what impacts the climate changes will have.

Since the climate changes are happening over time, it is necessary to make a clear description of the future in both scenarios; *with* and *without* climate changes including the amount of infrastructure, traffic growths and growth in GDP.

[9] Note that benefits can simply be perceived as negative costs.

Moreover it is necessary to describe how people and governmental agencies (e.g. road administrations) will react to climate changes. It is possible that climate changes could alter the road agency's plans of expanding the road network. Also, road users may alter their behaviour due to climate changes by choosing different modes of transportation or less climate affected routes in the future.

In the following it is assumed that climate changes will only affect the road agency's choice of adapting to the climate changes. That is, other choices made by the road agency (e.g. the extension of the road network), road users and others are not affected.

It is also assumed that the effects on infrastructure of climate changes will appear gradually following a linear path.

5.6.2 The user costs of climate related incidents

The cost of climate related incidents in the transport sector are - beside the repair and reconstruction cost etc. mentioned earlier in this chapter - primarily due to the traffic effects caused by the disruption of road service.

These costs can be divided into two main categories: 1) costs related to detours, and 2) costs related to delays. Detours are the result of major incidents where the road is closed for several days e.g. due to a complete wash away following a heavy rain fall. Delays are minor incidents where the road is closed for some hours e.g. due to water overtopping the road (flash floods).

The main costs for each category and stake holder are summarized in the table below.

Table 5.6 Main costs for each stake holder due to detours and delays

	Road users	**Road agency**	**Third party**
Detours / major incidents	Increased vehicle operating costs Increased time costs	Increased maintenance costs on alternative route	Increased external costs (pollution, accidents) due to more vehicle kilometre
Delays / minor incidents	Increased capital/opportunity costs Increased time costs	*- no or very small costs -*	*- no or very small costs -*

Based on the consultant's experience from several feasibility studies in Sub-Saharan Africa it is assessed that the main costs related to detours are born by the road users as the economic costs of pollution and increased maintenance costs per vehicle kilometre are marginal compared to the vehicle operating costs (VOC) and time costs (VOT) born by the road users. Therefore, the focus on the road user costs in this analysis.

The below table summarizes the applied economic costs incurred by road users in case of typical major and minor incidents.

Table 5.7 Economic costs to road users following typical major and minor incidents

2010-prices	**Description**	**USD per vehicle**
Major incidents	Road closed for several days. Average IRI of detour = 8, VOC = 0.63 USD/km, VOT = 0.03 USD/km	0.7 per km
Minor incidents	Road closed for few hours. Traffic waits for road to reopen. Capital / opportunity cost per vehicle is 1.49 USD/hour, Driver's and passengers time is 2.18 USD/hour	3.7 per hour

Source: Ongoing study of the Mekele-Abi Adi-Adwa road in northern Ethipia currently carried out by COWI A/S for the World Bank.[10]

Note: The used time values and vehicle operating costs implies that on average, vehicles will wait if the road is closed for less than 18 hours if the length of the detour is 100 kilometre.

In the following, incidents on major bridges (>30 m in length), minor bridges (<30 m.) and culverts are examined. These are assessed to be the most vulnerable elements of the Mozambican infrastructure.

[10] It has not been possible to obtain reliable estimates of VOC and VoT for Mozambique. Using estimates of VOC and VoT used in an Ethiopian context is not unreasonable, since the income level in the two countries is very similar. The two countries differ greatly in population density and geography which could have an impact on especially VOC. However, exploring the implications of these differences is beyound the scope of this study.

Figure 5.1 Bridge in Mozambique partly washed away

Source: Consultant

As described in chapter 3 as much as 50% of the bridges (mainly small and medium bridges/culverts) in Mozambique may already be experiencing capacity issues today. Based on the consultant's experience a best guess is that a typical culvert or minor bridge may be subject to a major incident (complete wash out) in a 100 year storm while minor incidents (water overtopping the road) occur to culverts in a 25 year storm and to minor bridges in a 50 year storm.

For major bridges the situation is slightly different. These bridges are not experiencing the same level of capacity issues today. Further, it is not expected that bridges of this magnitude are ever washed away. Instead there will be major incidents that require major repairs, and minor incidents that require minor repairs. It is the consultant's assessment that these large bridges may be subject to a major incident every 100 years and a minor incident every 50 years.

A major incident may close the road for up to 3 days before a temporary solution is established for a typical culvert. For bridges it may take as much as two weeks to establish a temporary solution.

Figure 5.2 Temporary bridge installation in Ethiopia

Source: Ethiopian Road Authority – Bridge management Branch

A typical minor incident of water overtopping the culvert/bridge could close the road for 8 hours. The below table summarizes the description of the typical effects on traffic and the yearly risk.

Table 5.8 Examples and description of typical traffic disturbances and effects on traffic

	Culverts	**Minor bridges (<30 m.)**	**Major bridges (>30 m.)**
Major incidents	Complete washout. Road is totally closed for 3 days until temporary solution is established. Length of detour is 100 km. For another few days the road has limited capacity. Yearly risk without climate changes - 1%	Complete washout. The bridge is totally closed for 14 days until temporary solution is established. Length of detour is 100 km. For another few weeks the bridge has limited capacity. Yearly risk without climate changes - 1%	Major damage. The bridge is totally closed for 14 days until temporary solution is established. Length of detour is 100 km. For another few weeks the bridge has limited capacity. Yearly risk without climate changes - 1%
Minor incidents	Water overtopping road. The road is closed for 8 hours until water is gone. Yearly risk without climate changes - 4%	Water overtopping bridge. The bridge is closed for 8 hours until water is gone. Yearly risk without climate changes - 2%	Water overtopping bridge. The bridge is closed for 8 hours until water is gone. Yearly risk without climate changes - 2%

Source: Interviews of local authorities in Addis Ababa and consultant's experience

Note: *Assume a typical federal road is designed for 2 year storm where 1/2 of the carriage is allowed to be flooded (this corresponds to a Design Standard 3 road (see ERA's Drainage Design Manual, Table 10-2). The AADT of the road is 1,000 and in case the road is flooded on average 150 meters are partly closed for 4 hours. In this time period the average travel speed is reduced from 80 km/h to 20 km/h. Including deceleration before and acceleration after the flooded part of the road each vehicle will be delayed for approximately 30 seconds.

Based on the information in Table 5.7 and Table 5.8 the cost of a major and minor incident can be estimated. The below table illustrates the costs for each category of important incidents on a road in Mozambique with an AADT of 1,000 vehicles.

Table 5.9 Typical road user cost of an incident on a road with an AADT of 1,000 vehicles, 2009-prices

1,000 USD per incident	**Culverts**	**Minor bridges**	**Major bridges**
Major incidents	198	925	925
- of which VOC	188	879	879
- of which VOT	10	46	46
Minor incidents	29	29	29
- of which capital costs	12	12	12
- of which time costs	17	17	17

Note: The above values are for 2009 for Ethiopia. As the value of time is expected to increase with GDP, the costs related to time are expected to be higher in the future.
Please note that the delays due to limited capacity on a temporary solution are not included in the calculations above as they are expected to be marginal compared to other costs.
* Since on average 1,000 x 4 / 24 cars are affected the total delay is on average 1.4 hours per incident. With capital costs being 1.49 USD/hour and time costs 2.18 USD/hour, the total cost of an incident is 5.1 USD.

The above table shows that the cost of climate related incidents may be significant. If a culvert is washed out the typical cost to road users is around 198,000 USD due to detours, while it may be as high as 925,000 USD when a bridge is washed out due to the long period where traffic has to use other routes.

The costs of a major incident to a minor and a major bridge are the same, as the consequences in terms of duration of closure and length of detour are assumed to be the same.

5.6.3 The expected road user costs in a scenario *without* climate changes

Given the yearly risk of major and minor incidents estimated in Table 5.8 the expected yearly costs to road users in a situation with no climate changes can be assessed for typical culverts and bridges.

For riverbank roads and inadequate drainages the expected costs have been calculated for one critical spot.

Table 5.10 Expected road user costs on a road with an AADT of 1000 vehicles, no climate changes, 2009-prices

1,000 USD per year	**Culverts**	**Minor bridges**	**Major bridges**
Total expected costs, 2009	3.2	9.8	9.8
Due to major incidents	2.0	9.2	9.2
- of which VOC	1.9	8.8	8.8
- of which VOT	0.1	0.5	0.5
Due to minor incidents	1.2	0.6	0.6
- of which capital costs	0.5	0.2	0.2
- of which time costs	0.7	0.3	0.3
Total expected costs, 2050*	3.2	9.8	9.8

Note: The above values are for 2009 for Ethiopia. As the value of time is expected to increase with GDP, the costs related to time are expected to be higher in the future.
*The expected yearly costs in 2050 are based on an average growth in time values of 4.4% corresponding to a growth factor of 5.7 from 2009 to 2050.

The above table illustrates that in 2009 the total expected road user cost due to climate related incidents is approximately 3,200 USD/year for a typical culvert while it is around 9,800 USD/year for a typical bridge.

In 2050 the costs are considerably higher, as the time value is expected to grow with GDP from 2009 to 2050 corresponding to 4.4% per year on average. In 2050 the expected cost on a road section with an AADT of 1,000 will be around 6,900 USD/year for culverts and 13,600 USD/year for a typical bridge.

5.6.4 The expected road user costs in a scenario *with* climate changes

In the future the yearly risk of major and minor incidents is expected to increase due to climate changes. How much the yearly risk of each type of incidents will change is very uncertain, but as based on the climate scenarios described in Chapter 2 and the hydraulic analysis in Chapter 4, the change could be as much as 25% by 2050 .

In the following, the expected road user costs are presented as a range. The endpoints of the range correspond to the expected costs associated with the two extremes in the climate scenarios described in Chapter 2. The full impact of the climate changes will not be felt until 2050.

The below table illustrates the yearly risk of each category of incidents with and without climate changes.

Table 5.11 Yearly risk of incidents with and without climate changes

	Culverts	Minor bridges	Major bridges
Risk in 2009 (i.e. without climate changes)			
Major incidents	1.0%	1.0%	1.0%
Minor incidents	4.0%	2.0%	2.0%
Risk in 2050 (i.e. with full climate changes)			
Major incidents	1.11%-1.25%	1.11%-1.25%	1.11%1.25%
Minor incidents	4.4%-5%	2.2%-2.5%	2.2%-2.5%

Note: The range with full climate change is the range in the applied scenarios

Given the expected change in the risk of major and minor incidents the cost of climate related incidents in a situation with climate changes can be estimated.

The expected yearly cost is estimated for a situation where the climate changes in 2050 are present today. That is, if the risk of incidents is 25% higher today as is the case in the scenario with the largest change (see Table 5.11) . This is done in order to give an illustration of how severity of climate changes with today's price level. In reality the climate changes will appear gradually over time.

The estimates are summarized in the table below.

Table 5.12 Future expected road user costs with climate changes costs on a road with an AADT of 1000 vehicles, 2009-prices

1,000 USD per year	Culverts		Minor bridges		Major bridges	
	Future expected cost	Increase due to climate changes	Future expected cost	Increase due to climate changes	Future expected cost	Increase due to climate changes
Total expected costs per year	3.5 - 3.9	0.3 - 0.8	10.9 - 12.3	1.1 - 2.5	10.9 - 12.3	1.1 - 2.5
Due to major incidents	2.2 - 2.5	0.2 - 0.5	10.3 - 11.6	1.0 - 2.3	10.3 - 11.6	1.0 - 2.3
- of which VOC	2.1 - 2.4	0.2 - 0.5	9.8 - 11.0	1.0 - 2.2	9.8 - 11.0	1.0 - 2.2
- of which VOT	0.1 - 0.1	0.0 - 0.0	0.5 - 0.6	0.1 - 0.1	0.5 - 0.6	0.1 - 0.1
Due to minor incidents	1.3 - 1.5	0.1 - 0.3	0.7 - 0.7	0.1 - 0.1	0.7 - 0.7	0.1 - 0.1
- of which capital costs	0.5 - 0.6	0.1 - 0.1	0.3 - 0.3	0.0 - 0.1	0.3 - 0.3	0.0 - 0.1
- of which time costs	0.8 - 0.9	0.1 - 0.2	0.4 - 0.4	0.0 - 0.1	0.4 - 0.4	0.0 - 0.1
Total expected costs, 2050*	7.6 - 8.6	0.8 - 1.7	15.1 - 17.0	1.5 - 3.4	15.1 - 17.0	1.5 - 3.4

Note: The above values are calculated for a situation where the climate changes are present in 2009. This is clearly not the case. However, the figures give an understanding of the costs, if we currently were living with the future climate changes.
* The expected yearly costs in 2050 are based on an average growth in time values of 4.4% corresponding to a growth factor of 5.7 from 2009 to 2050.

The above table illustrates that the expected cost of climate changes may be in the area of 300-800 USD per year for a typical culvert and 1,100-2,500 USD for at typical bridge in Mozambique if the climate changes were present in

2009. With an average GDP growth of 4.4% from 2010 to 2050 the expected costs in 2050 may be as high as 1,700 USD/year for a typical culvert and 3,400 USD/year for a typical bridge.

Clearly, the costs will vary significantly depending on the specific circumstances for each culvert and bridge. Not only due to variations in climate change related changes of risk, but also due to the length of available detours, the quality of detours, composition of vehicle types etc.

The traffic levels will also have a significant influence on the expected costs of climate changes. The costs of incidents and the traffic level are linear related such that e.g. a road with an AADT of 3,000 will have 3 times as high costs as the example with AADT 1,000.

5.6.5 Conclusion on the costs of climate related incidents

The above calculations has illustrated that the road user costs of climate related incidents may be substantial even with today's climate. In 2050 the climate change related costs may result in additional user costs of 10-20% depending on the climate scenario, if adaptation measures to compensate fro the changes have not been made.

6 Economic assessment of adapting to the climate changes

6.1 Costs and benefits of adaption

In section 5.6.2 the cost of climate changes were assessed for typical types of infrastructure based on general examples. The examples illustrated that the climate changes will increase the yearly expected road user costs for these infrastructures by 10-20% (see Table 5.12). In order to minimize the increase in these costs, an adaptation strategy could be beneficial.

Adapting to the climate changes is economically feasible if the costs of adaptation are lower than the cost of "doing nothing". Hence, one way to evaluate an adaptation strategy is to assess, whether the yearly costs of avoiding the increased risk due to climate changes are lower (and thus feasible) or higher (non-feasible) than the increase in the expected cost when doing nothing.

In Table 6.7 this means that if avoiding the increase in expected yearly costs in 2050 is lower than 1,700 USD per year for a typical culvert, the adaptation strategy is feasible.[11]

6.1.1 Adaptation: Making new roads climate resilient

One way to adapt to the future climate changes is to increase the size of culverts, bridges etc. on new/reconstructed roads in order to address the increased intensity in rain fall.

Example: A typical culvert
In order to avoid the increased risk of incidents following the climate changes, the size of a typical culvert needs to be increased by approximately 25%. The cost of increasing the size of a typical culverts are described in chapter 45 and are summarized in the table below just like the annualized costs are calculated based on the cost information.

[11] Please note that there are many ways to adapt to climate changes. One way is to fully avoid the increased risk of major and minor incidents. But it is possible that a less significant adaptation strategy, where only some of the increase in risk is avoided, is better. In order to keep the calculations general, only the former is evaluated here.

Figure 6.1 Example of inadequate culvert sizing when climate changes

Table 6.1 Adaptation costs: Increasing the size of culverts.

	Do nothing	Adaptation: Larger culverts	Difference: cost of adaptation
Construction costs	5,000	6,000	1,000
Life time	50	50	0
Yearly risk of destruction (major incident)	1.1%-1.3%	1.0%	0.1-0.3%
Repair costs*	6,000	7,200-9,000	1,200 - 3,000
Annualized costs			
Annualized construction costs	602	722	120 - 301
Annual expected repair costs	83-94	75	5 - 15
Total annualized costs	685-696	797	126 - 316

Note: The annualized costs have been calculated using a discount rate of 12%
*Repairing the culvert is more expensive in the adaptation-scenario. However, with larger culverts the damages to the surrounding road is less than in the "Do nothing"-scenario, so the repair cost of an incident is expected to be the same in both scenarios.

Table 6.1 illustrates that the cost of adaptation are relatively low for the typical culvert. It is estimated that the increased risk of incidents on a culvert can be eliminated for approximately 126-316 USD/year which is significantly less than the cost to road users in the "Do nothing"-scenario which is 800-1,700 USD/year (see Table 6.2 below).

Other examples

Similar calculations have been carried out for a typical minor bridge (20 m box culverts). This showed that the cost of adaptation for a typical minor bridge can be estimated to 13,794-31,350 USD/year which is much higher than the cost of

no adaptation which was assessed to be 1,500-3,400 USD/year for bridges (see Table 6.2 below).

For major bridges the cost of adaptation is prohibitively high at 63,400-357,000 USD/year. This exceeds the cost to road users by doing nothing by many orders of magnitude.

Table 6.2 Overview of adaptation cost and road users costs

USD/year per unit	**Culverts**	**Minor bridges**	**Major bridges**
Cost of adaptation	126-316	13,794-31,350	63,431-356,699
Road user costs if "do nothing", 2009	347-789	1,082-2,458	1,082-2,458
Road user costs if "do nothing", 2050	757-1,721	1,498-3,405	1,498-3,405
Is adaptation feasible?	Yes	No	No

Table 6.2 illustrates that for culverts only, the cost of adaptation is cheaper than the additional cost to road users without adaptation. This means that the road agency should adapt their design manuals on culverts to adapt to the expected climate changes.

The estimation of the expected costs to road users is based on an AADT of 1000. If the AADT is increased to 10,000, then it will become economically feasible to adapt to the climate changes on the minor bridges.

The very high costs of adaptation on the major bridges would require an AADT so large that it would probably exceed the bridges capacity.

6.1.2 The existing road network

It is also possible to reconstruct the existing road network in order to make it climate resilient in the future. This can be done by increasing the size of culverts, replacing existing bridges etc.

However, as long as the infrastructure is functioning at full capacity, the capital cost of adaptation will not merely be the difference in investment costs between designs with and without adaptation. The cost of adaptation will instead be the full investment cost of the new infrastructure.

Thus, it is assumed that on the existing road network, adaptation will take place as the life time of the infrastructure is exceeded or the infrastructure is destroyed by climate (or other) related incidents.

Hence, for the existing infrastructure the costs of the increased risk of incidents will be born partly by the road users who will experience a decrease in the network quality due to climate changes.

6.1.3 Conclusion on adaptation

Adapting to climate changes by eliminating the increase in road user costs completely (full adaptation) is likely to be a feasible strategy for most new road infrastructure.

Whether it is the best strategy is not investigated further in this project[12], but the increase in road user costs compared to the relatively low costs of adaptation indicates that a full adaptation strategy may be the best strategy.

For the existing network, an adaptation strategy where adaptation takes place as the life time of the infrastructure is exceeded or the infrastructure is destroyed by climate (or other) related incidents is expected to be preferable.

Since the road users do not experience any changes from climate changes with full adaptation, the cost of climate changes for new roads are the increased costs for the road agency.

6.2 A rough estimate of cost of climate changes in Mozambique 2010 - 2050

This section describes the methodology which should be applied for calculating the cost of climate changes. Unfortunately, the lack of data on the road network in Mozambique prevents a full calculation of the cost of climate changes.

Section 6.1 above illustrated that adapting to the climate changes are likely to be economically feasible for new roads. Note that the costs of fully adapting are not the same as the costs of climate changes.

In order to assess the feasibility of adaptation we compare a situation *with* climate changes and *no* adaptation to a situation *with* climate changes and *with* adaptation. When assessing the cost of climate changes we should compare a situation *without* climate changes (and hence no adaptation) to a situation *with* climate changes and 1) *with* adaptation if feasible, 2) *without* adaptation if adaptation is not feasible.

Earlier it was argued that it is not feasible for the existing road network therefore the costs related to climate changes are assessed using 2). For new roads adaptation is likely to be cheaper than no adaptation, and it is assessed that full adaptation for new roads is feasible and will be carried through. Hence, the assessment of the climate related costs for new roads apply to situation 1) above.

6.2.1 Costs related to the existing road network

The existing road network is the infrastructure which exists today. If a bridge or other infrastructure is reconstructed because it exceeds its life time or because it is washed away, it is assumed that the new bridge will be designed to be climate resistant such that after a reconstruction there are no longer any costs to road users due to climate changes.

[12] An adaptation strategy where the road users face some increase in their costs may be even better.

Road agency
The road agency incurs changes in four cost items:

1 An increase in the expected yearly reconstruction costs due to a higher risk of wash aways.

2 A higher reconstruction cost when the infrastructure exceeds its lifetime in order to make it climate resilient.

3 A change in the expected scrap value of the infrastructure in 2050 as the higher risk reduces the survival chances of the current infrastructure.

4 Increased costs to road maintenance due to more sedimentation and other factors related to climate.

For the first cost item, the road agency's costs in each scenario (*with* or *without* climate changes) can be calculated as the cumulated number of infrastructure items which are expected to be washed out or destroyed in another way due to climate changes x the yearly cost of building this infrastructure.

If e.g. 20 bridges are expected to be destroyed in 2020 *without* climate changes and 21 are expected to be destroyed in 2020 *with* climate changes, then the costs in each scenario are calculated as follows:

- Costs *without* climate changes: 20 bridges x yearly costs of *normal* bridge.

- Costs *with* climate changes: 21 bridges x yearly costs of *resilient* bridge.

The second cost item can be calculated as the cumulated number of infrastructure items which are expected to be washed out in *both* scenarios (*with* and *without* climate changes) x the early *extra* cost of building climate change resilient infrastructure.

That is, if 1,000 bridges are past their life time cycle in 2020, then the road agency's yearly extra costs of making these bridges climate resilient are

- 1,000 bridges times the extra yearly cost per bridge to make them climate resilient (see Table 6.2, " Cost of adaptation" in section 6.1).

The third cost item is the difference in the expected scrap value in 2050 given the risk of wash aways or other climate related incidents in each scenario *with* and *without* climate changes.

The fourth cost item can be estimated as the current optimal road maintenance budget times the necessary increase in maintenance in order to keep roads in an adequate condition. It is expected that the maintenance costs will increase with 105%-165%[13] in 2050 due to the climate changes. Therefore the increase in maintenance costs du to climate changes in 2050 can be estimated as the cost of the optimal maintenance strategy *without* climate changes times 105%-165%.

Cost item 1-3
It should be noted, that as indicated in section 4, as much as 54% of the current bridges and culverts may be in need of reconstruction simply to meet the hydrological demands today. It stands to reason, that as precipitation increases, even more bridges and culverts will suffer from inadequate hydrological capacity.

Unfortunately, the level of detail in the data available for Mozambique does not allow a detailed calculation of how increased precipitation affects the costs of repairs and reconstruction on bridges and culverts.

Cost item 4
Increased costs to road maintenance due to more sedimentation and other factors related to climate are related to cleaning of ditches, cleaning of roads after land slides etc. which can not easily be avoided by making the infrastructure climate resilient.

According to the PRISE implementation plan the expenditure on maintenance in 2009 will be roughly 100 million USD. Due to absorbtive capacity problems, the real need is at least 169%[14] of the budgeted maintenance.

Assuming that the increase happens (linear) gradually from 2010 to 2050 the net present value of the increase in maintenance costs to keep the original service level due to climate changes can be assessed to 292-459 million USD (net present value) in 2009.

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[13] In Ethiopia, it was estimated that the increase in maintenance would be 150% in the wet scenario. Due to a lack of data in Mozambique, this figure has been scaled by the differences in climate data, to yield this range.

[14] In the PRISE implementation plan it is stated that maintennance on unpaved roads is budgeted at 88.6 million USD while the actual needs are estimated to be close to 150 million USD. This provides a rough estimate of the ratio of needed maintenance over budgeted maintenance of 169%.

Conclusion on the road agency's total costs due to climate changes, existing network

Maintenance on the existing infrastructure alone will increase by approximately 300-450 million USD (measured in NPV). Thus, maintenance alone will pose a significant financial challenge.

Road users

In the future, the road users will experience more incidents where roads are closed etc. due to the climate changes.

These costs were calculated in Table 5.9, and given information about changes in risk and the number of each infrastructure the cost to road users due to climate changes can be estimated.

The below table summarizes the number of typical types of critical infrastructure on the federal network. The number of culverts in Mozambique has been estimated by comparing to Ethiopia and weighing by the size of the national road network in the respective countries. Further, it has been estimated, that 1/3 of all bridges are longer than 30 m.

Table 6.3 Amount of infrastructure

	Number of affected infrastructure
Culverts	25,457
Minor bridges	1,333
Major bridges	666

Source: ENA and own assumptions

Based on the figures from Table 6.3 and the information about road user costs following incidents and the future expected climate changes, the net present value of climate related costs can be assessed for each scenario, *with* and *without* climate changes. The result is presented in the table below.

Table 6.4 Road user costs due to climate related incidents 2010-2050, NPV 2009

NPV 2009, Million USD	**Culverts**	**Minor Bridges**	**Major Bridges**	**Total**
Without climate changes	1,033.9	104.2	52.1	1,190.1
With climate changes	1,056-1,083	106.2-108,8	53.1-54,4	1,215.3-1246.8
Difference: CoCC	22.1-49.8	2.0-4.6	1.0-2.3	25.1-56.7

The table above shows that the climate change related increase in road user costs on the existing network from 2010 to 2050 is around 25-57 million USD in net present value. The climate change related increase in road user costs are partly mitigated by the fact that destroyed infrastructure will be replaced by climate resilient infrastructure. If the reconstructed infrastructure was not climate resilient the increase in road user cost would be approximately 50% higher.

The major contributor to the increased costs is the increased risk of culvert incidents due to the very large number of culverts in the road network.

Third party costs
It is expected that the increase in emissions costs etc. due to detours following incidents are marginal compared to the road user costs, and these costs have not been estimated.

It should be noted that in case the adaptation strategies affect other stake holders in the economy, there may be third party costs. For example, some adaptation strategies (e.g. increasing the elevation of a road) may affect the behaviour of the water and divert it to other places, where it may harm crop production or the like.

Such potential costs should be handled as externalities of adaptation in the road sector when deciding whether an adaptation strategy is feasible or not.

6.2.2 Costs related to the future road network

There is no available information on the future investments in infrastructure in Mozambique. In the PRISE implementation plan, it is reported that the total budget for the road sector in Mozambique in the period 2007-2009 is roughly 1 billion USD. The budgeted investment in construction and reconstruction costs is roughly 780 million USD or 260 million USD/year.

In chapter 5.4 it was found that the increase in construction costs of adapting a paved road to climate changes in the period 2010 to 2050 will be in the range 6%-19%. The net present value of this increase in construction costs is 25.5-81 million USD if this annual investment level is maintained in the next 40 years. Again, the reason for this relatively low amount is that the increase in construction costs is assumed to appear gradually (i.e. linear) from 2010 to 2050.

Road users
Since the screened adaptation strategies eliminates the expected increases in risks of infrastructure failures, the cost to road users are zero.

That is, the road agency increases the design and maintenance standards such that the road users experience no climate change related increase in costs.

Third party costs
Since the adaptation strategies will ensure that the traffic is not affected, no cost for third party is expected.

It should again be noted that in case the adaptation strategies affect other stake holders in the economy, there may be third party costs. For example, some adaptation strategies (e.g. increasing the elevation of a road) may affect the behaviour of the water and divert it to other places, where it may harm crop production or the like.

Such potential costs should be handled as externalities of adaptation in the road sector when deciding whether an adaptation strategy is feasible or not.

6.2.3 Total costs of climate changes in the Mozambican road sector when adapting

In total the cost of climate changes could amount to 550-600 million USD (in net present value). As a point of comparison, according to the PRISE implementation plan, the total road sector budget for the period 2007-2009 was roughly 1,000 million USD, i.e. roughly 333 million USD per year.

Clearly, these estimates are very uncertain for several reasons. Besides the uncertainties about AADT, change in risk etc. as well as the assumptions made in order to generate key data, it is also unknown how correlated the risks are. If two culverts are washed out on the same road section the cost are likely to be less than two times the cost of one culvert, as it may be possible to repair both culverts simultaneously.

6.3 Economic summary and conclusions

Based on the economic screening of adaptation strategies above and the assessment of cost of climate changes, it can be concluded that

- The cost to road users due to climate related incidents may be substantial even with today's climate and are expected to increase with as much as 10-20% by 2050 assuming adaptation on new and reconstructed infrastructure only.

- Adapting to climate changes by eliminating the increase in road user costs completely (full adaptation) is likely to be a feasible strategy for some road infrastructure, e.g. culverts.

- For the existing network, an adaptation strategy where adaptation takes place as the life time of the infrastructure is exceeded or the infrastructure is destroyed by climate (or other) related incidents is expected to be preferable.

- For the existing road network the climate changes will incur costs on both road users and the road agency. The major cost item is expected to be increased maintenance in order to keep the roads up to design standards.

7 Policy implications, engineering measures and strategy for adaptation

7.1.1 Introduction

The cost of climate changes in the road sector from 2010 - 2050 is roughly estimated to be around 0.6 billion USD measured as net present value in 2009, but it is a very uncertain estimate. This is roughly 2 times the current annual road budget.

Mozambique has the principle knowledge needed to design and keep their roads up to standard, especially if some of the data gaps on current climate can be solved in the coming years. From the research done, a key element to ensuring climate resilience after the initial construction is sufficient maintenance. Without routine maintenance, there is no chance for a road to meet its design life in today's climate, let alone the future climate. The climate changes predicted do not suggest that the problems in the future cannot be accommodated with today's engineering solutions in Mozambique. A climate resilient road in the future in Mozambique will be very similar to a climate resilient road right now.

7.1.2 Policy implications

The road owners will experience increased costs to maintain current service levels for both existing and new infrastructure.

Yearly reconstruction costs for existing roads will increase because of a higher risk of damage each year (the average lifetime is decreased) in combination with higher unit reconstruction costs to make reconstructed roads climate resilient when they are damaged/their life time is exceeded.

For the existing network, an adaptation strategy where adaptation takes place as the life time of the infrastructure is exceeded or the infrastructure is destroyed by climate (or other) related incidents is expected to be economically preferable.

New climate resilient roads are more costly - roughly 6% to 20% higher costs - to build so investments budgets have to be increased or the amounts of new roads to be constructed will have to be reduced.

Revision of parameters used for the design storm in order to create a robust standard design flood estimation method for all drainage systems and structures

is essential and a continuously search for the optimal balance between climate risks and adaptation costs in the country is needed. Adapting fully to climate changes so transport users are not affected is likely to be a feasible strategy for some new road infrastructure - especially culverts and riverbank protection. For structures the specific conditions decide if it is economic feasible to adapt fully to the climate change.

Increasing sea levels and the large variation in ocean tides is a big challenge for part of the infrastructure and the cities located in low areas in Mozambique. Basically, the **choice is either to protect existing road infrastructure by investing in protective coastal defenses, e.g. sea walls, or gradually relocate the infrastructure** (and the population) to more stable areas. The obvious measure is not to rebuild in areas that will be destroyed from the next cyclone, or design protection so that the next cyclone effects will be diverted around important areas

During initial investigations for a new or reconstructed bridge/road or replacement of an existing infrastructure **the location should be thoroughly investigated.** It should be tested if the bridge or road could be placed in a more stable environment and if additional constructions costs over time will are likely to be more than covered by savings from a smaller risk of flooding.

Adequate road maintenance is essential for the lifetime and service level of both existing and new roads. The **key element to ensuring climate resilience after the initial construction is sufficient maintenance.** Without routine maintenance, there is no chance for a road to meet its design life in today's climate, let alone the future climate. **Strengthened focus on road maintenance and significantly more spending - probably up to around 0.5 billion USD over the next 40 years compared with today - will be a vital cost effective adaptation measure**. This will also benefit the road users dramatically but it requires a big change is current spending patterns in the road sector.

The general implication is that **only in exceptional cases it will be economically beneficial to reconstruct or strengthen existing roads and structures** before they are damaged/normal life time is expired.

Research to strengthen knowledge about the existing climate will be very valuable. This could include areas like hydrological data and models which will improve estimation of design floods or sea level data which can be used for more accurate assessments of the need for coastal defenses. Both types of data are essential for design and investment decisions. Finally, it is essential to record and analyze results of the ongoing innovative road and bridge constructions in Mozambique e.g. sections of N1 Highway near Xai Xai which has been designed with a series of smaller bridges in order to accommodate frequent flooding.

7.1.3 Engineering measures

The priority recommendations listed below cover measures and changes that can be started immediately. The following engineering measures are identified:

Design

- Revise parameters used for the design storm that is in order to create a robust standard design flood estimation method for all drainage systems and structures.
- Consensus detailed geotechnical, structural and bridge hydraulic design for scour related issues.
- Accommodate the SATCC guidelines to local conditions.
- Investigate the need for river training and increased channel maintenance and bridge scour protection.
- Design culverts that cause limited damage to road during floods.
- Investigate the use of spot improvements in high risk areas.
- Design gravel roads and community roads with a variety of materials suitable for the climate and topography.
- New alignments need to consider likely future changes to environment considering increases in rainfall, groundwater, etc.
- Robust Quality Control System for the data collected during the planning stage because these data will be used in the decision processes for subsequent activities.
- Due to lack of good material in some areas of the country, a full scale soil survey specifying the location of sources of materials (especially gravel for wearing course, fill material, selected subgrade, sand etc.) should be undertaken prior to the road construction.
- Develop Guidelines for Quality Assurance Procedures and Specifications for Road Works, subdividing the guidelines in regions focusing on local materials.
- Require 4 day soaked CBR testing for all soils materials tests.

Maintenance

- Prioritize 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.
- Repair and clean channel and drainage structures in high risk areas before the rainy season.
- Increase maintenance in structures if thermal expansion has not been considered and accounted for adequately.
- Prioritize paving maintenance in high rain areas.
- Allocate more funds for maintenance of the current roads.

- Community based labor for maintenance of rural roads.
- Append the Bridge Management Branch with the latest Plan of Action for Bridge Scour Evaluation from the FHWA (Federal Highway Administration from the United States of America).

Research

- Create database for bridges and culverts.
- Develop standard hydrological guidelines with rainfall maps for Mozambique that can be used by all engineering consultants on smaller infrastructure projects.
- Investigate the option of using different wearing courses other than gravel.
- Expand methods for slope stabilization and protection.
- Further research on suitability of marginal materials on road construction.
- Establishment of a database with an extensive inventory of road building materials.
- Add a chapter to the design manuals focusing on climates impacts on roads and bridges investigating engineering solutions.
- Continue improving models for the prediction of floods magnitudes and probability of these floods updating them with latest climate change scenarios data.

7.1.4 The strategy forward for climate change adaption in the road sector

A future strategy needs to be flexible, adaptive and robust - and acknowledge that the current scenarios and climate models show a large variability in predicted rainfall patterns, which are the most important design criteria for roads and structures.

Taking the mean of the climate scenarios/climate models used in this study as the most likely future development, the long term increase in engineering costs due to climate change may be important but not excessive if dealt with proactively in the regular planning and design processes.

In the short run (next 5 years) the following initiatives are recommended:

- Research is needed in the accuracy of the design parameters in predicting sedimentation and runoff
- Based on this research the design storm parameters for new roads and structures are recommended to be adjusted to reflect significant climate changes - after due consideration to an acceptable future safety level.
- The good and comprehensive design manuals are recommended to be revised so that the climate-related issues and solutions are presented clearly e.g. in an additional chapter. Having a chapter dedicated to the climate and

environmental impacts on the road would make it easier for the designer to choose quickly and efficiently

- As the maintenance need will increase according to the expected more frequent heavy rainfall It is recommended to investigate if it is feasibly to change and/or enlarge the drainage system in specific areas prone to erosion and flooding to reduce the risk of total failure and consequential damage and for reduction of the climate change related need for increased maintenance.

In the long run the following initiatives are recommended:

- Establishment of a process to review climate-related parts of the design guidelines at regular intervals (5 or 10 years) to take account of most updated information on observed climate change impacts and the need to balance climate risks and economic feasibility
- Ensure that the excellent maintenance strategy in the current Road Sector Plan is implemented
- Development of reliable and accurate hydrology models as it is a common problem that this is lacking

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9 Appendix

9.1 Climate impacts on road assets

9.1.1 Temperature

Bridges

The effect of temperature on bridges is mostly seen in the thermal expansion of the material used. The most common method of dealing with thermal expansion is the use of expansion joints. If the expansion joints are properly sized, a wide range of temperatures can be accommodated. A challenge with 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 temperature changes, the length of bridge, and the type of material used, (reinforced concrete, steel girder, etc.)

Pavement design

Temperature has an affect on the stiffness of the asphalt. A poor asphalt mix will have a greater chance of cracking and other deformations if the temperature gradients are not accounted for correctly in the design.

The difference in price between the various grades of penetration grade bitumen is not considerable. Designing for different temperature gradients in the future should not have an effect on the price.

9.1.2 Rain

Bridges

The largest immediate impact seen to bridges will come from the increased flow in the hydraulic channels. Flood events have the potential to cause serious damage around the abutment and pier substructure elements that hold the bridge up.

One of the most common causes of bridge failure comes from scour, or erosion of the bank materials. There are three types of scour affecting a bridge:

- Local scour occurs with the removal of materials around bridge piers or abutments.
- Contraction scour is the removal of river bed material from the bottom and sides of the channel that is caused by an increase in speed of the water due to the bridge opening being smaller than the natural channel.
- Degradation scour is a natural process of bed material being removed, but may remove large amounts of material at a time.

During flood events the increased energy of the river removes the supporting soils surrounding the piers or abutments. The piers eventually lose their structural integrity due to the loss of their foundations and collapse. The erosion on

the banks occurs in a similar mode. The flood waters erode the soil underneath or behind the abutments made into the existing banks of the river. As the soil is washed away, the abutment loses its reinforcing strength and bridge failure occurs.

Some of the low volume community roads use low cost solutions to span the river. With an increase in floods these can be expected to need replacing more frequently, with a greater disruption in the traffic flow.

A side effect of precipitation and increased flooding is the increase of sedimentation. Sedimentation material can come from anywhere in the watershed subject to runoff and erosion. Erosion is increased in areas with loose soils and little vegetation, which is exasperated by poor land management and drought. Sedimentation affects bridges by raising the water level of the channel upstream of the bridge. As the water level rises, the width of the river increases which adds increases in shear stresses on the abutment walls. The sedimentation is sometimes amplified by the structure itself. If the bridge or culvert is not sized large enough, the water will back up around the structure causing the velocity of the river to slow down, giving opportunity to greater sediment deposits. Once the flood waters recede, a large deposit will be left. If this deposit is not removed, during the next flood there may again be an increase in backwater from not only the undersized structure, but also the increase in sedimentation from the previous flood. It cannot always be expected that a future flood will remove the sediment deposited from the previous storm event.

In the last years several bridges collapsed due to floods caused by heavy rains and cyclones.

It can be assumed that the initial under sizing of the culvert has aided in these current problems. The original undersized culvert acted as a pinch point in the channel, causing the flood plain to widen, and the aggradation of the channel. Each replacement bridge has been undersized enough combined with the increase in flooding and sedimentation to increase the original problem. The cost of replacing these bridges is most likely more than building one hydraulically adequate, or even oversized bridge to begin with.

Increased precipitation also has the potential to increase standing water on the bridge platform. If the bridge deck poorly drains the water, there is the risk of hydroplaning. Increase in water on the bridge will also accelerate corrosion of the bridge substructure if water is allowed to leak through the expansion joints on the bridge or through potholes in the AC wearing course.

Culverts

Precipitation affects culverts in similar ways as bridges. Culverts are susceptible to scour in the same ways as bridges, and are subjected to similar problems with siltation and aggradation.

Culverts can be more susceptible to sedimentation deposits as Figure 9-1 shows. Due to their smaller opening sizes, they are more prone to plugging from flood debris and sedimentation. When the culverts are partially filled with

debris, their hydraulic capacity is reduced and the potential for failure is increased. A likely scenario for the culvert in Figure 9-1 is during the next storm, the water that is not able to pass through the culvert will overtop the road.

Side drainage is susceptible to get eroded, especially when the road profile is lower than the surrounding ground. The erosion problem results from various causes such as the materials used for the drains (earth drains) and the accepted flow velocities. The SATCC Standard regulates the maximum flow velocity for the prevention of scouring (erosion) as follows.

Table 9-1 Scour velocities for various materials

Material	Maximum permissible velocity (m/s)
Fine Sand	0.6
Loam	0.9
Clay	1.2
Gravel	1.5
Soft Shale	1.8
Hard Shale	2.4
Hard Rock	4.5

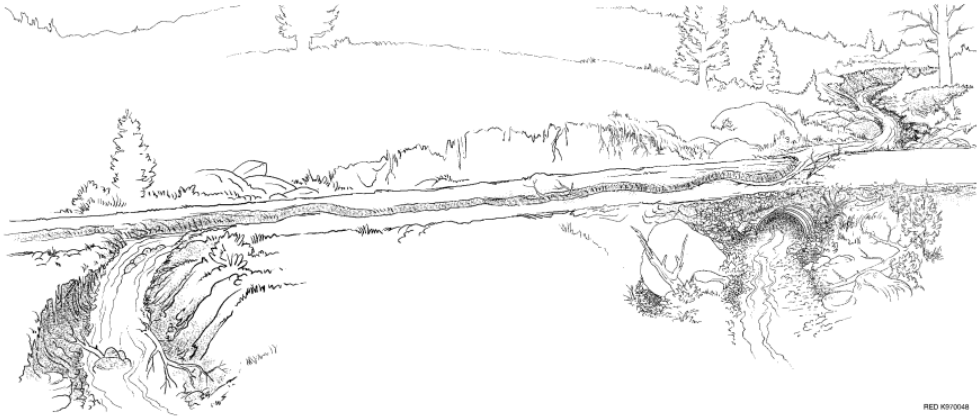
Source: Code of Practice for the Geometric Design of Trunk Roads (SATCC)

In order to ensure good drainage of the road and side earth drains, minimum longitudinal gradient are recommended for various flow velocities.

The damage from a flood that overtops the road depends on the size and force of the flood, and the wearing course and stability of the road. If a design storm were to pass through the culvert in the figure above there would be a temporary delay to traffic while the flood waters overtopped the road. The damage from limited overtopping usually results in some loss of pavement near the shoulders, loss of shoulder material, and some increased scouring around the inlet and outlet of the culvert as seen in Figure 9-2. The paved wearing course helps to keep the road intact during overtopping. Due to the siltation of the culvert in the figure above, the likelihood of overtopping and subsequent damage will occur more frequently than the 10-25 year design storm it was most likely designed for.

Depending on the stability of the road section, overtopping flood waters have the opportunity to travel through the roadway as seen in the figure below. This is called diversion potential, and is a common scenario with flooded culverts on gravel roads.

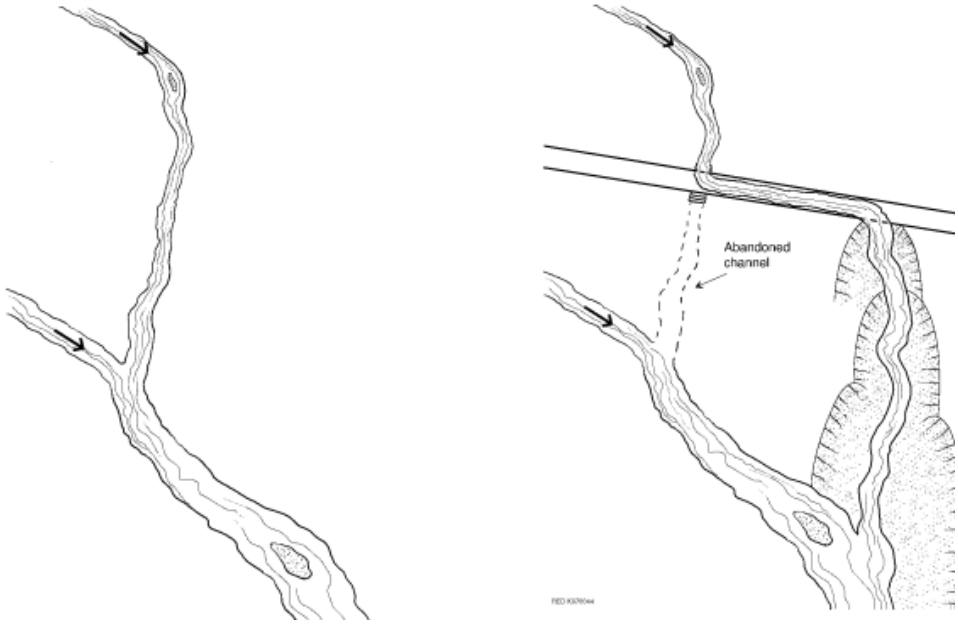
Figure 9-1 Diversion potential



Source: USDA

A study in the northwest of USA found that 50% of flooded culverts on gravel roads led to stream diversion along the roadway. The diverted stream will either travel through the roadway, or along the drainage ditches. Often the diverted stream will travel far enough down the roadway to enter another watershed seen in Figure 9-2. The further the stream is diverted, the more erosion will occur. This erosion is then added to the stream as sediment and potentially will be seen again downstream as deposit at another larger crossing such as the bridge example above.

Figure 9-2 Diversion potential



Source: USDA

Increased flows through the culverts will increase the scour and erosion on the inlets and outlets of the culverts.

Pavement design

(1) Subgrade

The largest effect of precipitation will be seen in subgrade and sub base materials which are poor draining and/or composed of expansive soils. With an increase in precipitation, there can be expected more swelling of the soils in the wet season. Soils are at their weakest when fully saturated. An increase in seasonal variability of rainfall will lead to more cases of extreme saturation, coupled with drying out of the upper subgrade soils during the dry season. This weakening could lead to cracking of the subgrade, which will be seen as deformation throughout the road structure. An increase in water table will have similar impacts to the road subgrade.

(2) Sub base layers

The base layers are their weakest when fully saturated, and need to be properly drained. The infiltration of water either from the surface (through cracks in the asphalt or from edge break of the road) or from the water table below will have detrimental effects on the base layers causing weakening of the structure. As for the subgrade there will be a seasonal variation of the sub base layer strength.

(3) Wearing Course

The wearing course can be divided into three different materials, each affected differently by precipitation: Paved surface, Gravel surface, Earth surface.

(a) Paved surface

The impact of increased precipitation on the paved surface is seen on the amount of standing water on the surface, and the infiltration of water through the surface into the base layers. One of the functions of a paved bound surface is to act as a waterproofing layer to protect the underlying materials. If water is not quickly drained away from the paved surface, it will settle into the base layers, weakening the structure, accelerating the formation of cracking, and potholes. Standing water on the road surface is also a driving hazard from the increase in hydroplaning and increased braking distance.

(b) Gravel surface

An increase in precipitation will lead to faster degradation of gravel surfaced roads. Increases in precipitation will accelerate gravel loss, requiring more maintenance and re-gravelling. Without proper maintenance, sufficient drainage can not be met, leading to standing water on the road surface, which aids in creating large rutting and potholes. Gravel surfaces are also more prone to being washed away during overtopping events due to the loose nature of the wearing course material.

Research in Vietnam (Rural Road Gravel Assessment Program RRGAP) has shown that gravel surfacing becomes an unsustainable mode of surfacing if the region receives more than 1000-2000 mm precipitation/year, or where road gradients are higher than 4%. Gravel surfacing should only be considered when:

- Quality material is located within 10km of the road
- Adequate drainage is guaranteed
- Flooding is only a minor local occurrence
- Rainfall < 1000 mm/year, gradients less than 6%
- Rainfall 1000 - 2000 mm/year, gradients less than 4%
- Rainfall is less than 2000 mm/year

Gravel surfaces also pose a health risk in very dry areas. If a reduction in precipitation is expected and extensive drying of the gravel road surface occurs, there can be increases in road dust. Road dust has been attributed to health issues, and is an overall nuisance to the road user and inhabitants alongside the roadway.

Due to the terrain and climate, the use of gravel wearing courses should be questioned many locations of the country. The maintenance costs associated with re-gravelling make the use of gravel roads a low initial cost investment with a high maintenance cost.

Research in Vietnam has shown the following are the key factors in contributing to unsustainable deterioration of unsealed gravel roads:

1. High rainfall
2. Flooding
3. Poor quality out-of-specification materials
4. Lack of maintenance
5. Poor drainage arrangements

1.), 2.), and 5.) are contributed to precipitation which is expected to increase in Mozambique.

Alternatives for gravel wearing course that have been tested in Vietnam (Rural Road Surfacing Research RRSR) include:

- Emulsion sand seal
- Emulsion chip seal
- Steel reinforced concrete
- Bamboo reinforced concrete
- Unreinforced concrete
- Engineered clay bricks
- Concrete bricks
- Dressed stone
- Cobble stones

The outcome of these alternatives is discussed in detail in the RRSR reports.

(c) Earth surface

A well engineered earth surface will be able to withstand a certain amount of precipitation. They are suitable for areas with up to 2000 mm/yr precipitation, gentle terrain and light vehicle loading up to 100 vehicles per day. The serviceability of the earth surface road will depend on the quality of the earth materials and subgrade, sufficient drainage, and vehicle loading. If the road is not properly designed for adequate drainage, the surface will erode quickly making the road unusable. Certain materials are much more suitable for wet environments than others. Clay materials can become impassable during the rainy season due to lack of traction if too much clay is used near the surface. Earth surfaced roads are usually used only for low volume community roads.

Slope stability

Rain has a large impact on the stability of slopes. The largest impact from rain to the slope stability is seen through landslides and erosion. Intense rainfall is a recognized trigger of landslides, and an increase in the intensity of rainfall will most likely mean an increase in landslides.

A landslide study was conducted in Lao PDR showing that the majority of landslides affecting roads occurred during the rainy season when there is higher groundwater and perched water levels in the roadside soils. The majority of slope failures in above road cuts were observed to originate from the upper portions of the cut slopes. Below road slope failures were observed in localized shallow failures in fill slopes and construction spoil or deeper failure of the natural hillside, some instances associated with river scour.

70% of the roadside slope failures recorded in the Lao study took place above the road. Shallow slope failures occurring above the road are typically less destructive to the road carriageway than those occurring below. Only 4% of the above road landslides resulted in total blockage of the carriageway. The most common result of these above road slope failures was blockage to the drainage system, which could lead to other problems in the road network if not quickly remedied. Slope failures below the road are a much larger risk to the structure of the road carriageway, often resulting in deformation or loss of the road. It also proves more difficult to observe the slopes below the road before there is a landslide as they are often out of sight.

Erosion from rainfall is a slower process than a landslide event, but over time can be as destructive to a road. Erosion of the slopes can quickly fill up the drainage system with sediment causing blockages and drainage failures.

Erosion is a typically a result of:

- the road side slopes being too steep or too long
- insufficient compaction of embankment materials
- concentrated road runoff allowed to drain off shoulders

Surface drainage
Adequate surface drainage is one of the key elements to a well functioning road, which high intensity rainfall and the associated flooding can quickly exceed. The impacts to the road from a drainage system that is not working properly, or has been flooded include:

- erosion or loss of material of road (especially gravel)
- loss of structures (bridges and culverts)
- undercutting of slopes
- flooded road section

Increase in high intensity storms also often mean an increase in the amount of erosion and sedimentation that is introduced into the drainage network. If this sedimentation is not flushed through the system naturally, it needs to be removed manually, an often time and labor-intensive task. Sediment that is not removed will cause a blockage and increase the sedimentation build up during the next flood.

9.2 Climate scenarios and prediction data

9.2.1 Introduction to scenarios and data

The World Bank has chosen 4 climate scenarios for Mozambique representing the span in expected future climate situations from dry to wet according to results from different combinations of emission scenarios (SRES) and GCM models.

The climate scenarios chosen by the World Bank are:

	GCM-model	Emission scenario
“Global Wet”:	NCAR-CCSM,	SRES A2
“Global Dry”:	SIRO-MK3.0,	SRES A2
“Mozambique Wet”:	IPSL,	SRES B1
“Mozambique Dry”:	UKMO,	SRES A2

For these scenarios, data and results have been processed by the University of Colorado especially for this study with focus on precipitation, temperature and run-off. The results are presented in the report "Statistical Analysis of Historical and Simulated Future Meteorological Data for the Purposes of Quantifying Potential Changes to Climate in Mozambique", March 2020. The report includes estimates for the present climate situation and the future situation in the period around 2050 and around 2100. The report, figures and climate data[15] processing was done by:

[15] The report and spreadsheets with all data and results are available in electronic form at the World Bank office in Washington.

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The following is a direct copy of the introduction to the report, why the references to figures, pages and appendix etc. goes on the analysis report and not on this MTCR report.

9.2.2 Statistical analysis of historical and simulated future meteorological data for the purposes of quantifying potential changes to climate in Mozambique

The purpose of this report is to provide The COWI Group with state-of-the-science information related to climate change predictions in Mozambique for the purpose of making the transport sector resilient to climate change. At the request of The World Bank to provide a consistent basis between two projects they are funding; "Making Transport Climate Resilient, Sub Sahara" and "Economics of Adaptation to Climate Change (EACC)", the authors have performed a statistical analysis of precipitation, temperature, and runoff.

Three time periods were used for this evaluation: a historical period from 1997 to 2006, a predicted period from 2046-2065 and another predicted period from 2081-2100. To maintain temporal consistency between all data sets, all data used in this analysis were *daily* data. Though a longer period of historical monthly data exist, these data would be inconsistent with the daily data used in the rest of the analysis. Therefore monthly statistics were computed from daily data. Four future climate predictions were used for each time period, therefore 9 sets of statistical maps were produced for this report.

Methods

The same four future climate predictions used in the EACC project were used here to provide a range of potential future climates. These climate estimates are typically disparate and assumed equally likely (or unlikely). Therefore any one prediction should be viewed with caution, however the range and variability of predictions is useful to plan resilient adaptation strategies.

Following work performed by The World Bank on global impacts of climate change, a "global wet" and "global dry" scenario were used. In addition, country-specific wet and dry scenarios were used representing the driest and wettest expectations from the available set of all Global Circulation Models and SRES emissions scenarios. Temperature and precipitation estimates from the following four Global Circulation Models were used:

"Global Wet" : NCAR-CCSM, SRES A2

"Global Dry" : CSIRO-MK3.0 SRES A2

"Mozambique Wet": IPSL, SRES B1

"Mozambique Dry": UKMO, SRES A2

Output data from these GCMs are available on a one-degree by one degree spatial resolution. Custom programming done in "MATLAB" was written to process daily precipitation and temperature output from these GCMs as well as the historical data set to compute the following statistics:

- Mean annual total precipitation
- Mean annual days with precipitation
- Mean monthly precipitation each month
- Mean monthly days with precipitation each month
- Mean annual 24 hours maximum rainfall (per year)
- Mean monthly 24 hours maximum rainfall (per month)
- Mean annual 5-day maximum rainfall (per year)
- Mean monthly 5-day maximum rainfall (per month)
- Coefficients of variation of mean rainfall
- Maximum annual, mean annual, and minimum annual daily temperature,
- Maximum daily, mean daily, and minimum daily temperature by month
- Mean annual duration in days of heat waves (>= 5 C above average daily maximum) (per year)
- Mean monthly duration in days of heat waves (>= 5 C above average daily maximum) (per month)

These statistics were computed for each grid cell in Ethiopia, and mapped using ESRI ArcGIS. These maps are presented below in Figures 1 through 216.

In addition to these statistics, potential changes to stream flow due to climate change were also evaluated at a ½ degree by ½ degree spatial resolution. While stream flow is driven by precipitation, changes in flow are not directly proportional to changes in precipitation due to non-linear watershed storage effects. Therefore an empirical stream flow relationship developed by the US Department of Agriculture (USDS) was used to estimate the potential change in stream flow. Details of this method are presented in Appendix A. 24-hour precipitation estimates from each GCM were used to develop estimates of the 1, 2, 5, 10, 20, 50, and 100 year 24 hour rainfall depths using a Gumble probability distribution. These estimates of rainfall depth were then used to estimate the change in stream flow from the historical 24 hour rainfall using the USDA Curve Number method. Maps of these ratios are presented below in Figures 217 through 224.

A limitation of this flow analysis is that only *changes* to flow were estimated, in the form of a ratio of future: historical. "Real" flows for any particular stream or location were not estimated. The computed ratios may be viewed as a proxy to the risk of increased flow. A ratio of 1.25 for the 50 year 24 hour rain,

for example, represents that within this grid cell, we expect the flows resulting from the 50 year, 24 hour rain to increase by 25%. It should be noted that the 24 hour rainfall may not be meaningful for small watersheds, therefore these data should be used with caution, especially for small watersheds.

Also due to limitations of the empirical method, numerical inconsistencies sometimes result in unrealistically high ratios. This is especially apparent for high frequency storms, ie. The one and two year rainfall depths. Therefore these data should also be used with some caution. Ratios that exceeded five were lumped in a common bin in the maps shown in figures 217-224.

Data sources

The historical data originated from the National Aeronautics and Space Administration's (NASA's) Prediction of World Energy Resource (POWER) project's database of climatology. <http://power.larc.nasa.gov/>. The GCM data were downloaded directly from the IPCC website < http://www.ipcc-data.org/ >.

Statistical maps of Ethiopia

The following 224 maps depict the statistical computations performed for this project. Tabular data for all maps are included in Appendix B, delivered as digital files in MS Excel format.

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