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World Bank

Making Transport Climate Resilient

Country Report: Ethiopia

August 2010

COWI A/S

Parallelvej 2
DK-2800 Kongens Lyngby
Denmark

Tel +45 45 97 22 11
Fax +45 45 97 22 12
www.cowi.com

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0 Executive summary

This report is the output of the World Bank-financed study on Making Transport Climate Resilient for Ethiopia, 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 lower temperatures and less rain than today to a "wet Ethiopia" future with more rain than today and an increase in heavy rain so that a 10- year storm in 2050 will be 25% more intensive than today. The foreseen increases in average temperatures range from -1 ^{O}C to 2 ^{O}C by 2050.

The design and maintenance of roads

The largest problems facing the current Ethiopian road network seem to be overloading and missing maintenance and repair. The most influential climate impact on roads will in the future come from changes in rain patterns and only to a smaller extent from increased temperatures.

A climate-resilient road in the future in Ethiopia will be very similar to a climate-resilient road right now. Ethiopia has the knowledge and materials 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 Ethiopia.

The publication of the Ethiopian design standards in 2002 is a large step in assuring the best possible road and structures construction in the future. The engineering solutions needed to make a climate-resilient road can to a very large extent be found in these manuals, from solutions to hydraulic-related problems such as scour and sedimentation to problem soils and sub-grade problems as well as slope stability and surface drainage solutions

The adaptation measures

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

Design:

- Investigate the need for river training and increased channel maintenance and bridge scour protection
- 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, etc

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:

- Further research into more initially robust scour prevention compared to long term maintenance savings
- Investigate the option of using different wearing courses other than gravel for areas with limited supplies
- Expand methods for slope stabilization and protection
- Append the design manuals with more low-cost engineering solutions for community roads

The economic assessment

The costs of climate changes in the period 2010 - 2050 are roughly estimated at around 0.7 - 2.0 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 and are expected to increase and may double in year 2050 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.

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. 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.

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 in the rapidly changing Ethiopian landscape.
- 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 good and comprehensive design manuals are recommended to be revised so that the climate-related issues and solutions are clearly presented, e.g. in an additional chapter. Having a chapter dedicated to the climate and environmental impacts on roads 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 feasible 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 dam-

age and to decrease 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 (every 5 or 10 years) to take account of the most updated information on observed climate change impacts and the need to balance climate risks and economic feasibility.
- Establishment of more focused maintenance strategies.
- Development of reliable and accurate hydrology models as it is a common problem that this is lacking.

1 Introduction and background

1.1 Introduction

1.1.1 Aim

The World Bank has contracted a study on "making transport climate resilient" as a Sub Saharan Africa initiative to respond to the impact of climate changes on road transport.

The objective of the study is to:

- establish a knowledge base on extent and nature of technical and economical challenges the road sector is facing due to climate change, climate variability and extreme weather events;
- to undertake analytical work to deliver guidelines for road transport policy decision makers on options to protect Africa's transport infrastructure and services; and
- contribute to the process of creating awareness on climate risk and how Africa's transport could adapt to climate change

The work is based on desk research and information on the situation in two case countries selected by the World Bank: Ethiopia and Mozambique[1].

This report covers the findings for Ethiopia based on desk research and data and information collected during a mission in Ethiopia May 2009 where a good and fruitful dialogue with key national stakeholders was initiated.

The consultant COWI A/S (Denmark) has been contracted to conduct the study.

1.1.2 Approach

The approach has been:

i. Establishment of a consolidated presentation of currently modeled climate change scenarios for year 2050 with emphasis on parameters of particular importance for road transport.

[1] Ghana may at a later stage be included in the study as a third case country.

ii. Quantification of impacts of climate change on road assets and road transport services based on data on existing road infrastructure classified according to standard/quality and climate impact risk.

iii. Developing and preliminary costing adaption measures and presenting needs for changes in the road sector.

Good and robust design practices for transport infrastructure have always depended on sound knowledge of all background conditions including the climatic and hydrological conditions at the actual location for the infrastructure. This ensures that decisions on types of design and specific location can be based on good and transparent understanding of the chosen safety and service level for the infrastructure. The safety level can then be considered together with construction and maintenance costs and the costs/benefits for the transport users and the society in general.

Road projects most often have to state what their environmental impact will be. But it is equally important to ask how the climate and environment can be expected to affect the infrastructure.

Road design and specific climate conditions should always be closely linked. The challenge in many countries, including Ethiopia, is that climate change will result in a deviation from the observed historical climate conditions and therefore potentially lead to new requirements to design standards if the same levels of service and safety of today shall be maintained for the future.

1.1.3 Outputs

The main outputs and recommendations from the study are summarized in this chapter trying to answer the following main questions:

- What are the current predictions for the future climate and how certain are the changes?
- What are the most important challenges in relation to climate change for road assets and what measures can be taken?
- What are the additional costs for making roads climate resilient?
- What are the most important costs to transport users if road designs are not adapted to climate change?
- What are the recommended measures in a short and long term perspective?

1.2 Summary of conclusions

1.2.1 Climate change scenarios and predictions

The observed trends in climate change in Ethiopia so far shows:

- increased average temperatures;
- increased number of hot days and nights;
- larger variations from year to year in intensity of extreme events; and
- no significant trend in average annual rainfall

The weighted climate change predictions found and reported by UNDP in the Climate Change Country Profile for Ethiopia 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	"Ethiopia Wet"	NCAR-CCSM,	SRES A1b
4	"Ethiopia Dry"	IPSL	SRES B1

The two "wet" scenarios result in lower temperatures than today and the two "dry" scenarios in higher temperatures. The "Global Dry" scenario results in less annual precipitation but with a slightly higher intensity than today. The other scenarios result in more annual rain and with significantly higher intensity.

The main findings can be summarized as follows:

- The mean temperature increase will range from -1 ^{O}C to 2 ^{O}C and the number of annual days with heat waves will increase with 0 to 3 days/year. The impact is higher asphalt temperature, dust, increased evaporation
- The annual rainfall increase will range from - 17% till 28%, most in south and less in north. 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 4-25% in intensity for a 10-year storm and with 13% - 43% 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 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 and the "Ethiopia Dry" scenario results in almost identical requirements to changes in design parameters.

1.2.2 The current road network

Ethiopia had in 2008 an estimated classified road network of approximately 38,000 km of which around 6,000 km are paved. An estimated 55% of the roads are in flat terrain. In addition the road network comprises approximately 4,400 bridges and more than 40,000 culverts. According to Ethiopian Road Authority (ERA) 30% of the 2955 bridges registered in the federal road network need some form of rehabilitation, and 3.6% are due for replacement.

All elements of design for all types of roads and structures (paved trunk roads, gravel, community roads) are included in the ERA manuals from 2002 which are mandatory for all types of roads.

The type of road in Ethiopia 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 Ethiopia 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 Ethiopian road network seem to be overloading and missing maintenance and repair. The most influential climate impacts on roads will in the future 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.

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 design requirements for the new federal paved trunk roads are on a high level. The problems seen today in the federal trunk 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. 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.

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 Ethiopia 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.

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
The design storms in the different regions, wet as well as dry areas, have similar rainfall amounts. The predicted climate change in heavy rainfalls seems to follow almost the same pattern in the regions. The big difference in the predicted change is in average monthly precipitation. The predictions indicate that the wet areas are getting dryer and the dry areas are getting more wet, but the design storms are predicted to increase in frequency and intensity in all areas.

The publication of the Ethiopian Design standards in 2002 is a large step in assuring the best possible road and structures construction in the future. The majority of the ERA manuals are taken from other well established manuals such as the Overseas Road Notes, and AASHTO design recommendations.

The engineering solutions needed to make a climate resilient road can to a very large extent be found in these 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.

A common problem that is found throughout Ethiopia's hydraulic structure designs is the use of reliable and accurate hydrology models.

Research is needed in the accuracy of the design parameters in predicting sedimentation and runoff in the rapidly changing Ethiopian landscape. The design storm parameters are recommended to be adjusted to reflect the anticipated climate changes. A first preliminary estimate of the need for changes in the design parameters is made in the report but more work is recommended.

Specific recommendations to the manuals
It is suggested to organize 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 climate and environmental impacts on the road would make it easier for the designer to choose quickly and efficiently.

The recommendations listed in this report cover guidelines for climate and environmental considerations that should be started immediately in relation to the very first planning considerations and in the later design, maintenance and research.

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 Ethiopia. The standards that they are designed for now and should be built at are at a high level.

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 DS3/DS4 standard road with an average cost of around 536,000 USD per km (2008 costs based on actual awarded contracts) 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 Other scenarios
General costs during construction for staff (not related to climate)	6.8%	0%	0%
Site clearance	0.2%	0%	0%
Drainage	5.3%	7%	33%
Earth works	14.3%	1% - 10%	10% - 20%
Subbase, road base and gravel wearing course & bituminous surfacing	62.5%	1 % - 10 %	5 % - 20 %
Structures	5.2%	13%	43%
Ancillary work (guardrails, landscaping, river bank and scour protection)	4.3%	1%	5%
Dayworks	1.4%	0%	0%
Total	***100.0%***	***2% -9%***	***9% -19%***

The largest 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 Ethiopian 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 0% and 20% 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 expected to increase roughly between 15% and 30%.

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 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 0.7 - 2.0 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 100% 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 and riverbank protection. For structures the specific conditions decide if it is economic feasible to adapt fully to the 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 Ethiopia will be very similar to a climate resilient road right now. Ethiopia has the knowledge and materials needed to design and keep their roads up to standard. A key element to ensuring climate resilience after the initial construction is sufficient maintenance. Ethiopia has in general a very large challenge in building climate resilient roads due to its difficult terrain and high amounts of rainfall in some parts of the country.

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

- Research is needed in the accuracy of the design parameters in predicting sedimentation and runoff in the rapidly changing Ethiopian landscape.
- 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 term the following initiatives are recommended:

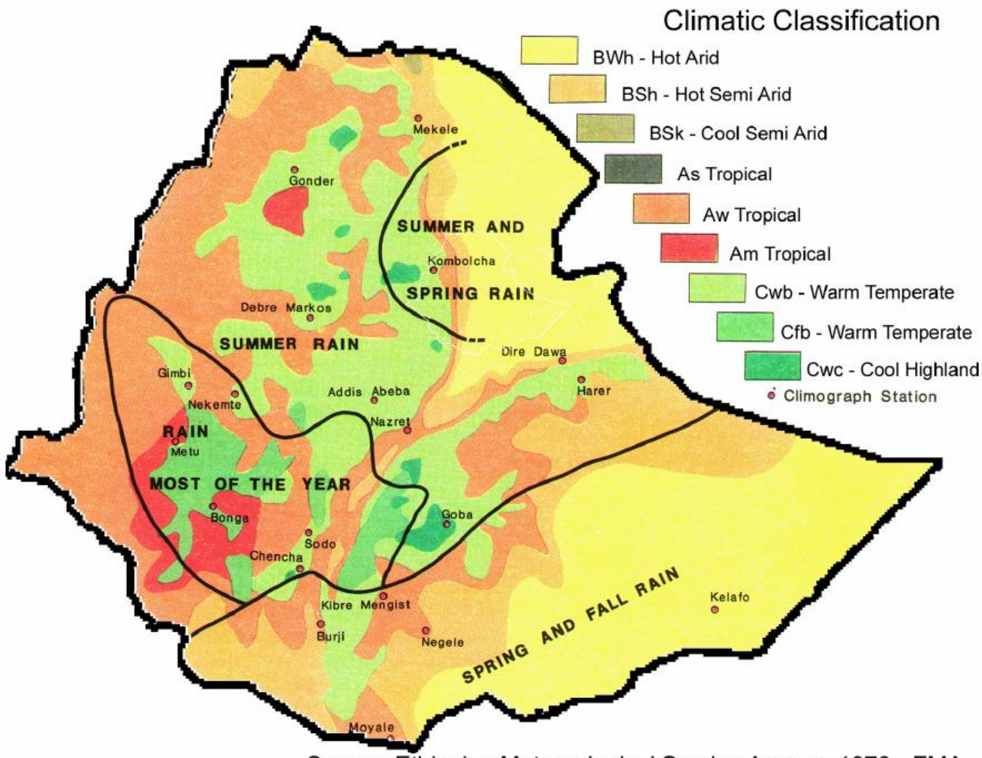
- Establishment of a process to review climate-related parts of the design guidelines at regular intervals (5 or 10 years) to take account of most updated information on observed climate change impacts and the need to balance climate risks and economic feasibility
- Establishment of more focused maintenance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

2 Climate risk scenarios for Ethiopia

2.1 Climate characteristics for Ethiopia

The overall climate characteristic for Ethiopia is illustrated below.

Figure 2-1 Overall climate characteristics for Ethiopia. Climate classification after Köppen.[2]



Source: Ethiopian Meteorological Service Agency, 1976 - EMA

Ethiopia is a part of the East African 'Horn of Africa'. The climate[3] is typically tropical in the south-eastern and north-eastern lowland regions, and cooler in

[2] Data on the present climate is available at e.g. the CRU homepage and can be delivered on request from the NMA, National Meteorological Agency, Federal Democratic Republic of Ethiopia

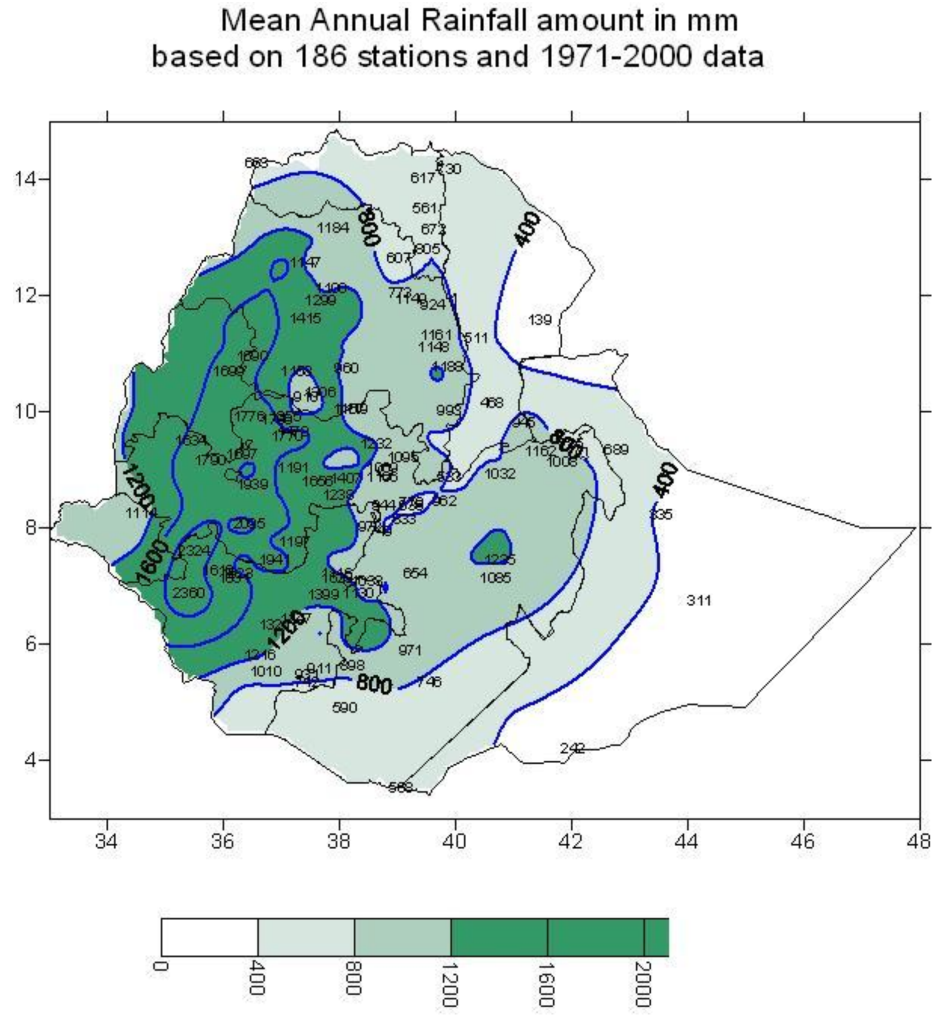
[3] The description builds on the UNDP Climate Change Country Profile for Ethiopia:

the large central highland regions of the country. Mean annual temperatures are around 15-20^{O}C in these high altitude regions, whilst 25-30^{O}C in the lowlands.

Seasonal rainfall in Ethiopia is driven mainly by the migration of the Inter-Tropical Convergence Zone (ITCZ). The exact position of the ITCZ changes over the course of the year, oscillating across the equator from its northern most position over northern Ethiopia in July and August, to its southern most position over southern Kenya in January and February. Most of Ethiopia experiences one main wet season (called 'Kiremt') from mid-June to mid-September (up to 350mm per month in the wettest regions), when the ITCZ is at its northern-most position. Parts of northern and central Ethiopia also have a secondary wet season of sporadic, and considerably lesser, rainfall from February to May (called the 'Belg'). The southern regions of Ethiopia experience two distinct wet seasons which occur as the ITCZ passes through this more southern position. The March to May 'Belg' season is the main rainfall season yielding 100-200mm per month, followed by a lesser rainfall season in October to December called 'Bega' (around 100mm per month). The eastern most corner of Ethiopia receives very little rainfall at any time of year.

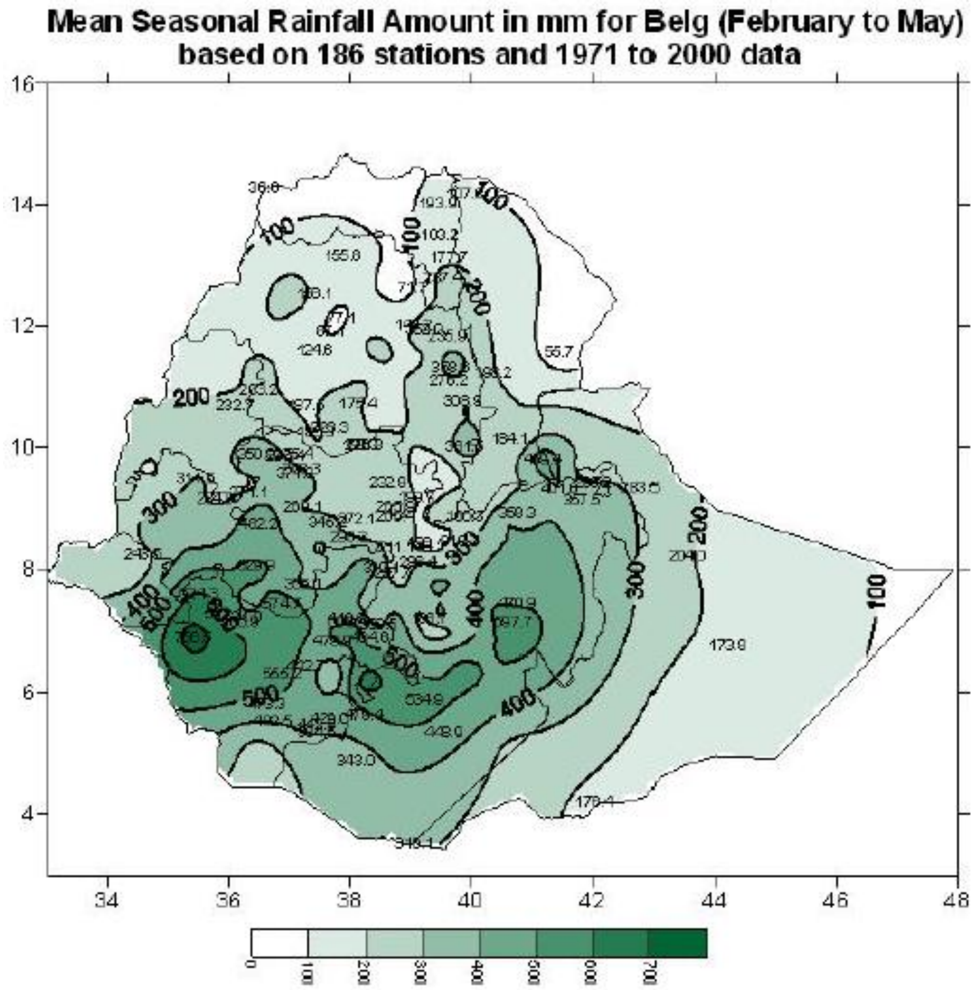
The movements of the ITCZ are sensitive to variations in Indian Ocean sea-surface temperatures and vary from year to year, hence the onset and duration of the rainfall seasons vary considerably inter-annually, causing frequent drought. The most well documented cause of this variability is the El Niño Southern Oscillation (ENSO). Warm phases of ENSO (El Niño) have been associated with reduced rainfall in the main wet season, JAS, in north and central Ethiopia causing severe drought and famine, but also with enhanced rainfalls in the earlier February to April rainfall season which mainly affects southern Ethiopia.

Figure 2-2 Mean annual precipitation



Source: RANET

Figure 2-3 Mean seasonal precipitation in the Belg (Feb-May) season



Source: RANET

2.1.1 Experienced droughts and floods

Droughts

As described in the National Adaptation Programme of Action (NAPA) Ethiopia is highly vulnerable to drought. Most of the country is prone to drought (NMSA, 1996, Degefu, W., 1987). Drought is the single most important climate-related natural hazard impacting the country from time to time. Drought occurs anywhere in the world but its damage is not as severe as in Africa in general and in Ethiopia in particular due to low adaptive capacity. Recurrent drought events in the past have resulted in huge loss of life and property as well as migration of people. The eastern part of the country is most prone to droughts while the highlands and western part of the country is less prone to droughts.

Flooding

The other climate-related hazards that affect Ethiopia from time to time are flash and seasonal river floods. Areas in the Afar Region along the Awash River, in the Somali Region along the Wabi Shebele River and in the Gambela Region along the Baro-Akobo River, in the Southern Region along the Oomo-

Gibe River, Bahirdar Zuria and Fogera areas along the Abbay River in the Amhara Region are prone to seasonal river floods (Endalkchew, B, etal, 2004).

Major floods which caused loss of life and property occurred in different parts of the country in 1988, 1993, 1994, 1995, 1996 and 2006. For example in the 2006 main rainy season (June- September), flood caused the following disasters (NMA, 2006):

- More than 250 people died, about 250 people were unaccounted for and more than 10,000 people became homeless. Due to the Dire Dawa flood.
- More than 364 people died, and more than 6000 people were displaced due to flooding of about 14 villages in South Omo.
- More than 16,000 people were displaced in West Shewa.
- Similar situations also occurred over Afar, Western Tigray, Gambella Zuria and the low lying areas of Lake Tana.

The flooding in the Dire Dawa caused very serious road damages and more roads along the river were flushed away. The loss in property is estimated in the order of tenth of millions of dollars.

Figure 2-4 Flood prone areas in Ethiopia. The red areas are areas where floods occur very frequent. Ref. NMA.

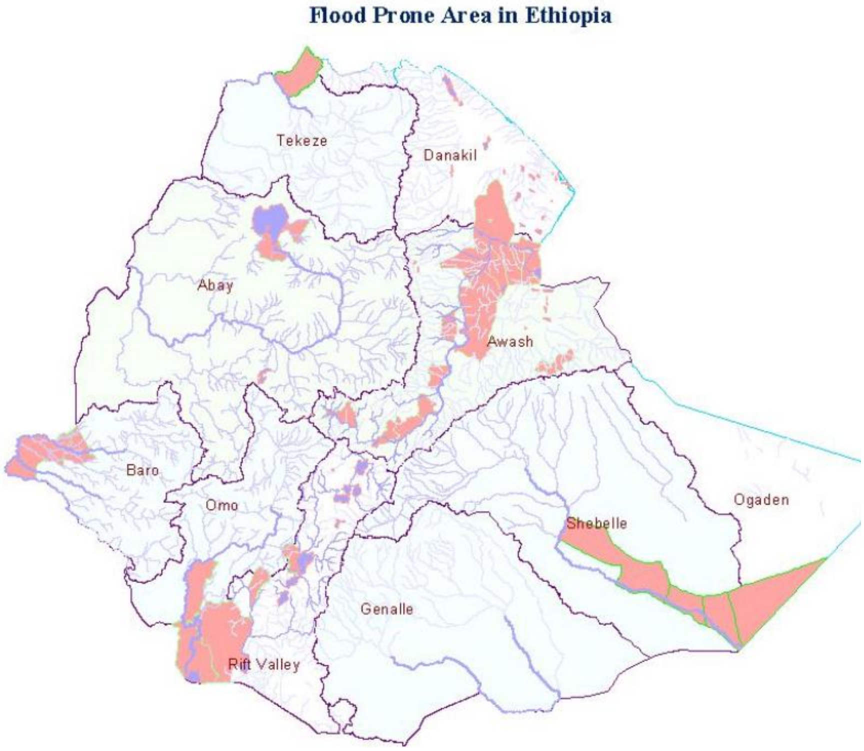


Figure 2-5 Details of the very flood prone area around Dire Dawa and upstream areas. The red areas are areas where floods occur very frequent. Ref. NMA.

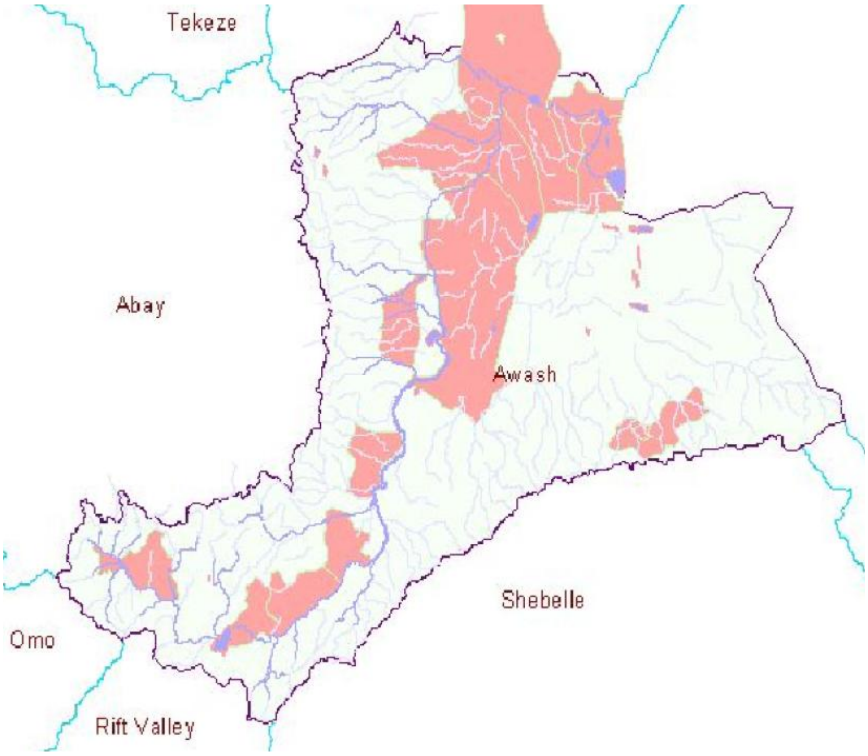
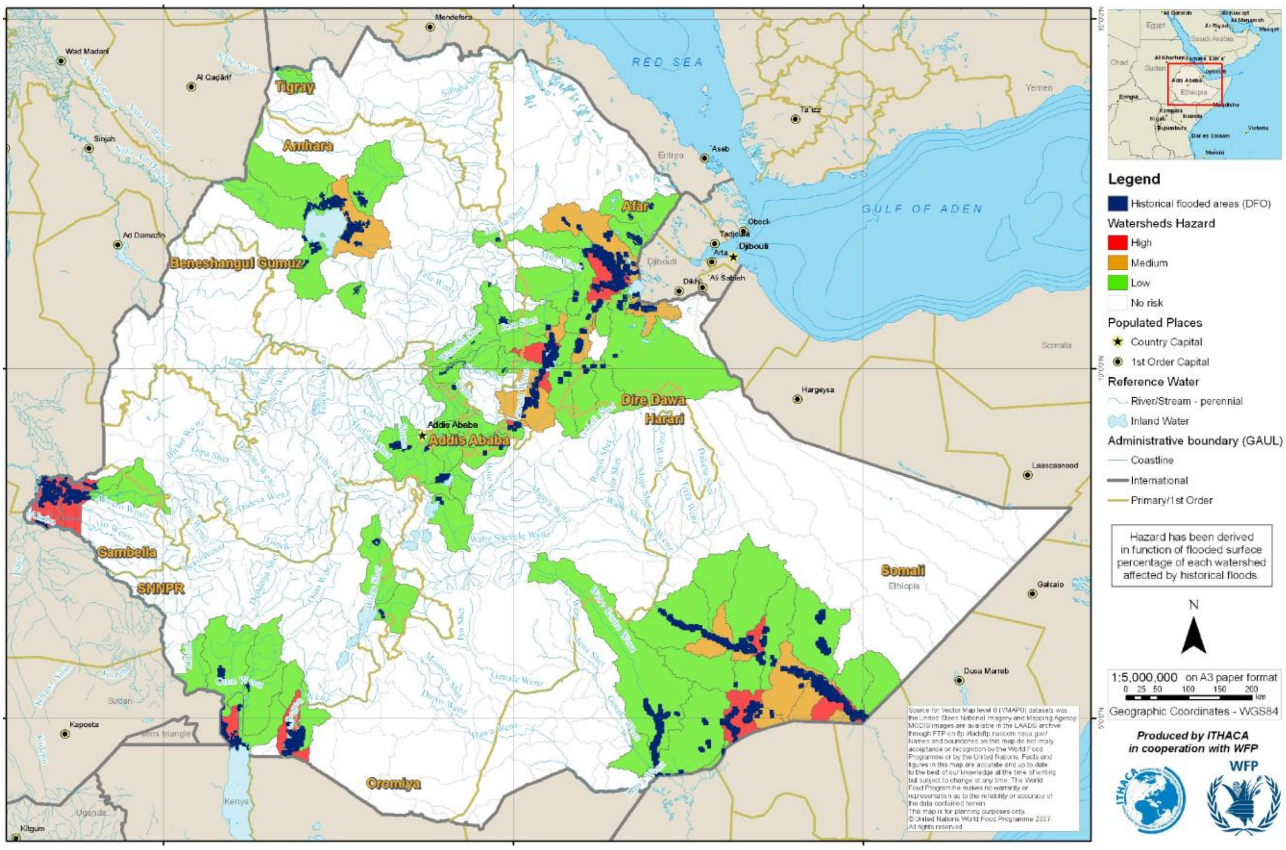


Figure 2-6 Watersheds hazard. Overview of historical flooded areas and the flood hazard in the different watersheds.



2.1.2 Trends in climate change so far

The trend in climate change so far shows:

- increased temperature (about 0.37OC every ten years according to NAPA),
- increased number of hot days and nights
- larger variations from year to year and in intensity of extreme events and
- no significant trend in annual rainfall

In the UNDP Climate Change Country Profile the recent climate trends (1960-2003/6) are described briefly as:

Temperature:

- **Mean annual temperature** has increased by 1.3OC between 1960 and 2006, an average rate of 0.28OC per decade. The increase in temperature in Ethiopia has been most rapid in JAS4 at a rate of 0.32OC per decade.

[4] The quarters of the year are generally referred to as JFM, AMJ, JAS, OND

- Daily temperature observations show significantly increasing trends in the **frequency of hot days**, and much large increasing trends in the frequency of hot nights. (‘Hot’ day or ‘hot’ night is defined by the temperature exceeded on 10% of days or nights in current climate of that region and season.)

  - The average number of ‘hot’ days per year in Ethiopia has increased by 73 (an additional 20% of days) between 1960 and 2003. The rate of increase is seen most strongly in JJA when the average number of hot JJA days has increased by 9.9 days per month (an additional 32% of JJA days) over this period.
  - The average number of ‘hot’ nights per year increased by 137 (an additional 37.5% of nights) between 1960 and 2003. The rate of increase is seen most strongly in JJA when the average number of hot JJA nights has increased by 18 days per month (an additional 58.8% of JJA nights) over this period.

- The **frequency of cold days** has decreased significantly in all seasons except DJF. The frequency of cold nights has decreased more rapidly and significantly in all seasons (‘Cold’ days or ‘cold’ nights are defined as the temperature below which 10% of days or nights are recorded in current climate of that region or season.)

  - The average number of ‘cold ‘days per year has decreased by 21 (5.8% of days) between 1960 and 2003. This rate of decrease is most rapid in SON when the average number of cold SON days has decreased by 2.3 days per month (7.4% of SON days) over this period.
  - The average number of ‘cold’ nights per year has decreased by 41 (11.2% of days). This rate of decrease is most rapid in JJA when the average number of cold JJA nights has decreased by 3.7 nights per month (12% of JJA nights) over this period.

Precipitation

- The strong inter-annual and inter-decadal variability in Ethiopia’s rainfall makes it difficult to detect long-term trends. There is not a statistically significant trend in observed mean rainfall in any season in Ethiopia between 1960 and 2006. Decreases in JAS rainfall observed in the 1980s have shown recovery in the 1990s and 2000s.
- There are insufficient daily rainfall records available to identify trends in daily rainfall variability.

2.1.3 Climate zones

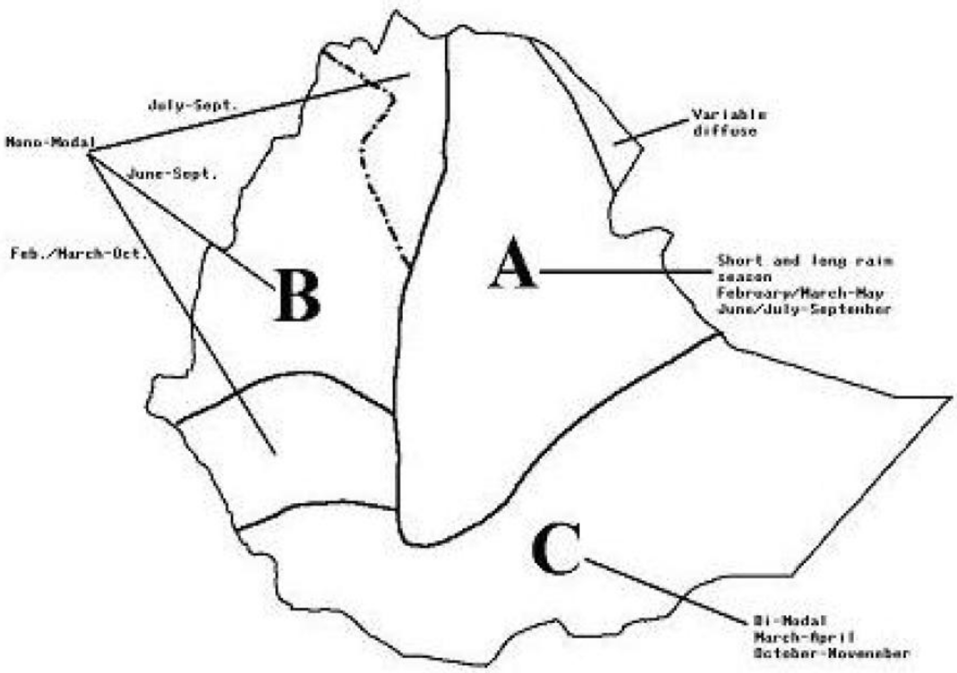
Ethiopia is divided into different climate zones depending on the purpose for the zoning. The metrological institute uses one zoning for the pattern and volume of precipitation, the drainage design manual use one zoning for heavy rain and agriculture use zones for the conditions for agriculture (based on elevation assuming that there is a direct relation to temperature, rainfall and moisture in the soil).

The three most common climate zonings in Ethiopia (except for the more detailed by Köppen presented in Figure 2.1) are shown below:

1. Climate zoning related to the seasonal rainfall pattern.

This climate zoning is given and used by NMA, National Meteorological Agency, Federal Democratic Republic of Ethiopia and is related to the rainfall pattern and seasonal rainfall in the country.

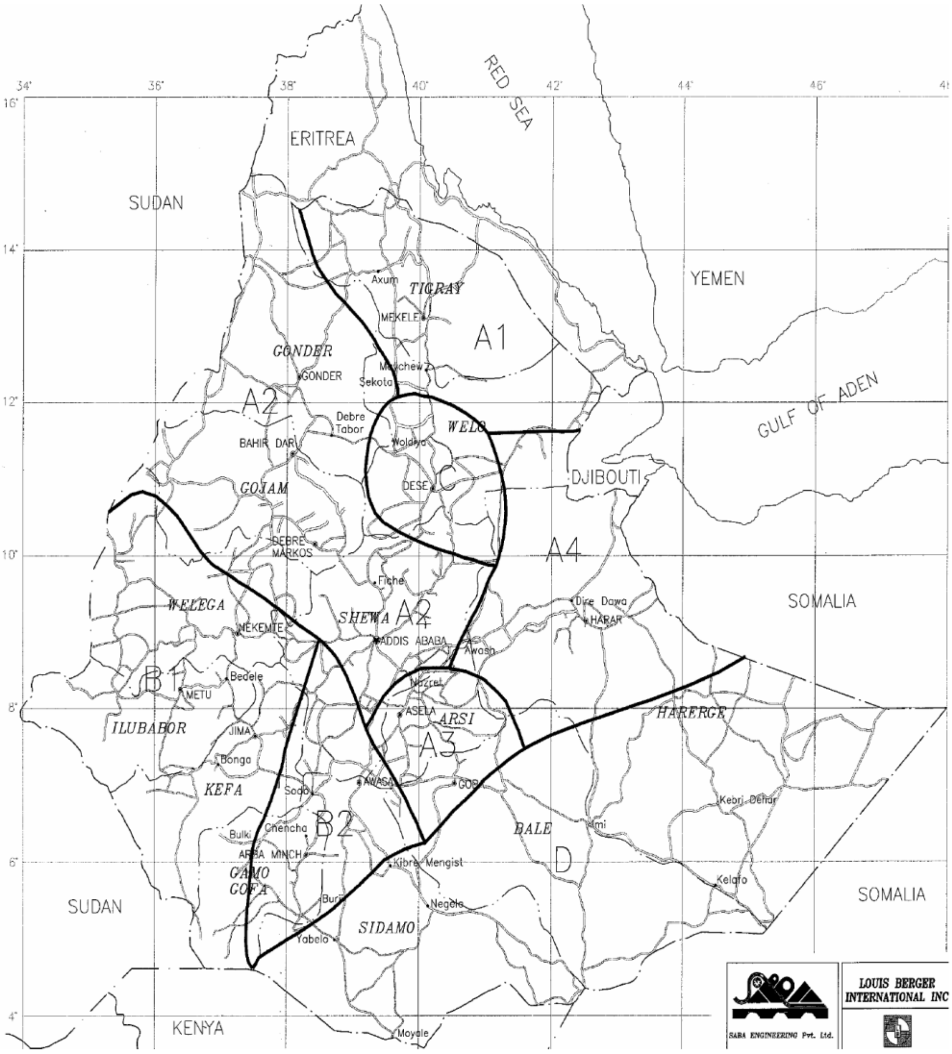
Figure 2-7 Climate zones related to Rainfall Regimes over Ethiopia (after Tesfaye Haile). NMA, National Meteorological Agency, Federal Democratic Republic of Ethiopia.



2. Climate zoning related to heavy rain intensity and frequency.

This climate zoning is given in the Drainage Design Manual (ERA, Ethiopian Road Authority, 2002) and is used for design of all structures that can be affected by or used for collection and discharge of storm water.

Figure 2-8 Climate zones related to intensity and frequency of heavy rainfall, from Drainage Design Manual, Hydrology, ERA, Ethiopian Roads Authority, 2002.

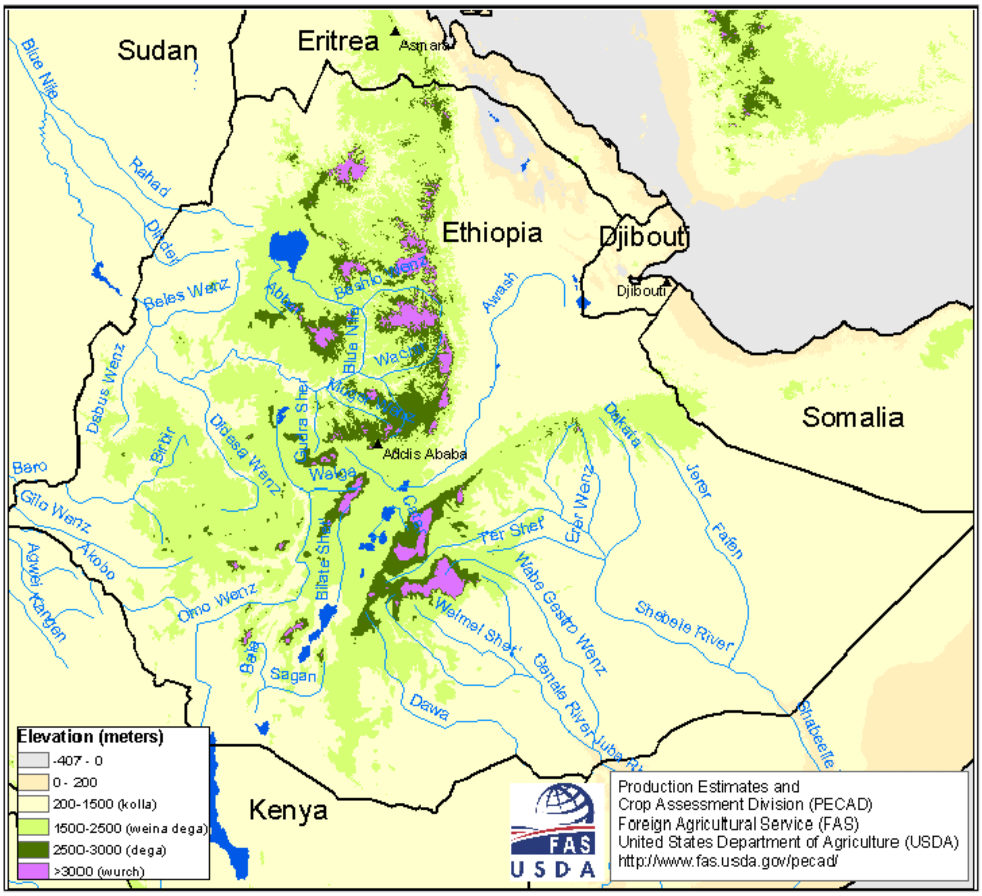


Rainfall data used in the preparation of the climate zones have been collected from many Ministry of Water Resources meteorological stations. The data have been analyzed statistically and the results indicate that the country can be divided into the shown hydrological regions/zones displaying similar rainfall patterns. Most of the statistics are based on records and estimates of 24 hours precipitation for meteorological stations in the areas.

3. Climate zoning related to agriculture (agroclimatic zones).

United States Department of Agriculture (USDA) and Foreign Agricultural Service (FAS) have divided Ethiopia into five climatic zones according to elevation and Ethiopian tradition[5].

Figure 2-9 Climate Zones related to agriculture, Agroclimatic zones, based on elevation. Used by PECAD, FAS and USDA for Crop Assessment.



According to USDA each zone has its own pattern rainfall pattern and agricultural production system. In general, the highland zones (Dega and Wiena Dega zones) contain most of the agricultural areas, while the semi-arid and arid lowlands zones (Kolla and Behera) are dominated by livestock in agropastoral and pastoral production systems.

5 http://www.fas.usda.gov/pecad2/highlights/2002/10/ethiopia/baseline/Eth_Agroeco_Zones.htm

Description of the five agroclimatic zones:

- Wurch (Cold highlands): Areas above 3000 meters and annual rainfall is above 2200-mm. Barley is the dominate crop and light frost often forms at night.
- Dega (Cool, humid, highlands): Areas from 2500-3000 meters where annual rainfall ranges from 1200 to 2200-mm. Barley and wheat are the dominate crops.
- Weina Dega (Temperate, cool sub-humid, highlands): Areas between 1500 to 2500 meters, where annual rainfall ranges from 800-1200-mm. This is where most of the population lives and all regional types of crops are grown, especially teff.
- Kolla (Warm, semi-arid lowlands): Areas below 1500 meters with annual rainfall ranges from 200-800 mm. Sorghum and corn are grown, with teff grown in the better areas. The kolla is warm year round and temperatures range from 27 to 50 degrees Celsius.
- Bereha (Hot and hyper-arid): General term that refers to the extreme form of kolla, where annual rainfall is less than 200-mm. The bereha has desert type vegetation where pastoralism is the main economic activity. This area encompasses the Denakil Depression, the Eritrean lowlands, the eastern Ogaden, the deep tropical valleys of the Blue Nile and Tekezé rivers, and the peripheral areas along the Sudanese and Kenyan borders

Climate zoning used in this study
In this study the different types of climate zones or combinations of zones are used to suit the purpose of the current work. In general terms the climate zones have been used as follows:

1. Climate zoning related to the seasonal rainfall pattern.
Discharge in rivers, erosion, groundwater and soil moisture, land slide, stability of roads,

2. Climate zoning related to heavy rain intensity and frequency.
Design storms for all structures and drainage, frequency of flash flooding, frequency and extent of damages caused by extreme events, erosion,

3. Climate zoning related to agriculture (Agroclimatic Zones).
Temperature related damages and maintenance, evaporation,

2.2 Emission scenarios and climate models

2.2.1 SRES emissions scenario by IPCC

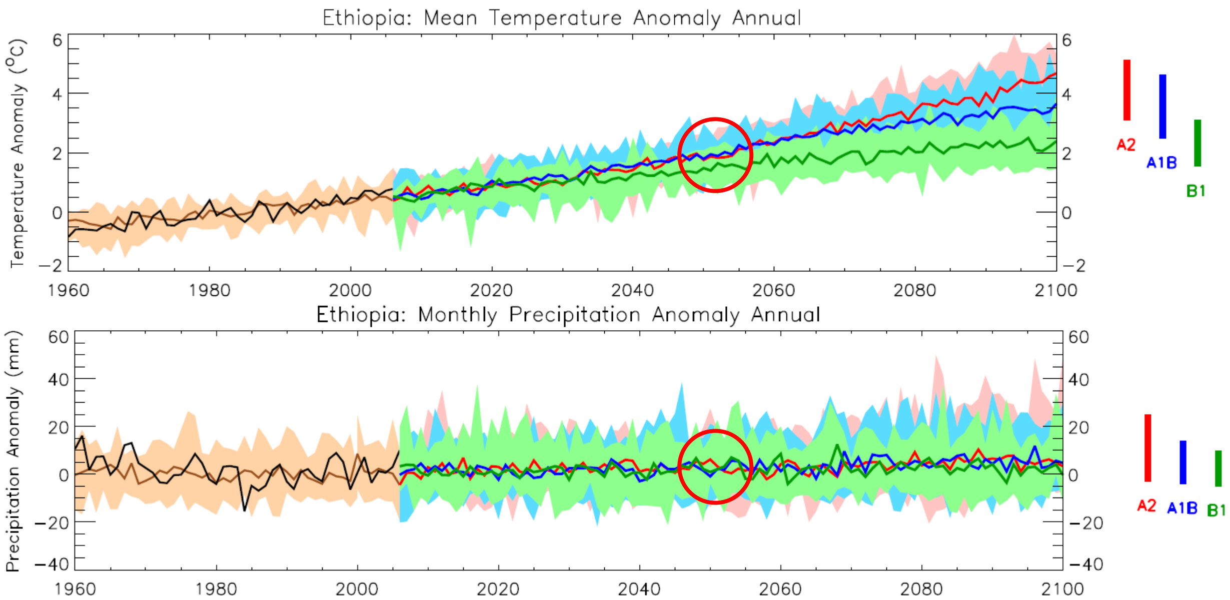
IPCC has given four main emission scenarios and more sub-scenarios in the IPCC Special Report on Emissions Scenarios, 2000, (SRES).

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 Ethiopia 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 and A1B scenarios as presented in the figure below and higher than 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 consequences seems to accelerate in the period from 2040 to 2100.

Figure 2-10 Comparison of climate consequences 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.

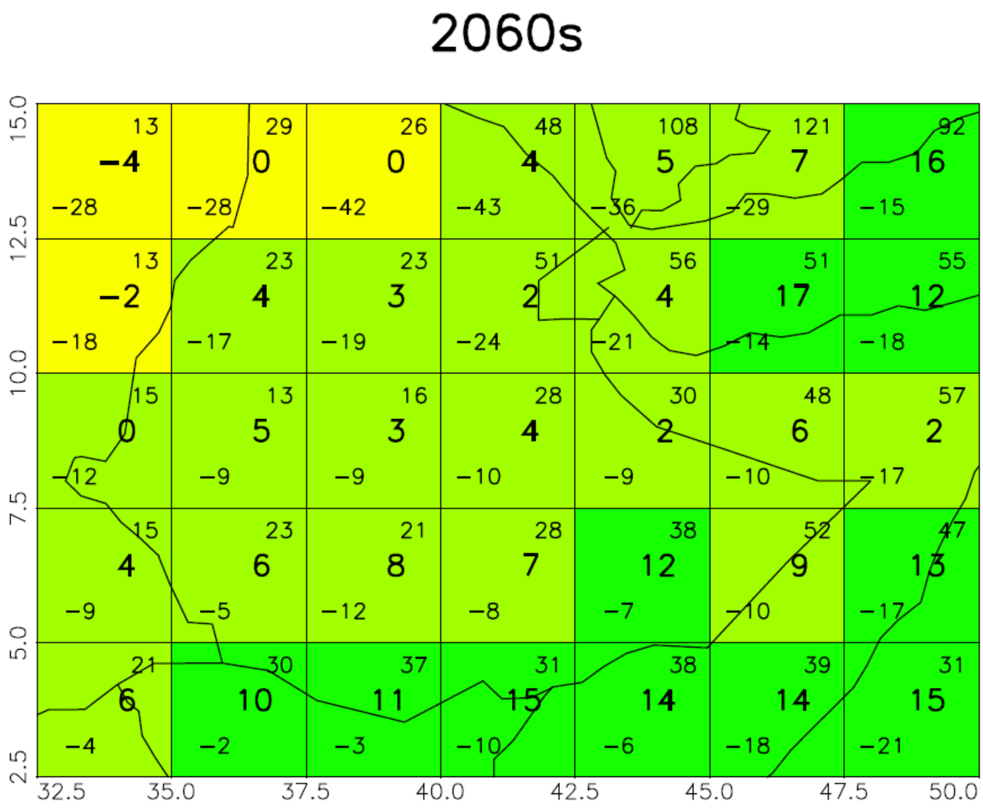
In this study it is chosen to use the weighted climate change predictions found and reported by UNDP in the Climate Change Country Profile for Ethiopia for the general description of the expected climate change in Ethiopia. More detailed information on the estimated climate change consequences for the 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 Ethiopia. These illustrations should argue for a relaxed relationship to the accuracy in the results and forecasts based on different SRES and GCM.

Example 1:

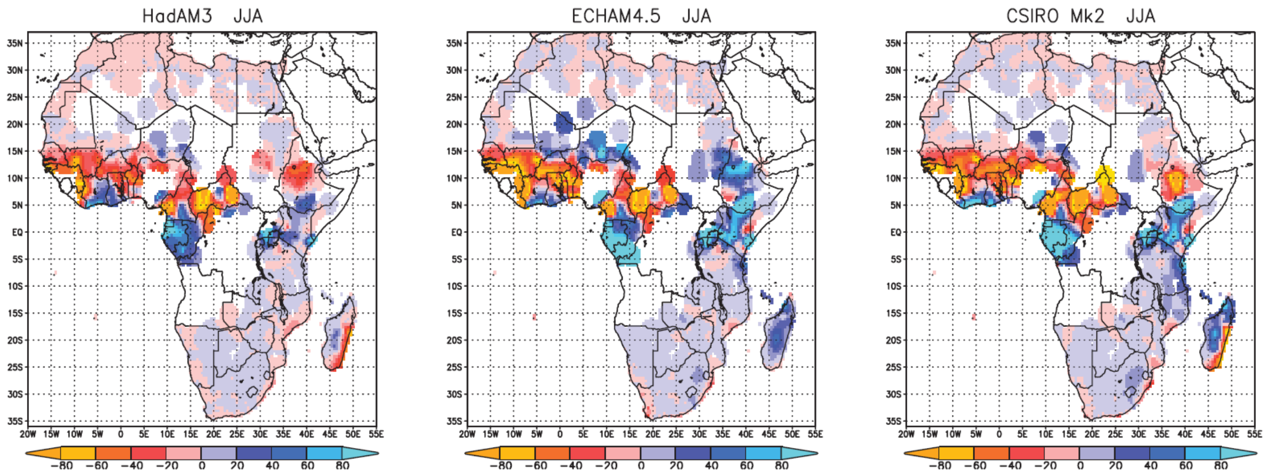
Figure 2-11 UNDP illustration of maximum, weighted average and minimum or %-change in monthly precipitation (annual average) in Ethiopia from the period around 1985 until the period around 2060. Results from 15 GCM, as 10 years average for each model. SRES A2 scenario.



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.

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 a big difference in the predicted monthly precipitation in the central part of Ethiopia between ECHAM4.5 indicating + 80 mm and CSIRO Mk2 indicating -60 mm.

2.3 Climate change characteristics

2.3.1 Climate change in general for Ethiopia

Following general comments on climate change in Ethiopia until 2060 are based on the information in the UNDP Climate Change Country Report for the SRES A2 scenario.

Temperature

- The mean annual temperature is projected to increase by 2.7^{O}C by the 2060s for SRES A2 emissions scenario. The projected changes from different models span from $2.0\,^{O}$C to 3.1^{O}C.
- 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 26-40% of days by the 2060s. Days that are considered 'hot' for their season are projected to increase the most rapidly in JAS, occurring on 39-67% of days in JAS 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 40-65% of nights by the 2060s. Nights that are considered ‘hot’ for their season are projected to increase the most rapidly in JAS, occurring on 60-90% of nights in JAS by the 2060s.

- All projections indicate decreases in the frequency of days and nights that are considered ‘cold’ in current climate. Cold nights decrease in frequency more rapidly than cold days.

Precipitation

- Projections from different models in the ensemble are broadly consistent in indicating increases in annual rainfall in Ethiopia. These increases are largely a result of increasing rainfall in the ‘short’ rainfall season (OND) in southern Ethiopia.
  - OND rainfall is projected to change by -8 to +48% as an average over the whole of Ethiopia until 2060s.
  - Proportional increases in OND rainfall in the driest, eastern most parts of Ethiopia are large.
- Projections of change in the main rainy seasons AMJ and JAS which affect the larger portions of Ethiopia are more mixed, but tend towards slight increases in the south west and deceases in the north east.
- The models in the ensemble are broadly consistent in indicating increases in the proportion of total rainfall that falls in ‘heavy’ events, with annual changes ranging from -3 to +8% until 2060s. The largest increases are seen in JAS and OND rainfall.
- The models in the ensemble are broadly consistent in indicating increases in the magnitude of 1- and 5-day rainfall maxima. The annual increases arise largely due to increases in OND.
- The changes in maxima in 1-day events in OND range from 0 to +16mm and -3 to +24mm in 5-day events until 2060s.

UNDP Climate Change Country Report for Ethiopia does not cover changes in wind or sea level rise as this is not considered relevant for Ethiopia.

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

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

- Temperature (and evaporation),
- Rain (intensity/frequency and volume) and

There are no coastlines in Ethiopia why the sea level rise is not relevant.

There are no forecasts of winds but the general trend and model results from elsewhere indicate increased frequency of extreme winds in the region.

The general key figures for the relevant changes in Ethiopia 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 ^{O}C to 2 ^{O}C and the number of annual days with heat waves will increase with 0 to 3 days/year. The impact is higher asphalt temperature, dust, increased evaporation
- The annual rainfall increase will range from - 17% till 28%, most in south and less in north. The impacts 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 4-25% in intensity for a 10-year storm and with 13-43% for a 100 year storm. The impacts is increased frequency of flash floods, erosion, sediment and landslide

The predicted change in temperature in the 4 scenarios until 205 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 driest season OND (October - December) and especially in the southern part of the country. In the season April - June the precipitation in the central and wet area in Ethiopia, will decrease. On annual basis the precipitation will increase most in the south-eastern part of the country and less in the northern part.

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. The climate zoning related to the seasonal rainfall pattern combined with the precipitation pattern and temperature (evaporation) in the most critical season is used for the estimate of the extent of the consequences of increased flow and more wet soil.

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 Manual are based on historical 24-hour rainfalls in the different zones. These data are used to find design curves for shorter and more intensive storms. The design curves are calibrated to some actually measured storms.

In this study the same calculation method as used in the Drainage Manual (except for the calibration) is used to establish new design curves for year 2050. In the wet north-western part of the country the wet months are July and August and in the south-western part the wet months are April-May and October.

2.4 Climate change for scenarios in this study

The specific analyses in this study are based on 4 climate scenarios for Ethiopia 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
"Ethiopia Wet":	NCAR-CCSM,	SRES A1b
"Ethiopia Dry":	IPSL,	SRES B1

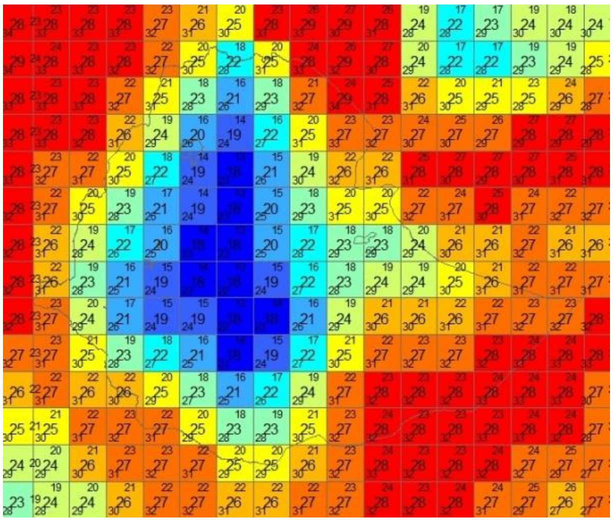
For these scenarios data and results have been processed by the University of Colorado[6] especially for this study with focus on precipitation, temperature and run-off for the present climate situation and the future situation in the period around 2050 and around 2100. An introduction to the data base and data processing can be found in the appendix.

2.4.1 Key figures for the climate scenarios

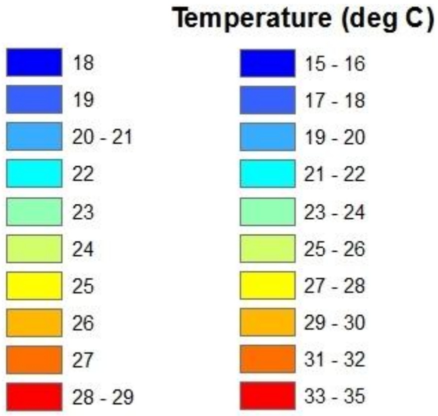
Some of the most essential figures for the climate information are presented below. The focus is on temperature and precipitation in heavy events.

[6] 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.

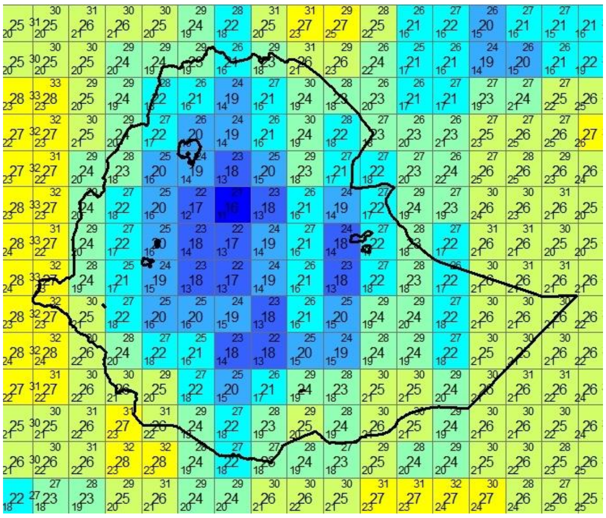
Figure 2-13 Temperature. Annual daily temperature, max, mean and min.



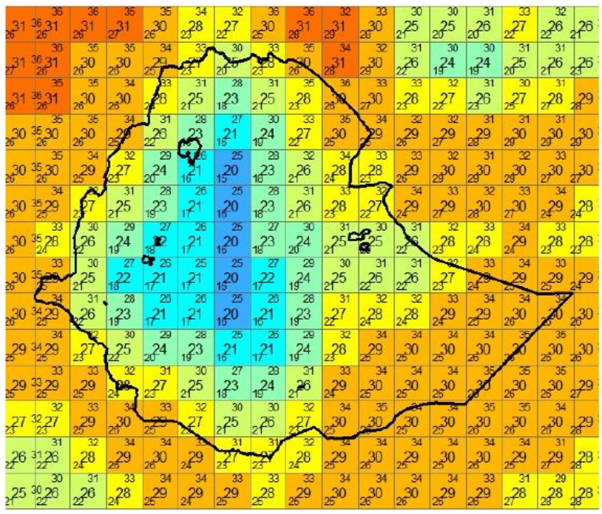
Historical, 1997-2006



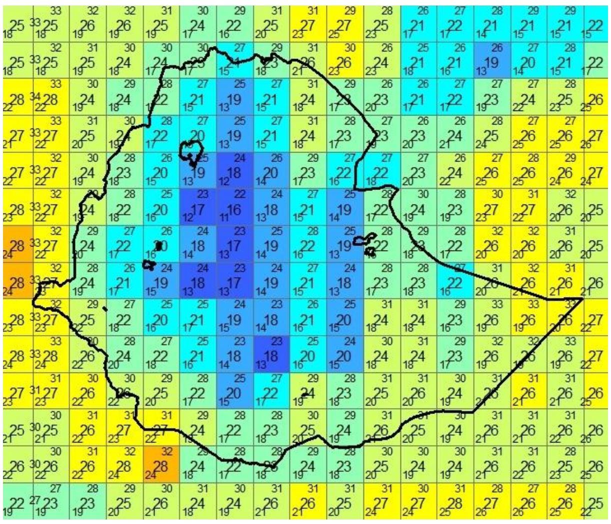
Historical Scenarios



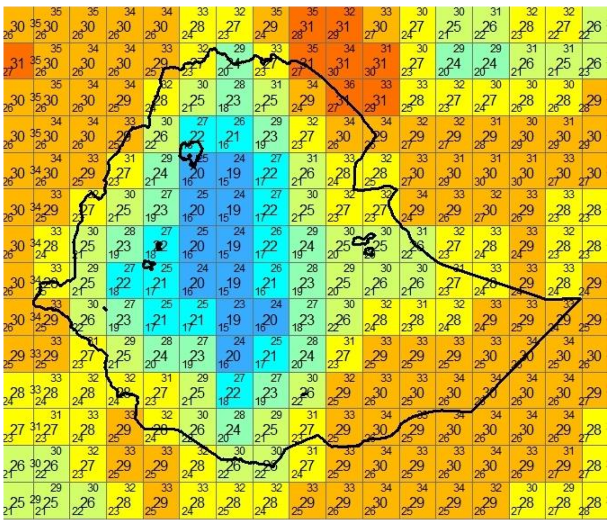
“Global Wet”: NCAR-CCSM, SRES A2



“Global Dry”: CSIRO-MK3.0, SRES A2

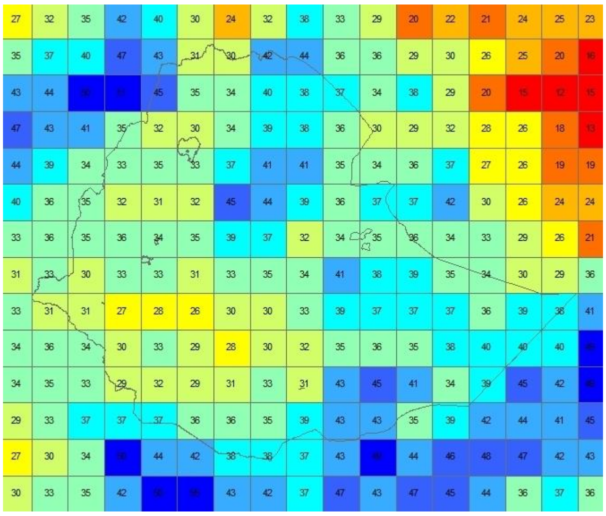


“Ethiopia Wet”: NCAR-CCSM, SRES A1b

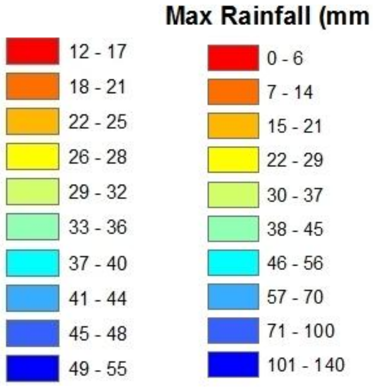


“Ethiopia Dry”: IPSL, SRES B1

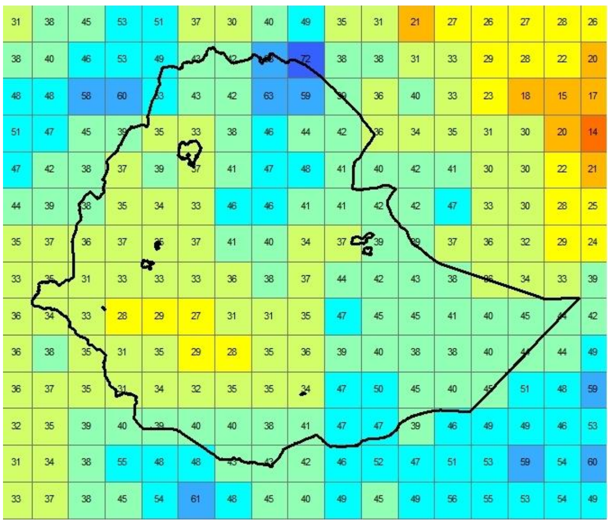
Figure 2-14 Precipitation. Annual 24 hours maximum rainfall (pr year)



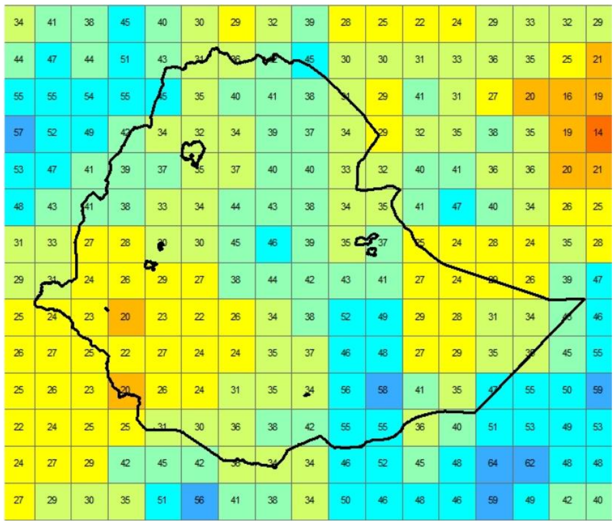
Historical, 1997-2006



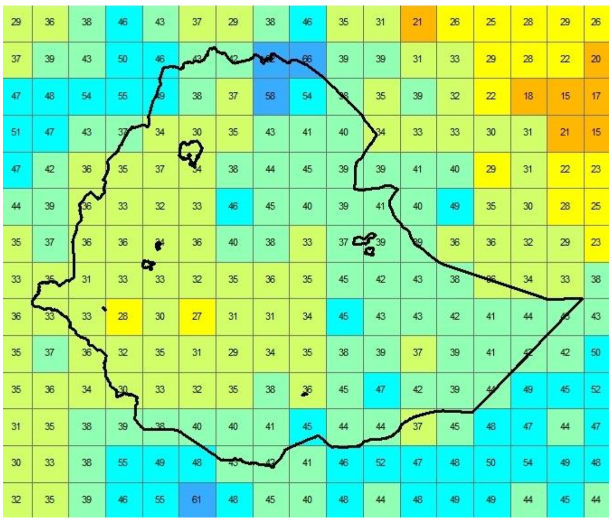
Historical Scenarios



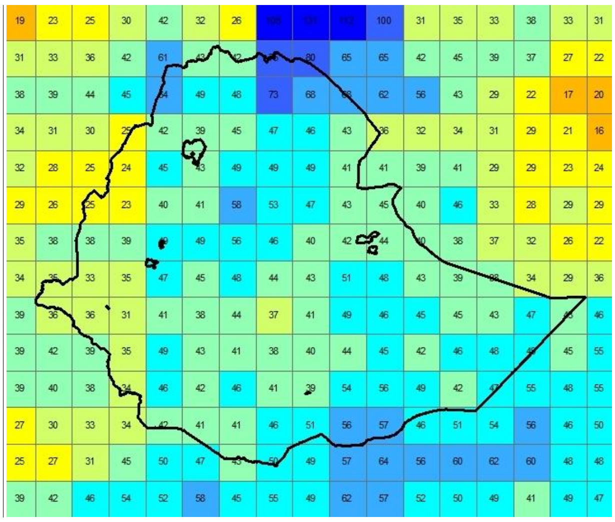
“Global Wet”: NCAR-CCSM, SRES A2



“Global Dry”: CSIRO-MK3.0, SRES A2



“Ethiopia Wet”: NCAR-CCSM, SRES A1b



“Ethiopia Dry”: IPSL, SRES B1

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 Ethiopia, rain and temperature

Climate 2050 on Average in Ethiopia, rain and temperature						
		Hist	GW-NCAR,A2	GD-CSIRO,A2	EW-NCAR,A1B	ED-IPSL,B1
Precipitation:						
Annual Mean Rainfall	mm/y	686	875	570	817	844
Annual Mean 24 hrs Max. Rainfall	mm/24h	35	39	35	38	45
Annual Mean 5 days Max. Rainfall	mm/5d	79	91	80	87	97
Annual days with rainfall	days/y	154	160	133	156	217
Temperature:						
Annual Mean	deg C	23	22	25	22	25
Annual Min.	deg C	19	17	21	17	21
Annual Max.	deg C	28	27	30	27	29
Annual days with heat waves	days/y	2	4	2	5	2

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

Climate Change 2000->2050 on Average in Ethiopia					
Increase from 2000 to 2050		GW-NCAR,A2	GD-CSIRO,A2	EW-NCAR,A1B	ED-IPSL,B1
Precipitation:					
Annual Mean Rainfall	mm/y	189	-116	131	158
Annual Mean 24 hrs Max. Rainfall	mm/24h	4	0	3	10
Annual Mean 5 days Max. Rainfall	mm/5d	12	1	8	18
Annual days with rainfall	days/y	6	-21	2	63
Temperature:					
Annual Mean	deg C	-1	2	-1	2
Annual Min.	deg C	-2	2	-2	2
Annual Max.	deg C	-1	2	-1	1
Annual days with heat waves	days/y	2	0	3	0

Table 2-3 % Climate 2000-2050 on average in Ethiopia

% Climate Change 2000->2050 on Average in Ethiopia					
% Increase from 2000 to 2050		**GW-NCAR,A2**	**GD-CSIRO,A2**	**EW-NCAR,A1B**	**ED-IPSL,B1**
Precipitation:					
Annual Mean Rainfall	mm/y	28%	-17%	19%	23%
Annual Mean 24 hrs Max. Rainfall	mm/24h	11%	0%	9%	29%
Annual Mean 5 days Max. Rainfall	mm/5d	15%	1%	10%	23%
Annual days with rainfall	days/y	4%	-14%	1%	41%
Temperature:					
Annual Mean	deg C	-4%	9%	-4%	9%
Annual Min.	deg C	-11%	11%	-11%	11%
Annual Max.	deg C	-4%	7%	-4%	4%
Annual days with heat waves	days/y	100%	0%	150%	0%

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 use design storms based on the 24 hour precipitation for different return periods. In the following tables some of the key results from this study 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 present design manual.

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 on heavy storm curves for evaluation of the change in return periods. The directly calculated curves are used as basis curves for design of new structures and enlargement or reinforcement of existing roads, culverts, bridges etc., except for the values for a 1 year storm which seems to be very uncertain - and not relevant for designs.

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, calculated as an average curve for Ethiopia, use precipitation design values that are about 50 % 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 percentage 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 20 year in the future (2050), if the predictions for "Global Wet"; NCAR-CCSM, SRES A2, are correct for Ethiopia - 5 times more often than today.

Table 2-4 Calculated return periods

24 hour precipitation depth (mm) vs frequency (yrs), Average in Eth. (directly from GCM data):							
mm/24hrs. Return reriod in years	**1**	**2**	**5**	**10**	**20**	**50**	**100**
Historical	9	41	59	68	76	86	92
"Global Wet"; NCAR-CCSM, SRES A2	12	46	68	83	98	117	132
"Global Dry"; CSIRO-MK3.0, SRES A2	20	45	61	71	81	94	104
"Ethiopia Wet"; NCAR-CCSM, SRES A1b	NA	49	71	85	99	118	132
"Ethiopia Dry"; IPSL, SRES B1	15	48	69	83	96	114	127

24 hour precipitation depth (mm) vs frequency (yrs), Average in Eth. (based on formula+GCM):							
mm/24hrs. Return reriod in years	**1**	**2**	**5**	**10**	**20**	**50**	**100**
Historical	31	41	54	63	73	86	95
"Global Wet"; NCAR-CCSM, SRES A2	30	45	65	81	96	116	131
"Global Dry"; CSIRO-MK3.0, SRES A2	35	45	59	70	80	94	104
"Ethiopia Wet"; NCAR-CCSM, SRES A1b	35	50	69	83	98	117	132
"Ethiopia Dry"; IPSL, SRES B1	34	48	66	80	94	112	126

Note: formula = "smooth" curves

The following table is used for increase in design and for enlargement and reinforcement of roads, culverts, ditches, bridges etc.

Table 2-5 % change in precipitation per return period

% - Change in 24 hour precipitation depth (mm) vs frequency (yrs), Average in Eth.(directly from GCM data):							
% increase 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	NA	11%	16%	22%	29%	37%	43%
"Global Dry"; CSIRO-MK3.0, SRES A2	NA	9%	3%	4%	6%	10%	13%
"Ethiopia Wet"; NCAR-CCSM, SRES A1b	NA	18%	20%	25%	30%	37%	43%
"Ethiopia Dry"; IPSL, SRES B1	NA	15%	17%	21%	26%	33%	38%

Table 2-6 Absolute change in precipitation per return period

mm - Change in 24 hour precipitation depth (mm) vs frequency (yrs), Average in Eth.(directly from GCM data):							
mm increase in design values based om Climate Change up to 2050 compared to present perecipitation							
Future - historical, mm	**1**	**2**	**5**	**10**	**20**	**50**	**100**
Historical	0	0	0	0	0	0	0
"Global Wet"; NCAR-CCSM, SRES A2	3	5	10	15	22	32	40
"Global Dry"; CSIRO-MK3.0, SRES A2	10	4	2	3	5	8	12
"Ethiopia Wet"; NCAR-CCSM, SRES A1b	NA	8	12	17	23	32	39
"Ethiopia Dry"; IPSL, SRES B1	6	6	10	14	20	28	35

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.

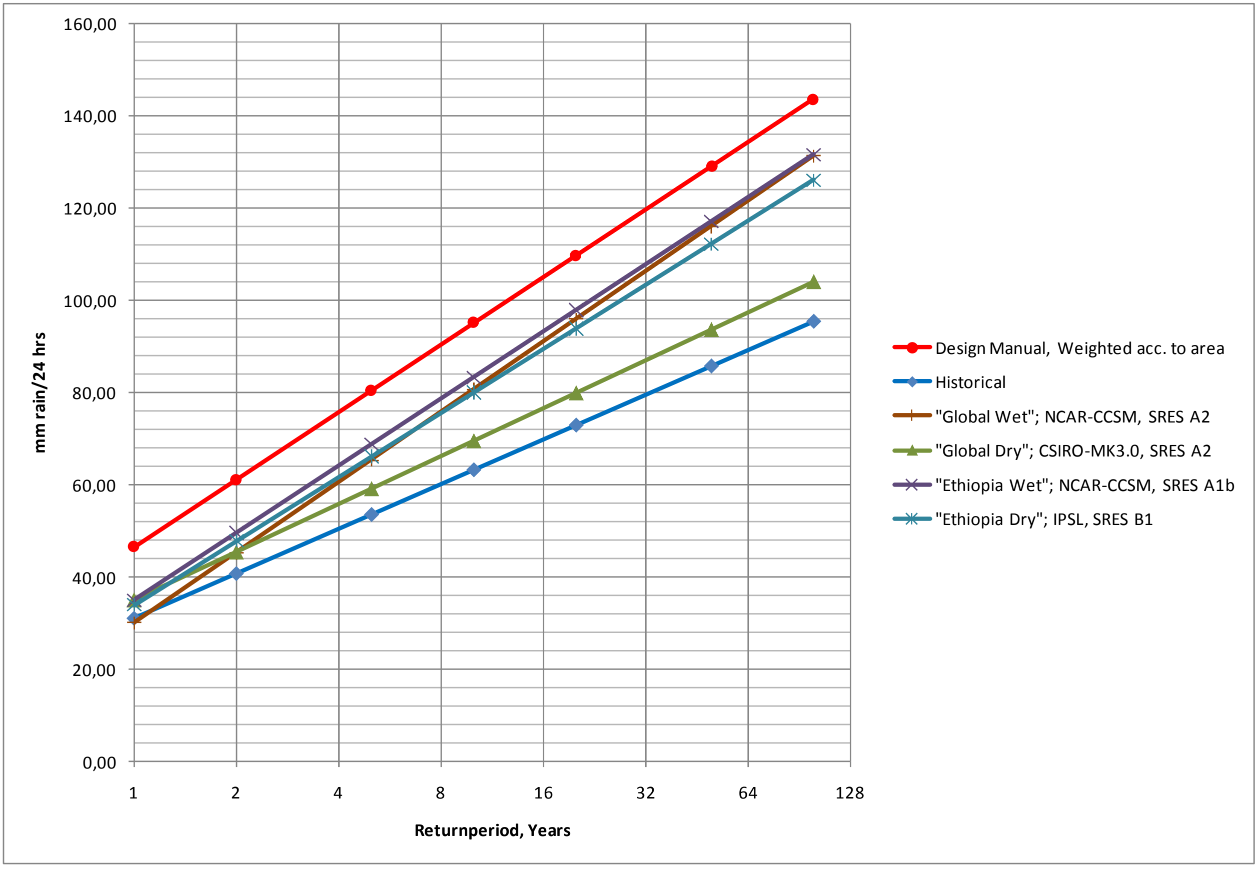
Table 2-7 Future return period in years

New returnperiod - 24 hour prec. depth (mm) vs frequency (yrs), Average in Eth. (based on formula+GCM):							
Future returnperiod in years for a present XX year storm							
Return reriod 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	2	3	5	7	13	20
"Global Dry"; CSIRO-MK3.0, SRES A2	1	1	3	7	13	30	56
"Ethiopia Wet"; NCAR-CCSM, SRES A1b	1	1	2	4	6	11	18
"Ethiopia Dry"; IPSL, SRES B1	1	1	3	4	7	13	22

Note: formula = "smooth" curves

The figures for present and future 24 hour maximum rainfall are represented in the following graph together with the present average design curve for Ethiopia. The average design curve is based on the present curves for different districts weighted according to the area they represent.

Figure 2-15 Calculated design curves



The graph shows that three of the climate scenarios result similar design curves, which can not for any practicable purpose be differentiated. Only "Global Dry", CIRO-MK3.0; A2 shows a different pattern as it follows the same pattern as the historical curve, but the values for 24 hours precipitation are approximately 10 % higher. The current design curve is still seen to be above the theoretical requirements in the climate situation in 2050 for all 4 scenarios.

3 Ethiopian road network

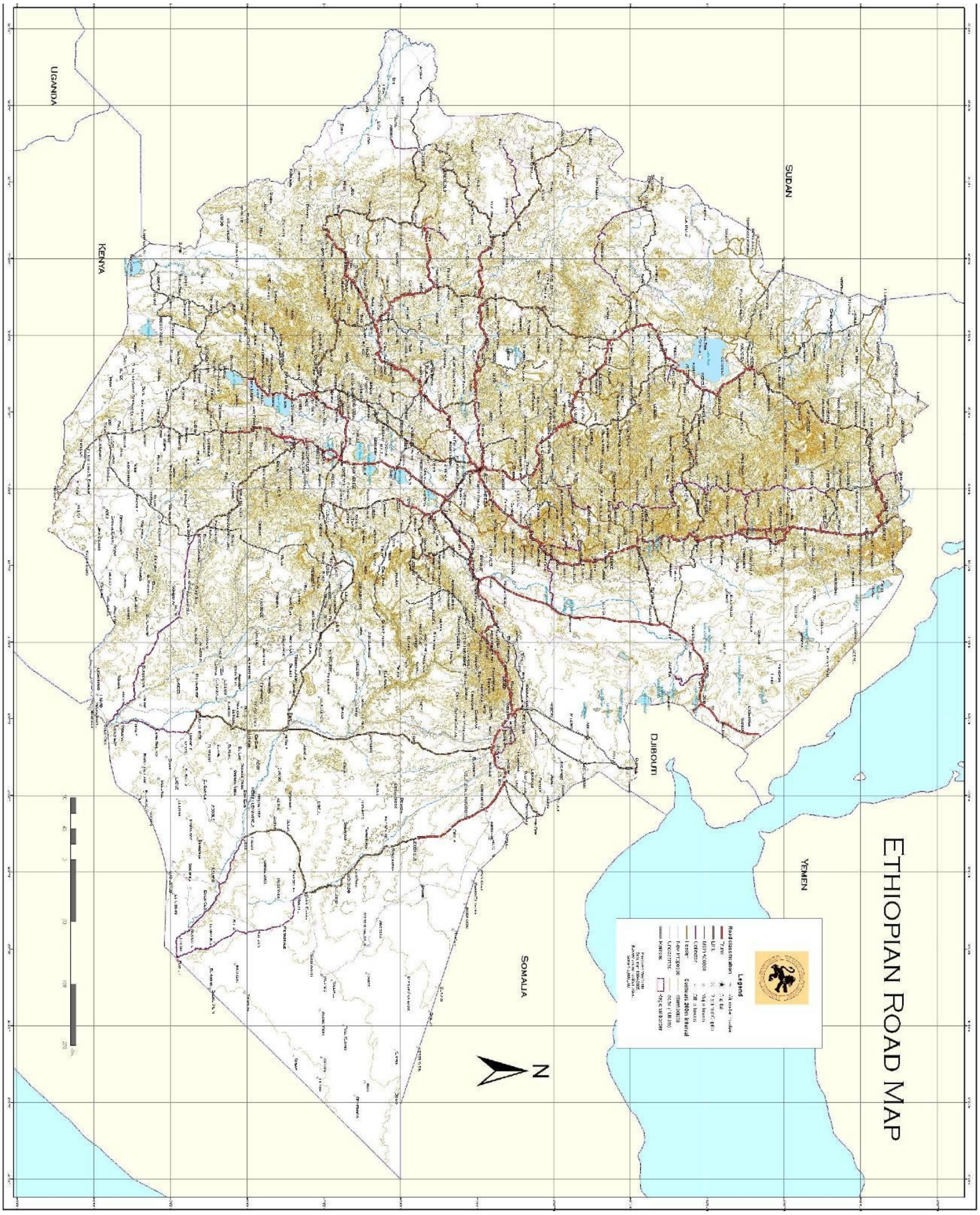
3.1 Introduction

As of September 2008, Ethiopia has an estimated road network of approximately 38,000 km. Based on GIS models and an existing 200m contour Digital Terrain Models (DTM), the network can be divided into the four terrain classes used by ERA: Escarpment 5%, Mountainous 15%, Rolling 25%, and Flat 55%. Ethiopian roads are governed and maintained by several different organizations including: Ethiopian Road Authority (ERA), and the Regional Road Authority (RRA.)

ERA manages the federal road network which comprises of 20,400 km of road, of which 6000 is paved. The roads outside ERA governance are the responsibility of the Regional Road authority as well as other local authorities. There are 11 regions in Ethiopia, with each region having authority for the regional roads within its boundaries.

ERA has developed their road design manuals using 10 different standards of road from DS1 to DS10. DS1 through DS4 cover the paved roads, while the remainder of standards is for unpaved roads. The level of standard to design and construct a road is chosen based on the design traffic flow (AADT.)

Figure 3-1 Ethiopia road network



Source: ERA 2008

Figure 3-2 ERA design standards

Road Functional Classification	Design Standard No.	Design Traffic Flow (AADT)
Trunk	DS1	10,000 – 15,000
Trunk, Link	DS2	5,000 – 10,000
Trunk, Link	DS3	1,000 – 5,000
Trunk, Link, Main Access	DS4	200 – 1,000
Trunk, Link, Main Access, Collector	DS5	100 – 200
Link, Main Access, Collector, Feeder	DS6	50 – 100
Main Access, Collector, Feeder	DS7	30 – 75
Collector, Feeder	DS8	25 – 50
Feeder	DS9	0 – 25
Feeder	DS10	0 – 15

Source: ERA

The feeder roads, (DS9 and DS10) are typically earth bound community roads constructed by labor-based methods. All elements of the road design are reflected in their design standard number, from geometric design, the road cross section, and surface drainage. The ERA manuals referred in this report include:

Drainage Design Manual-2002
Bridge Design Manual-2002
Geometric Design Manual-2002
Pavement Design Manual-2002
Pavement Rehabilitation and Asphalt Overlay Manual-2002
Site Investigation Manual-2002
Standard Technical Specifications-2002
Standard Detail Drawings-2002

It is intended that all new road construction in Ethiopia follow these guidelines regardless of the level of standard, or the jurisdiction the road is under. It is understood that ERA currently is in the process of updating some of the geometric requirements but as this updating is not yet official, it will not be covered in this report.

3.2 Current road assets in Ethiopia

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

The Bridge Management System (BMS) was initiated in Ethiopia to aid in the maintenance and rehabilitation of Ethiopia's bridge network. BMS has a database of the majority of bridges and culverts in Ethiopia. As of 2008, 4407 bridges and 40567 culverts have been registered in Ethiopia. The registration is different for each structure and ranges from only its location to a detailed report of the structure including photos. Figure 3-3 below summarizes the number of bridges and culverts and their respective managing agency in Ethiopia.

Table 3-1 Bridges and culverts in Ethiopia

It. No	Road Agency	Road length Km	Bridges Length => 4.0 mt	Culverts, Length <4.0 mt
1	ERA - Federal Roads	20429	2955	25457
2	Tigray RRA	1197	248	2629
3	Afar RRA	455	35	493
4	Amhara RRA	2197	219	2231
5	Oromia RRA	5209	440	5014
6	Somali RRA	2011	6	
7	Southern RA	2947	251	1938
8	Gambella RRA	436	15	422
9	Benishangul Gumz RRA	596	66	512
10	Harere RRA	150	7	175
11	Diredawa RA	200	15	200
12	Addis Ababa City RA	3896	150	1500
Total		**38098**	**4407**	**40567**

Source: Ethiopian Bridge Management System, April 2009

A bridge in Ethiopia is classified as a structure with a span between abutment faces of 4 to 6 meters or more. There is some discrepancy between the ERA Drainage Manuals, and the tables presented in a report by the Bridge Management System. The ERA guidelines say a bridge is longer than 6 meters, where the tables in the BMS manual list bridges as longer than 4 meters. A bridge consists of a substructure and a superstructure. The substructure includes the piers and abutments which hold the superstructure (bridge deck) up.

Figure 3-3 Bridge Wukro Agridat Zalambesa road

Source: Consultant

The type of bridge selected depends on many different factors such as budget, live loading, hydrology, span distance, etc., and can range from a long reinforced concrete structure to a low level water crossing. Where the traffic levels are highest on the main trunk roads, it is expected to find a higher investment in the bridge structure to ensure year round passage.

In Ethiopia bridges are defined as:

- structures that transport traffic over waterways or other obstructions;
- part of a stream crossing system that includes the approach roadway over the flood plain, relief openings, and the bridge structure;
- structures with a centerline span of 6 meters or more, structures such as large box culverts of multi-plate arches, designed hydraulically as bridges

A culvert is a structure with a maximum 6 meter total open span used to convey water flow. Typically, culverts are covered with embankment and are commonly made with structural material around the entire perimeter. Culverts are often constructed as reinforced concrete slabs as shown in Figure 3-4 or as reinforced concrete pipe as shown in Figure 3-5.

Figure 3-4 Slab concrete culvert Wukro Agridat Zalambesa road

Source: Consultant

Figure 3-5 Concrete pipe culvert Mekele - Abi Adi- Adwa road

Source: Consultant

Table 3-2 shows the distribution of bridge lengths for a sample of 2754 bridges in Ethiopia. Over 60% of the bridges are less than 20 meters in length.

Table 3-2 Distribution of bridge length in Ethiopia

Bridge Length m	Bridges	%	Accumulated %
4-10	850	30.9%	30.9%
10-20	881	32.0%	62.9%
20-30	417	15.1%	78.0%
30-40	261	9.5%	87.5%
40-50	140	5.1%	92.6%
50-60	77	2.8%	95.4%
60-70	42	1.5%	96.9%
70-80	29	1.1%	97.9%
80-90	16	0.6%	98.5%
90-100	11	0.4%	98.9%
100-	30	1.1%	100.0%
Total	**2754**	**100.0%**	

Source: ERA BMS, April 2009

Of the 2955 bridges registered in the federal road network, 30% need some form of rehabilitation, and 3.6% are due for replacement. Table 3-3 shows the distribution of the ages of the bridges in the federal road network. More than 37% of the bridges are 60 years or older. Typically, bridges today used in the federal trunk roads are designed and built with a lifespan of 50 to 100 years. Many of the bridges built by the Italians between 1936 and 1941 still appear to be in good shape with sufficient structural integrity.

Table 3-3 Bridge age distribution in Ethiopian federal road network

Bridge Age (years)	0-9	10-19	20-29	30-39	40-49	50-59	60 +	Total
Number Bridges	530	423	444	310	104	31	1111	2953
Percentage (%)	17.9%	14.3%	15.0%	10.5%	3.5%	1.0%	37.6%	100.0%

Source: ERA BMS April 2009

Current design practices

Since 2002, the ERA design manuals are the recommending starting point for all bridge and culvert design in Ethiopia. It is difficult to quantify the standards and design flows that were used to design these structures before the design manuals were published and used in road design. In the case of a road rehabilitation or upgrade, the structures hydraulic adequacy is checked through the use of hydrologic calculations such as the SMS or Rational Method. Their adequacy can also be checked from local observations and discussions with local residents.

Currently, Ethiopia uses an average temperature range of 30 degrees C, as set by the Ethiopian Building Code Standard. Seasonal temperature variation is found from local data, or if this is not available, from the National Atlas of Ethiopia 1988 for the closest location.

Temperature gradient investigation is not required on all new bridges in Ethiopia. If experience has shown that neglecting temperature gradient in the design of a given type of structure has not led to structural distress, ERA may choose to exclude temperature gradient. (ERA Bridge Design Manual)

Long span bridges >50 m are designed for a lifetime of 100 years. These bridges are designed to withstand a 100 year recurring flood in the watercourse they pass over, with a hydraulic capacity check of a 500 year storm, as well as scour protection associated with a 500 year recurring flood. The information used to calculate these flows is taken from the ERA drainage manual, relevant Ethiopian ministries, and site observations. There is not 100 years of accurate hydrologic data, giving rise to the question of how accurate the 100 year design flow predictions are, but this is a common problem in most parts of the world.

Long span bridges are built for a 100 year life span regardless of the level of standard of the road that uses it. Short span bridges 15-50m are designed for a life of 50 to 100 years depending on the level of standard of the road.

Culverts are designed to withstand a design storm between 5 and 50 years depending on the standard of road. It has been observed in practice from areas around the world that reinforced concrete pipe culverts can have a structural life of 50 - 100 years. Reinforced culvert pipes are becoming the chosen mode for culverts in Ethiopia, as their availability is increasing.

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. A gravel wearing course is comprised of a specified graded material that should meet testing standards covered in the ERA design manuals. 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 (level of standard DS9 or DS10.)

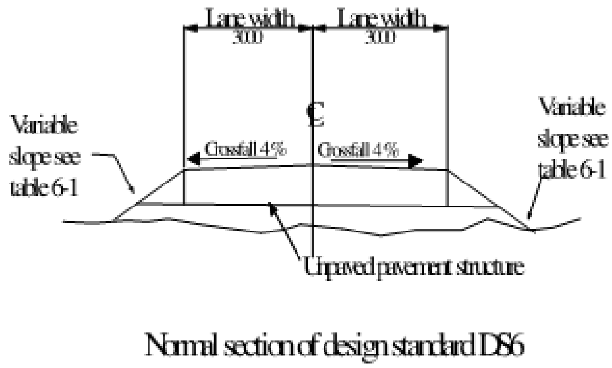
Table 3-4 ERA paved and unpaved roads federal network

	Paved (km)	Unpaved (km)	Total
Trunk	4750	612	**5362**
Link	724	4788	**5512**
Main Access	587	4388	**4975**
Collector	0	2123	**2123**
Feeder	5	2452	**2457**
	6066	**14363**	**20429**

Source: ERA Network Management, 2008

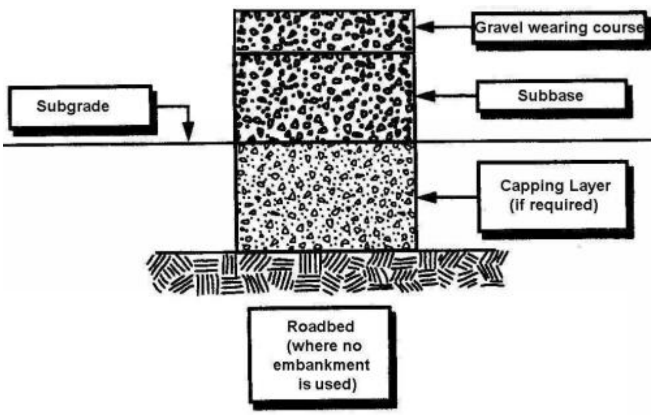
The road section for a paved or gravel road follows a similar structure. Typically, the structure includes the subgrade, capping layer, the sub base materials and a wearing course. The sub base materials and thicknesses are adjusted or left alone depending on the strength and quality of the subgrade. 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 (DS no.)

Figure 3-6 Typical road section DS6



Source: ERA

Figure 3-7 Typical elements of a gravel road DS6



Source: ERA

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: Pavement Design Manual Volume 1 and Volume 2. The manual covers design for both paved trunk roads, as well as gravel and community roads. New roads in Ethiopia have been using these manuals since 2002. Roads built before the publication of the design manuals followed the Overseas Road Note 31, which sections of the ERA Pavement Design Volume closely follow.

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 ERA manuals. The type of testing and frequency is dependent on the level of standard of the road, as well as the location in Ethiopia. In arid regions, the engineer can decide if a 4 day soaked CBR test is 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 such as the community roads is not up to the same standard due to the financial aspects as well as availability of skilled technicians to perform the testing. The lack of testing makes it more difficult to ensure an economically feasible strong design.

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 are discussed in Site Investigation Manual-2002. A deep seated failure is much more destructive and there is a limited amount of economical engineering solutions for prevention.

There is a limited amount of information available on the impact of landslides in Ethiopia. From discussions with ERA, landslides are most commonly seen as rock fall. It is difficult to quantify how many of the landslides are a direct result from the road construction, and how many are occurring from natural processes, or amplified from poor land use.

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.

Current design practices
The design of the interaction between the road slopes and the landscape is covered in the ERA design manuals. Slope requirements used in road construction is dependent on the geology, soil conditions, and evidence of past slope instability.

3.2.5 Surface drainage

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 3-5 shows the design storms used for designing the most common drainage elements.

Table 3-5 ERA design storm frequency

Structure Type	Geometric Design Standard			
	DS1/DS2	DS3/DS4	DS5/6/7	DS8/9/10
Gutters and Inlets*	10/5	2	2	-
Side Ditches	10	10	5	5
Ford/Low-Water Bridge	-	-	-	5
Culvert, pipe (see Note) Span<2m	25	10	5	5
Culvert, 2m<span <6m	50	25	10	10
Short Span Bridges 6m<span<15m	50	50	25	25
Medium Span Bridges 15m<span<50m	100	50	50	50
Long Span Bridges spans>50m	100	100	100	100
Check/Review Flood	200	200	100	100

Source: ERA Drainage Design Manual

Current design practices
The extensive ERA Drainage Design Manual is to be used in guidance for all road related drainage. Within the manual are precipitation charts and relevant design storms that are used for the design of drainage structures. These charts are based on historical data collected by relevant ministries in Ethiopia, but are to be updated using the climate prediction models funded by the World Bank.

3.2.6 Summary

The road assets in Ethiopia vary 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, 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 Ethiopia. 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 Ethiopia. The explanation for the lack of maintenance is lack of funding and available equipment. The majority of money allocated to maintaining roads in Ethiopia 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 Ethiopia 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 and adaption measures for road assets

4.1 Introduction

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

- Temperature
- Rain

4.2 Temperature

4.2.1 Introduction

In Ethiopia, the mean annual temperature is projected to increase by around 2 ^{O}C by the 2050. An increase in temperature is expected to have the largest impact on:

- Bridges
- Bituminous pavements

4.2.2 Bridges

Impact of climate change and Countermeasures

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. 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 evapo-transpiration, 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.

Bridges are already designed with temperature gradients in mind. The temperature changes in Ethiopia 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 properly. In order to ensure longevity of the bridge structure, these expansion joints will require increased maintenance, or engineering solutions requiring less maintenance.

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.

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.

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

4.2.3 Pavement design

Impact of climate change and countermeasures
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.

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.

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 should not be expected, but in case it was necessary to adjust 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.

4.2.4 Climate change impacts temperature summary table

Table 4-1 Climate Change 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	-1 to +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	

4.3 Rain

4.3.1 Introduction

In Ethiopia, climate associated with rainfall has the largest impact on roads. This chapter covers major elements of a road 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. See Table 3-5 for overview of current design storms required for design by ERA. 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 ERA guidelines to determine new sizing requirements, and/or more appropriate engineering solutions. Because the values for the Global Wet, Ethiopia Wet, and Ethiopia Dry scenarios are so similar, only the Global Dry scenarios and Ethiopia Wet scenarios are used in analysis.

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

% - Change in 24 hour precipitation depth (mm) vs frequency (yrs), Average in Eth.(directly from GCM data):							
(Future-historical)/historical	1	2	5	10	20	50	100
Historical	0%	0%	0%	0%	0%	0%	0%
"Global Wet"; NCAR-CCSM, SRES A2	33%	11%	16%	22%	29%	37%	43%
"Global Dry"; CSIRO-MK3.0, SRES A2	115%	9%	3%	4%	6%	10%	13%
"Ethiopia Wet"; NCAR-CCSM, SRES A1b	NA	18%	20%	25%	30%	37%	43%
"Ethiopia Dry"; IPSL, SRES B1	61%	15%	17%	21%	26%	33%	38%

Source: Chapter 2.4

Increased rain will have the largest impact on the road network of the expected climate changes. This report covers the impacts that rain has on:

- Bridges
- Culverts
- Pavement Design
- Slope Stability
- Surface Drainage

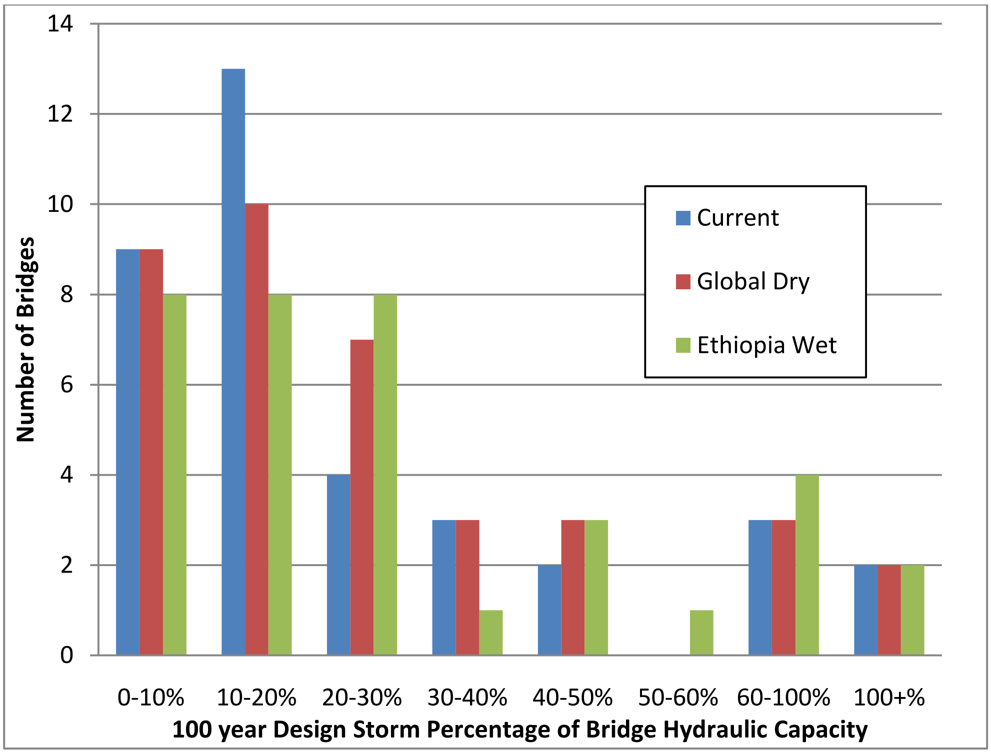
4.3.2 Bridges

Impact of climate change

An in-depth hydrologic analysis was performed on 36 bridges ranging from 6 to 60 meters for a previous COWI project in the northern region of Ethiopia. The hydrologic analysis was done using the SCS method for design storms ranging from 10 to 100 year frequency. The hydrologic analysis was updated using the Global Dry and Ethiopia Wet scenarios.

Figure 4-3 shows the relationship between the existing bridges and their hydraulic capacity for a 100 year storm. The hydraulic capacity takes into account the vertical clearance at design flood level of between 0.3 and 1.2 meters required by ERA dependent on flows. The horizontal axis of Figure 4-3 describes how much of the overall hydraulic capacity of the bridge the design storm is utilizing. A bridge that falls into the category of 0-10% means that less than 10% of the overall hydraulic capacity is being used. For example, for a bridge in the 0-10% category, if the design storm was 10 cms, the hydraulic capacity of the bridge is 100 cms.

Figure 4-1 Mekele Abi Adi Adwa Bridge Hydraulic Capacities under 100 year storm



The majority of these bridges (86% for both the Dry and Wet scenarios) will have the hydraulic capacity to withstand a 100 year storm for the future scenarios. The few bridges that will not be able to withstand the future flows already have capacity issues for the current storms. The likelihood for these bridges is that the watershed they were designed for are in fact much larger than originally calculated. Most of these bridges are built with a surplus of hydraulic capacity. The available topographic maps, as well as hydrology data have become more accurate since the bridges were constructed. For bridges that do not hydraulic capacity, then there is likelihood that severe damage will occur most likely in a bridge washout.

The hydraulic investigations are showing that the majority of these 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. This report only deals with bridge failures due to climate impacts.

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. A new bridge that follows the ERA guidelines must be able to withstand a scour event associated with at least a 100 year storm, but this does not necessarily apply to all bridges that were built before the ERA guidelines became official in 2002. Table 3-3 shows the age distribution for bridges in the Federal network with over 80% of the bridges being over 10 years old, and over 37% being over 60 years old. 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.

Table 4-3 New Calculated Return period – 24 hour precipitation depth (mm) vs frequency (yrs), Average in Eth.:

Future return period in years of a present XX year storm								
Historical return period	**1**	**2**	**5**	**10**	**20**	**50**	**100**	year
"Global Wet"; NCAR-CCSM, SRES A2	1	2	3	5	7	13	20	year
"Global Dry"; CSIRO-MK3.0, SRES A2	1	1	3	7	13	30	56	year
"Ethiopia Wet"; NCAR-CCSM, SRES A1b	1	1	2	4	6	11	18	year
"Ethiopia Dry"; IPSL, SRES B1	1	1	3	4	7	13	22	year

Source: Chapter 2.4

Table 4-3 shows the new return intervals for the different design storms with the new climate scenarios. Under the Ethiopia Wet scenario, a storm that is today experienced with a rate of once every 100 years will in 2060 be experienced on average once every 18 years. This means that these current 100 year level design storms will be experienced with an increase in frequency of around 5 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 Ethiopia 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 300 and 500%. 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 Ethiopia Wet scenario, maintenance or reconstruction would be required every 4 to 6 years.

Climate impact countermeasures

If a bridge does not have hydraulic capacity, then the likelihood of a washout becomes severe. Some options to increase capacity are to make a larger bridge, or to accommodate the extra water in overflow channels, through extra culverts, or temporary flooding over the roadway in a location away from the bridge. It is financially more sensible to allow a small section of the road to be flooded or washed out, than the actual bridge. If capacity is not increased, then velocities around the bridge foundations can be expected to increase leading to increases in scour.

One of the largest threats to bridges from an increase in precipitation is associated with 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 implications of scour are well discussed in the ERA drainage design manual, as well as many other technical reports. Scour is a common problem with bridges around the world, and not just isolated to bridges in Ethiopia. There is ongoing research on the best engineering methods to implement scour prevention. The United States Federal Highway Administration has published very comprehensive design documents “Bridge Scour and Stream Instability Countermeasures” that thoroughly cover bridge scour and appropriate countermeasures.

Current ERA Bridge guidelines call for designing scour protection up to a 500 year super flood. The Ethiopia Wet climate scenario is showing that a 100 year flood will be experienced on average every 18 years, a 5 time increase, the future 500 year super flood can be expected to occur with a similar increase in frequency, in the future every 100 years or so. There is doubt into how many flooding events bridges are designed to encounter. Even if a bridge is able to withstand a flooding event of a 100 year storm, will it then be able to handle another event of similar magnitude shortly after? The Ethiopia Wet scenario is showing that these high magnitude events will occur more frequently, and thus the damage caused by them can also be expected to occur more frequently. Hydraulic analysis has shown that many of the structures have the hydraulic capacity to accommodate these floods, but say nothing about the bridge substructures interaction with the surrounding environment. If a bridge endures a 100 or 500 year super flood, what protection is left afterwards? With all the new climate scenarios showing large increases in the frequency of large scale events, it becomes imperative that the scour and embankment protection is repaired to its original design levels as soon as possible after flooding events. This requires a large increase in the year round inspection and maintenance of bridges. It may also warrant different tactics into the repair works of bridges.

Some preventive measures for scour are discussed in the ERA drainage manual and already used extensively in Ethiopia. The most common method for prevention of scour is the use of riprap or gabions. 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.

Figure 4-2 Downstream scour protection using gabions Mekele-Adwa km 156+751

Source: Consultant

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. The ERA Bridge management system (BMS) is already established to aid in monitoring and repair of bridges. It is suggested to supplement the BMS with a bridge scour action plan based on the US Department of Transportation's "Plan of action for scour critical bridges." Scour countermeasures can range from simply placing riprap in the scour voids, to highly technical structures including monitoring devices. The decision for which type of adaptation measures used should be decided upon on a case by case basis using a full life cycle analysis.

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.

Figure 4-3 Local bridge scour Wukro Agridat Zalambesa road

Source: Consultant

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 4-4 Large scale river works effort using rock gabions Mekele-Adwa

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.

Figure 4-5 Small bridge in need of channel maintenance Wukro Agridat Zalambesa

Source: Consultant

A common problem that is found throughout Ethiopia'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. The bridges hydraulic capacity is designed to withstand a 100 year recurring flood and have scour protection up to a 500 year super flood. 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. 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.

Figure 4-6 Bridge scour, Mekele Abi Adi Adwa road, km 73+685

Source: Consultant

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. It is a requirement in ERA drainage manual to ensure that the bridge decking properly drains.

It will be nearly financially impossible to design and build a bridge that will be able to withstand 100 years of flooding events without maintenance. Bridges cannot be built and then forgot about. The current Ethiopian climate warrants having rigorous maintenance, and the different climate scenarios are all showing severe increases in precipitation. With an increase in precipitation, the most important factor to a bridges survival is maintenance. Even a well designed bridge will still require maintenance to meet its 100 year design life. The amount of maintenance is dependent on the storms that are experienced, and needs to be flexible, yet thorough. Without maintaining the structural integrity of the bridge substructure, 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 in scour and sedimentation. There needs to be a greater investment into scour protection during initial construction, and countermeasures need to be implemented where needed. 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. Upstream river training is needed in unstable flood plains where the river has the opportunity to change its course. The suitability of the bridge's location for future flows needs to be considered.

<u>Climate impact summary</u>

Ethiopia Wet; NCAR-CCSM, SRES A1b

- Washouts due to lack of hydraulic capacity increase approx. 10-20%
- Scour damage increase 300-500%

Global Dry; CSIRO-MK3.0, SRES A2

- Washouts due to lack of hydraulic capacity increase approximately 5%
- Scour damage increase 50-70%

<u>Climate impact countermeasure summary</u>

- Append BMS with Scour Action plan
- Install flood overflow conduits for bridges with obvious lack of capacity
- Continue to use local materials to counteract scour, using examples from FHWA reports
- Perform lifecycle approach for bridge maintenance and repair on case by case basis
- Increase in inspection and repair budgets associated with bridge scour maintenance from where it should be today
    - 300%-500% for Ethiopia Wet Scenario
    - 50-70% for Global Dry Scenario

4.3.3 Culverts

Figure 4-7 Slab culvert filled with sediment Wukro Agridat Zalambesa

Source: Consultant

Impact of climate change

After analyzing hundreds of culverts that have been measured in the Tigray region of Ethiopia with the new climate prediction scenarios, it is found that a high percentage of the culverts that serve smaller watersheds, < 0.5km^2, will still have sufficient capacity to meet the 100 year flows of the new design storms with a headwater depth to culvert depth ratio (Hw:D) of maximum 1.5, (the maximum allowed by ERA.) On this stretch of road, the average sized culvert was 1000mm which gives a large factor of safety that allows the culverts to have sufficient capacity to meet the rainfall runoff that is experienced on many of these small watersheds. Even though the culverts have hydraulic capacity with an Hw:D ratio of 1.5, it is often seen that the inlet control is not designed to handle an Hw:D of greater than 1, let alone 1.5.

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. With an 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 an Hw:D ratio of 1.5 will have nearly twice the capacity of a culvert with an 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, 300-500% for the Ethiopia Wet scenario, and 50-70% for the Global Dry scenario.

Table 4-4 and Table 4-5 show the percentage of culverts that have capacity for the design storm with a HW:D ratio of 1 and 1.5 for the current situation as well as the different climate scenarios. These culverts are located on a road designed for DS3/DS4 standards that require culvert pipes with a span<2m to withstand a 10 year storm, and culverts with a span 2m<span<6m to withstand a 25 year storm with a max Hw:D of 1.5. Watershed runoff has been calculated using the rational method for watersheds < $0.5km^2$ (table a), and the SCS method for watersheds > 1 km^2 (table b). Nearly 90% of the culverts that drain watersheds <$0.5km^2$ have a combined culvert span of <2m.

Table 4-4 Percent of culverts with capacity for design storm frequency with Hw:D of 1 and 1.5; watersheds <$0.5km^2$

Design Storm	Current Climate		Global Dry		Ethiopia Wet	
	Hw:D		Hw:D		Hw:D	
	1	**1.5**	**1**	**1.5**	**1**	**1.5**
2	**88%**	**98%**	**86%**	**96%**	**85%**	**96%**
10	**74%**	**91%**	**73%**	**89%**	**66%**	**86%**
25	**67%**	**86%**	**65%**	**84%**	**56%**	**78%**
50	**61%**	**81%**	**56%**	**78%**	**48%**	**70%**
100	**56%**	**78%**	**50%**	**74%**	**45%**	**67%**

Table 4-5 Percent of culverts with capacity for design storm frequency with Hw:D of 1 and 1.5; watersheds >$0.5km^2$

Design Storm	Current Climate		Global Dry		Ethiopia Wet	
	Hw:D		Hw:D		Hw:D	
	1	1.5	1	1.5	1	1.5
10	**95%**	**95%**	**88%**	**95%**	**81%**	**95%**
25	**71%**	**95%**	**67%**	**90%**	**62%**	**83%**
50	**67%**	**83%**	**64%**	**83%**	**57%**	**67%**

Table 4-4 shows nearly 10% of existing culverts would not be able to withstand a 10 year design storm with an Hw:D of less than 1.5 under the current conditions. There is relatively small difference in the percentage of culverts with capacity under the different scenarios for a 10 year storm. Approximately 4% more culverts are expected to not withstand the 10 year design storm under the Ethiopia wet scenario. For the larger design storms, the number of existing culverts with capacity quickly diminishes, as they are not designed to accommodate such large storms. A large storm in the Ethiopia wet scenario will have much larger consequences on the existing culvert network; approximately an additional 11% of the culverts will not have capacity for the increased flows.

Table 4-5 shows similar results as Table 4-4. One thing to note is that many of the culverts serving the larger watersheds are built as slab or box culverts where the roadway can be placed nearly directly on top of the culvert ceiling. This makes it sometimes impossible to achieve an Hw:D much larger than 1 as the water will begin to flow over the roadway.

Figure 4-8 Percent of culverts with capacity for a 25 year storm with a Hw:D<1.5 compared to catchment area

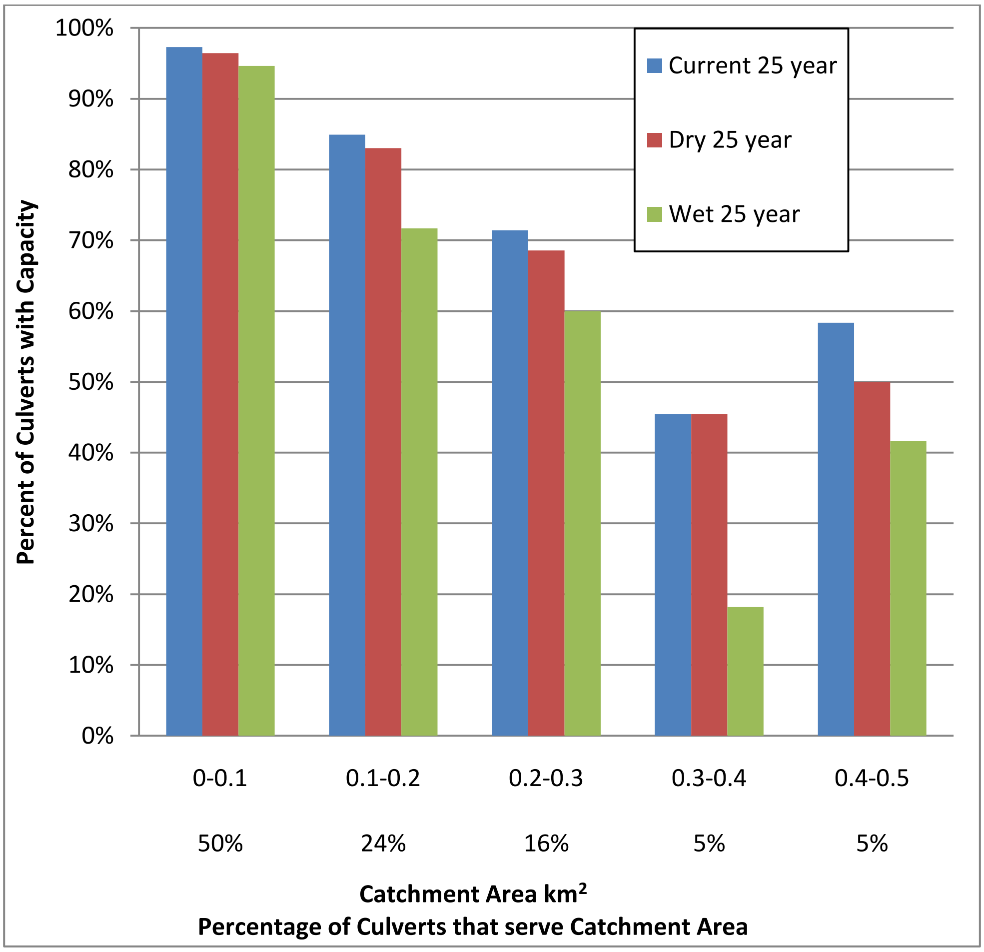


Figure 4-8 shows the distribution of culverts with capacity for a 25 year storm based on the catchment area they serve. For this particular area, the average culvert diameter used was 1000 mm. It is clearly seen that the percentage of culverts with capacity is nearly 100% for the small watersheds less than 0.1 km^2 for all the scenarios. This is a benefit of using a larger minimum culvert size. 50 percent of the culverts on this stretch of road serve catchment areas less than 0.1 km^2. For the larger catchment areas, the percentage of culverts with capacity drops dramatically; however, the number of overall culverts that serve these areas is lower.

These culverts analyzed are from one region in Ethiopia, but it is felt that they give a good representation of the existing road network in Ethiopia. It is often found that during upgrading projects, the existing drainage infrastructure is reused as often as possible and the current drainage structures could continue to be reused for the next 50 years if their condition allows it.

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. The Ethiopia Bridge Management system has already been established, and this system should continue to be used to help in monitoring and maintaining culverts.

Figure 4-9 Pipe culvert filled with sediment Mekele-Adwa km 24+931

Source: Consultant

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 750 mm diameter. 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. Reinforced 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. The easiest approach is to increase the culvert size but this may not be economically feasible. Culvert sizes should be increased in areas where the potential for damage is greatest, such as in areas with large fills. 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. This has been discussed in the ERA drainage design manual.

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 reenter the stream on the other side of the road causing only local damage to the road fill. The economic cost of a traffic delay on the majority of the lower traffic roads due to some temporary flooding is still cheaper than a culvert washout. 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 4-10 Eroded culvert outlet protection Mekele-Adwa km 39+038

Source: Consultant

For low speed gravel and community 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 DS5 roads and lower standard. A drainage swale is only suitable where it is acceptable to have a speed barrier. It is most suitable for low speed gravel and community 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 4-11.

Figure 4-11 Diversion potential through gravel road Mekele-Adwa km 165+946

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 areas that are hard to reach, culverts should be oversized to allow for some siltation but still allow hydraulic capacity.

Scour protection for culverts is just as important as it is for bridges. Culverts are usually not designed to accommodate large floods, and during these floods the capacity can be expected to be exceeded, leading to ponding of water and localized scour around the inlets and outlets. Scour countermeasures as discussed in the bridge chapter need to be utilized. The economic investments in protection methods should be chosen on a case by case basis, depending on the importance and expected lifespan of the road. When designing new culvert or culvert replacements, a cost comparison should be performed on the cost savings of using a larger culvert compared to using a smaller culvert with greater inlet and outlet scour control. A larger culvert that better matches the existing stream geometry will allow water to pass with fewer disturbances to the surrounding environment.

Figure 4-12 Road shoulder erosion caused from overtopping culvert with limited scour protection, Tanzania

Source: Consultant

More outfall protection will be required on the downstream side of culverts. Higher flows will increase the potential for downstream scour and erosion.

Figure 4-13 Increased culvert outlet protection Mekele-Adwa km 68+722

Source: Consultant

Summary
Culvert design needs to take into account expected increases in rain and frequency of design storms. 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. Culvert sizing should be designed taking into account the cost to repair a failure. Maintenance needs to be increased for all culverts in high risk areas

Climate Impact Summary

Ethiopia Wet; NCAR-CCSM, SRES A1b

- Washouts/Road overtopping due to lack of hydraulic capacity increase approximately 8-16%
- Scour damage increase 300-500%

Global Dry; CSIRO-MK3.0, SRES A2

- Washouts/Road overtopping due to lack of hydraulic capacity increase approximately 3-6%
- Scour damage increase 50-70%

Climate impact countermeasure summary

- Append BMS with Scour Action plan for culverts
- Continue to use local materials to counteract scour, using examples from FHWA reports
- Perform lifecycle approach for culvert maintenance and repair on case by case basis
- Increase in inspection and repair budgets associated with bridge scour maintenance from where it should be today
  - 300%-500% for Ethiopia Wet Scenario
  - 50-70% for Global Dry Scenario

4.3.4 Pavement design

Impact of climate change
Most of the climate scenarios are showing 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 Ethiopia 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. 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.

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 soils that are detrimentally affected by high moisture content will increase. There are mitigation measures covered in ERA Site Investigation Manual-2002, as well as ERA Pavement Design Volume 1-2002. 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 is briefly discussed in the ERA Design manuals. 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 ERA 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 Ethiopia that it is at the engineer's discretion whether a 4 day soaked test is 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.

In areas that experience frequent flooding leading to unusable road conditions, 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. The ERA design manuals cover the benefits and technical requirements of raising the roadway. There must be care taken when raising the roadway in floodplains or near rivers. The raised roadway can unintentionally act as a flood barrier increasing flooding and damage in other areas. When it is decided to raise the roadway, an experienced hydrologist should be included in the decision making to lessen the risks of flooding or increased damage from flooding in other areas.

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

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

(2) Sub base layers

There are technical methods discussed in the ERA 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. 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

(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 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 which is discussed in the ERA design manuals will help aid 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

(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 unsustainable 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 gravel materials have not been able to be supplied in sufficient quantities. However, areas of Ethiopia have large supplies of material suitable for a gravel wearing course, and the use of gravel will continue to be a viable material for using as road surfacing. Gravel can still be a suitable solution so long as the roads are regularly maintained. In areas where gravel supplies are not sustainable or economically feasible, alternatives for a wearing course can include: emulsion sand seal, emulsion chip seal, steel reinforced concrete, bamboo reinforced concrete, un-reinforced concrete, natural gravel/laterite, cobble stones, or slurry seal. These materials may have an initially more expensive cost of installation, but their long term maintenance costs will be lower. The experiences of using these alternative road building materials have been covered in the RRGAP projects in South East Asia. There are many more examples for surfacing alternatives in the World Bank published document "Surfacing Alternatives for Unsealed Rural Roads" published in 2005.

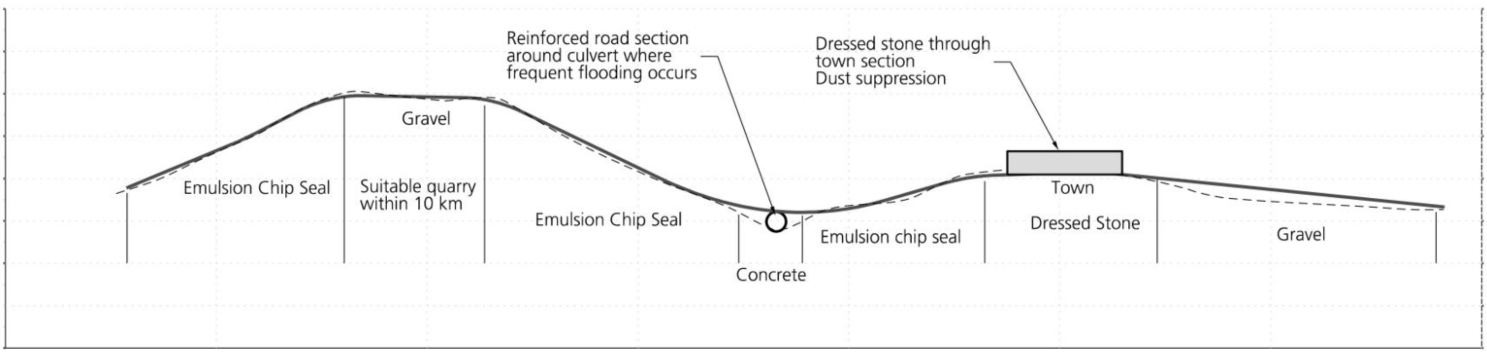
In areas where gravel roads are suitable, those with lower gradients, less rainfall, and suitable amounts of available gravel for maintenance, a climate resilient gravel surfaced road needs to meet similar requirements as a paved road to meet its design life. It must have a well functioning subgrade, sufficient drainage, and routine maintenance. 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, 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 every 2 to 5 years, and are dependent on a plentiful source of quality material.

In areas with higher precipitation and/or gradients, alternative methods of road construction should be used. This includes paving and the use of sealants as improvements in the areas most likely to be damaged. Spot improvements include updating the drainage or sealing the road 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 maintenance. 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 4-14 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 discussed in RRGAP reports. Community roads have a narrower carriageway making them more suitable to methods such as cobble stones or engineered bricks. If the local material is suitable, it may be enough to only shape the existing terrain so that water flow is directed away from the road surface, and only use native materials. 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. Community roads need to account for the expected loading of vehicles on the roads. Overloaded trucks and busses will quickly destroy an engineered road surface that is saturated and not designed for heavy loading.

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. These wheel tracks can be constructed with cobblestones, locally produced bricks, or concrete if available. Other paving methods include: cobble stones, telford paving, dressed stone, or concrete brick. There are many examples for surfacing alternatives in the World Bank published document “Surfacing Alternatives for Unsealed Rural Roads” published in 2005.

Like a climate resilient gravel road, a climate resilient earth surfaced road will be constructed of different elements that are locally available 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 4-15 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 design requirements for the new federal paved trunk roads are on a high level. The problems seen today in the federal trunk 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. The quality of the road surface is very dependent on a well functioning drainage system of culverts, bridges, and surface drainage.

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.

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.

There is high likelihood that the large increases in rainfall seen in the Ethiopia Wet scenario will have severe consequences for landslides and erosion. The frequency of large storms is may to increase over 500%. There is not enough data on landslides related to precipitation in Ethiopia to accurately predict the increase in slide activities. Areas that 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 on slope stability.

Figure 4-16 Small slip landslide Mekele-Abi Adi-Adwa km 115+800

Source: Consultant

Climate impact countermeasures

It is usually not cost-beneficial or technically possible to build a road in a mountainous region that is not affected by slope failures. Damage to the road should be expected from slope failures in geologically unstable areas. 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 mountainous regions. 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. The 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. 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 4-17 Rockfall protection retaining wall Mekele-Abi Adi-Adwa km 52+3

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 stabilization 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 ERA 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 ERA 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.

Figure 4-18 Retaining wall Mekele-Abi Adi-Adwa km 110+5

Source: Consultant

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 4-19 Gabions used as bank protection Mekele-Abi Adi- Adwa km 83

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. Methods suitable for high investment trunk roads are listed in the ERA design manuals. 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.

Figure 4-20 Bank stabilization and river protection Mekel-Abi Adi-Adwa km 71+9

Source: Consultant

On roads built in flood plains, there needs to be more effort on bank stabilization projects. The photo of the bank erosion on the road in Dire Dawa, Figure 4-21 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 4-19 or concrete retaining walls as seen in Figure 4-18. On the trunk road between Dengego and Dire Dawa, 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 4-21 Roadside erosion Dire Dawa Region

Source: ERA Network Management

Figure 4-22 Alternative roadway alignment out of flood limits Dire Dawa Region

Source: Google Earth

There are a number of slope stability measures and techniques that are currently used in Ethiopia that are successful. It is suggested to continue using these methods, and slowly adapt newer techniques as their availability and knowledge become more known in the region in order to adapt to the negative impacts of climate change.

Summary
The stability of slopes will be adversely affected by an increase in precipitation. The investment spent on preventing landslides is only cost beneficial if it is a vital link. It is better to invest in slope protection measures and use best practices during construction for the lower class roads. Landslides are a natural oc-

currence 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 the suitability of building roads in river valleys needs 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.

4.3.6 Surface drainage

Impact of climate change

The Ethiopia Wet and Global Dry scenarios are showing that the intensity of design storms for 2 to 10 year storms will increase by 3% to 25%. 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 200%. 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 leading to increased events of water on the roads. Water velocities will be higher than designed for leading to increased scour damage of roadside drainage.

Figure 4-23 Poor surface drainage on gravel road Mekele-Adwa km 164+213

Source: COWI

Climate impact countermeasures

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.

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, there is an increase in the risk of multiple failures occurring at the same time. 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.

Figure 4-24 Roadside ditches filled with sediment through town section Hagera Salam

Source: Consultant

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 Ethiopian landscape. The design storm parameters should be adjusted to reflect the anticipated climate changes.

4.3.7 Climate change impacts rain summary table

Table 4-6 Climate change impacts-rain

Climate Variable	Road Asset	Climate Change	Climate Change Impact to Asset	Recommended Climate Change Countermeasure
Flooding	Bridges	+13% to 43% 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	Pre-emptive maintenance; Use storm water systems that can accommodate more siltation, and require less maintenance
Average annual precipitation; Groundwater levels	Pavement Design	Up to +189mm increase 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 of Ethiopia; Increased use of chemical stabilizers, geotextiles; 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; Investigation of the slope grades allowed by ERA.
	Surface Drainage		Increased siltation leading to increased flooding of the drainage systems	Pre-emptive maintenance; Storm water systems that can accommodate more siltation, and require less maintenance

4.4 National design standards in Ethiopia

4.4.1 Introduction

The publication of the Ethiopian Design standards is a large step in assuring the best possible road construction in the future. The majority of the ERA manuals are taken from other well used manuals such as the Overseas Road Notes, and AASHTO design recommendations.

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 Site investigation and Pavement design manuals. Slope stability and surface drainage solutions can also be found spread throughout the manuals.

4.4.2 Recommendations to the manuals

The largest problems facing the Ethiopian road network are climate-related. It is suggested to organize 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 update the Drainage Design Manual with the updated drainage charts included in this report.

It is recommended to adjust the requirements for testing of subgrade materials to always use a 4 day soak, even in Arid areas, (Site Investigation Manual, Section 3.4, note 2.)

If the intention is to use the ERA manuals for all new roads in Ethiopia, including the low cost community roads DS9 and DS10, it is suggested to append the manuals with more low cost engineering solutions. The manuals are sufficient for building the high investment link and trunk roads, but lack low cost engineering solutions that can be constructed using labor-based methods, such as are found in the report from Cambodia, Seacap 19 Technical note 2, "Behavior of Engineered Natural Surfaced Roads", or in the World Bank funded Rural Road Transport Project 2 in Vietnam. There may also be lessons learned from the current USAID and Virginia Tech project currently working in Ethiopia on a training program based on maintaining community roads.

4.5 Nature and extent of climate impacts

4.5.1 Introduction

One common theme of the climate predictions for Ethiopia is the variability in results, which could be due to the extremely varied terrain and climate that is found in Ethiopia now. The climate is unpredictable in Ethiopia, and the results of the climate change studies only add to the unpredictability.

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 Ethiopia. Regardless of climate change in the future, Ethiopia 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 Ethiopia 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 Ethiopian road network without some sort of study on each kilometer of road. The location and extent of soft spots in the network were found from dialogue with ERA network management, as well as from the findings of site investigations done on previous COWI projects in Ethiopia.

An overall theme of the largest and most frequent problems that network management faces are regarding drainage structures, especially culverts and bridges. 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.

Most of the current and future impacts are directly related to rainfall. There has been large damage recently to drainage structures in ERA rainfall region B2 and A4 from flash floods (see photos in Appendix.) Damages have occurred particularly on the road connecting Sodo and Gidole in rainfall region B2, as well roads in the Dire Dawa region in rainfall region A4. These regions on average experience different rainfall patterns. Rainfall in region B2 is heavy over the entire region and heaviest over isolated peaks and high spots in the landscape. The rainfall in region A4 is low over the entire region on average, with very heavy rain in small isolated locations. However, the roads affected share similar traits regarding their placement in the landscape. The affected roads in these areas are located near the foot of the mountains where the watersheds begin to flatten out. Particularly on the road between Sodo and Gidole which is built in an alluvial fan. The watercourses are very unstable, and likely to change direction depending on the size of the storm event. The roads in the Dire Dawa region are built along broad river valleys, with unstable water courses subject to moving direction during large floods.

The area around Debre Markos in region A2 frequently experiences landslides. It is the feeling of ERA network management that the landslides in this area are caused more from poor geological stability, rather than the negative impacts of the road alignment. Heavy machinery is stockpiled along trunk roads with frequent landslides to aid in quick repair of the road.

It is impossible to narrow down the largest problems to only a few specific areas. Ethiopia's terrain and climate is so varied that problems could arise anywhere depending on the severity of the storms seen during that particular rainy season. There are not many areas in Ethiopia that are not susceptible to flood related problems. Even areas in the arid regions of Ethiopia are still susceptible to heavy flash flooding requiring as large drainage structures as those located in the wetter areas of Ethiopia.

4.5.3 Future climate impacts on the road infrastructure

The Ethiopia Wet climate scenario predicts large increases in the severity of heavy events for the year 2050. Large increases in precipitation are expected over most of the country, putting road infrastructure at the limits of its design. The large increase in precipitation means that it will become more difficult to deal with climate problems in the future, if the strategies towards maintenance and design are not flexible enough to accommodate these changes.

The Global Dry scenario is showing more varied predictions with some decreases in rain in some areas with small increases in other areas. It is not expected that decreases in rain will have detrimental effects on the existing or future road infrastructure. Caution should be taken however in areas that experience long periods of dry weather. Drainage structures in these areas are still susceptible to scour and large sedimentation deposits from smaller storms. Also, dry areas can still experience large flash flooding which will have devastating effects on infrastructure that has been ignored.

4.6 Maintenance

4.6.1 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 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.

4.6.2 Adaptation strategy

We summarize the basic strategy as:[7]

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 level[8]. Only if this is insufficient in relation to the climate impact, reconstruction should be considered.[9]

c) Maintenance measures shall initially be designed to cope with existing climate while reconstructions (strengthening) of road sections (soft spots) shall be designed to cope with future climate.

d) Further 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[10].

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[7] 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.

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

[9] 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.

4.6.3 Economy

It should be realized that present road maintenance 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. This should be a general ambition, however amplified as maintenance activities can be 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).

4.6.4 Overview

Maintenance categories

We consider three principal maintenance approaches:

- Routine maintenance Conditional maintenance
- Corrective 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.

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.

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

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, 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.

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 their 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	Condi-tional	Cor-rective	Central ized	De-centra-lized	Equip ment based	Labor-based	Force ac-count	Con-tract-ing
Grading	x	x		x		x		x	x
Spot mainten-ance			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 ab-utments		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

4.6.5 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, holding re-levant 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[11] 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-

[11] 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 Ethiopia the wages are much lower that in the industrialized countries. The economical optimal balance between equipment and labor input will therefore 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[12]. 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.

4.7 Recommendations

Introduction

The priority recommendations listed below cover simple changes that can be started immediately. A climate resilient road in the future in Ethiopia will be very similar to a climate resilient road right now. Ethiopia has the knowledge and materials needed to design and keep their roads up to standard. From the research done, 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. Ethiopia has a very large challenge in building climate resilient roads due to its difficult terrain and high amounts of rainfall. The climate changes predicted do not suggest that the problems in the future cannot be accommodated with today's engineering solutions in Ethiopia.

Design

- Revise parameters used for the design storm that is used for all drainage systems and structures on every 5 to 10 years.
- Investigate the need for river training and increased channel maintenance and bridge scour protection.

[12] 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.

- 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 materials suitable for the climate and topography that are locally sustainable and economically feasible.
- New alignments need to consider likely future changes to environment considering increases in rainfall, groundwater, etc.
- Require 4 day soaked CBR testing for all soils materials tests.

Maintenance

- Develop a database for road maintenance
- Investigate the economics of Labor-Based Technology
- 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.
- Prioritize paving maintenance in high rain areas.
- Allocate more funds for maintenance of the current roads.

Research

- Further research into more initially robust scour prevention compared to long term maintenance savings.
- Investigate the option of using different wearing courses other than gravel for areas with limited supplies.
- Expand methods for slope stabilization and protection.
- Append the design manuals with more low cost engineering solutions for community roads.
- Add a chapter to the design manuals focusing on climates impacts on roads and engineering solutions.

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 Surfacings and Road Bases
- Structures
- Ancillary Works

5.2 Current costs

For construction of new roads, upgrading, and rehabilitation; the costs per kilometer have been obtained from ERA for 2008 as listed in Table 5-1 . The class of these roads is unknown, but based on previous cost estimates, it can be assumed that the paved roads relate to DS 4 and better.

Table 5-1 Average cost/km for contracts awarded by ERA in 2008

Construction Type	**Cost/km USD**
Construction New Gravel Road	554,000.00
Upgrading Gravel to Paved/Rehabilitation Paved road	576,000.00
Average cost/km	565,000.00

Source: ERA May 2009

These values per kilometer typically account for a 10% contingency fee, and may also include engineering fees and VAT. Actual construction costs are around 10% to 40% less. Based on recent cost estimates the consultant has done in Ethiopia for upgrading from a gravel road to a paved DS3/DS4 standard as well as rehabilitation of a paved road to DS3/DS4 standard,, the average percentage of cost per work items can be calculated as shown in Table 5-2. The associated cost/km are taken from the average cost/km of upgrading from gravel to paved shown in Table 5-1.

Table 5-2 Cost item percentages

Description	Percentage	cost/km USD
General	6.8%	25,259
Site Clearance	0.2%	717
Drainage	5.3%	19,837
Earthworks	14.3%	53,452
Subbase, Road Base and Gravel Wearing Course Bituminous Surfacings and Road Bases	62.5%	233,012
Structures	5.2%	19,401
Ancillary Works	4.3%	16,181
Dayworks	1.4%	5,041
	100%	372,900

Note: The cost/km is the pure construction costs excluding VAT, contingency fees, engineering fees; the total is therefore substantially lower than the average total costs for roads in ERA contracts
Source: COWI 2009

5.3 Climate impact

Rainfall will have the most significant cost impact on the Ethiopian road network. Temperature 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.

The climate scenarios are used to calculate the additional sizing required for drainage structures and pavement design so that the design will be able to accommodate the increased flows as required by the ERA drainage design storm standards. The hydrology calculations using the ERA Drainage Manual take into account the rational method and SCS method, which utilize IDF curves and maximum 24 hour rain predictions, respectively.

5.4 Costs increases for construction of a climate resilient road

5.4.1 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 includes costing for accommodation, office space, AIDS prevention, and various other items generally unrelated to climate.

5.4.2 Site clearance

The costs associated with site clearance are not expected to increase significantly with increased rainfall.

5.4.3 Drainage

The cost item Drainage includes: culverts, inlet and outlet protection, side drains, as well as subsurface drains.

A hydrologic assessment was conducted for all drainage structures on the Mekele - Abi Adi - Adwa Road in northern Ethiopia. Out of 231 existing concrete culvert pipes ranging from 750 mm to 1200 mm, 14 culverts for the Global Dry scenario, and 37 culverts for the Ethiopia Wet scenario that have hydraulic capacity (for their design storm) as of 2008 will not have hydraulic capacity in 2050 using a maximum HW/D of 1.5. The average culvert size on this stretch of road is 1000 mm, and the majority of culverts are serving small watersheds. This has the added benefit that the majority of culverts should have capacity to handle much larger storms than their 10 year design storm as dictated by ERA standards.

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.

Culvert sizing for new construction is expected to follow a similar pattern as that found in the Mekele - Abi Adi - Adwa road upgrading example. The minimum culvert size recommended by ERA is 750 mm, however if 900 or 1000 mm is used, even with a 43% increase in 24 hour precipitation, this size will be sufficient for most small watersheds for a 10 year design storm. Table 5-3 shows the relationship between culvert sizing and cost increases.

Table 5-3 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

Using data from a recent project on the Wukro-Agridat-Zalambesa Road, 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.

For the same project, increasing the capacity of the culverts and associated headwalls by 100% would cost an additional 82% to the drainage item, 10% to the total project, or approximately an additional 30,000 USD/km. It is still suggested to use a cost economic analysis to decide the choice of drainage sizing, and its cost savings if any compared to maintenance.

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

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, 32% for the Ethiopia Wet, and 7% 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. For road upgrading, it is expected that the costs for structures will increase 22% for the Ethiopia Wet, and 5% for the Global Dry scenarios.

5.4.4 Earthworks

The cost item Earthworks include all the initial excavation and compacted fill, up to top of subgrade level. 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. The practice of raising the roadway and chemical stabilization is only sensible in certain locations of the country. As more areas in Ethiopia are developed, more problem soils will be encountered requiring more use of these options.

For a road section requiring chemical stabilization, the increased costs associated are approximately 41,000 USD/km. Raising the roadway one meter costs approximately 9,000 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 Ethiopia Wet scenario will require between10% to 20% more investment in earthwork stabilization due to climate change. The Global dry scenario will require approximately 1% 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.

5.4.5 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 the cheapest to construct.

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. Gravel losses are not expected to be much higher in 2050, than they are currently. Using the climate models and the TRL gravel loss formula covered in the ERA pavement design manual, gravel loss is expected to increase around 4% (an additional 1 to 2 mm/year) for the year 2050 for the Global Dry scenario. The cost increases associated with this are minimal. This does not mean that alternatives should not 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.

Bituminous surfacings are typically the most expensive cost item of road and 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. From reconnaissance on the Mekele - Abi Adi - Adwa road which is currently gravel surfaced being considered for an upgrade to paved, over 48% of the road which is in mountainous-escarpment terrain has road gradients over 6%, which is approximately 16% of the entire road. Research from Vietnam suggests sealing roads with gradients higher than 6% that receive more than 1000 mm of rain per year. From the ERA rainfall maps, nearly half of Ethiopia receives more than 800-1200 mm rain/year. If approximately 20% of the gravel roads in Ethiopia are in mountainous to escarpment terrain, and 48% of those have gradients above 6%, then it is suggested to seal at least 10% of the gravel roads, namely the areas with high gradients and high rainfall.

The cost difference between a bituminous paved road and a high standard gravel road varies significantly depending on type of sealant used. For AC, it is on the order of an additional 50% per kilometer, but less expensive sealing options are available. By choosing to seal 10% of the gravel roads, an expected cost increase of 15% can be expected for the construction of gravel roads in mountainous areas with limited sealing.

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

25,000 USD/km. Paving shoulders is expected to cost an additional 11% for this work item.

There is not an expected increase in the cost of paving materials associated with increased rainfall, only the amount of them used if decided to pave shoulders or sections of gravel roads. The main cost increases come from increased maintenance assuring that the paved surface stays waterproof protecting the subbase materials underneath.

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 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 5% and 20% under the Ethiopia Wet scenario and between 1% and 10% for the Global Dry scenario.

5.4.6 Structures

The cost item structures include large works such as bridges, box culverts, and retaining walls and their associated river bank and scour protection. There are some bridges found from the hydrological assessment of the Mekele - Abi Adi - Adwa Road that will not have hydraulic capacity for a 50 year storm in 2050. The cost of replacing these bridges will be much higher than if they were designed with sufficient capacity to begin with. 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 37% more expensive for the Ethiopia Wet scenario, and 10% higher for the Global Dry scenario. This follows that the IDF curves for a 50 year storm are on the order of 37% higher than the IDF curves for a 25 year curve (Ethiopia Wet), and the bridge must be a minimum 37% 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 37% for the Ethiopia Wet scenario, and 10% for 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 in Ethiopia were built based on the optimal river crossing, which often gives flow capacity larger than the design storm. Many 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.

There is expected to be a large need for an increase in the amount of bank and scour protection in rivers. The climate scenarios are showing that the frequency of large storms will increase dramatically. Even if the bridges have hydraulic capacity, this does not necessarily mean that they have the bank and soil cohesion to withstand large floods. There must also be investment and insurance that the river will not change course during a large flood event. If the river is allowed to change course during a large flood event, then there is no reason to design a bridge for a 100 year return interval. The costs associated with increased river protection will vary depending on geology and flows of the surrounding area.

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 200% for the Ethiopia Wet scenario and 50% 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 is not expected to increase significantly with the increases in rain predicted by the climate change scenarios. 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. To prevent the destruction of the road in the Dire Dawa region, it is estimated that 2 km of bank protection would have been needed. Protecting this road from a flood of this magnitude using local materials such as gabions or masonry retaining walls is estimated to cost on the order of 1.5 Million USD for 2 km of bank protection 3 meters high. Alternatively, relocating this road for 3 km would cost on the order of 1.8 Million dollars assuming a construction cost of 600,000 USD/km.

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, 43% for the Ethiopia Wet, and 13% 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, 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. For road upgrading, it is expected that the costs for structures will increase 22% for the Ethiopia Wet, and 6% for the Global Dry scenarios.

5.4.7 Ancillary works

Ancillary works includes items such as guardrails, signage, and landscaping. Landscaping is already a high cost item and is not expected to require increases in investments in the future. It may be necessary to investigate the use of more flood and drought resilient plants, as well as invest in the necessary agricultural effort and maintenance after they are planted to insure that the landscaping investment is met. If the plantings are allowed to die due to drought, or be washed away in flood events, then there is no sense in using these methods to begin with.

There are expected to be minor costs associated with ancillary works due to climate change, more resilient guardrails, planting, etc., approx 5% for the Ethiopia Wet and 1% for the Global Dry scenarios.

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. The cost of manual labor in Ethiopia is a fraction of that compared to the cost of the materials used to build a new road. A climate resilient road will require full time maintenance, rather than annual or biannual maintenance. It is suggested to develop cooperation between ERA maintenance organizations and available local labor for the year round maintenance and repair of the Ethiopian road network.

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 five times in the Ethiopia wet scenario. Maintenance budgets, monitoring and repair for drainage structures is expected to need to be increased on a similar ratio in order to insure 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 43% and 13% for the Ethiopia Wet and Global Dry scenarios respectively. Maintenance budgets are expected to need to be increased 150% for the Ethiopia Wet scenario, and 50% for the Global Dry scenarios from where they should ideally be now.

5.4.9 Summary of engineering cost increase

For a high standard (DS4 and better) road, the cost increases for upgrading to paved standard taking into account the climate changes in 2050 are summarized in Table 5-4.

Table 5-4 Summary of cost increases to paved road DS4 and better - price level 2009

Description	**Current cost/km USD**	**Global Dry Scenario cost/km USD**	**Increase cost percentage Global Dry**	**Ethiopia Wet Scenario cost/km USD**	**Increase cost percentage Ethiopia Wet**
General	25,259	25,259	0%	25,259	0%
Site Clearance	717	717	0%	717	0%
Drainage	19,837	21,225	7%	25,193	33%
Earthworks, Subgrade Stabilization	53,452	53,987-58,797	1-10%	58,797-64,142	10-20%
Subbase, Road Base and Gravel Wearing Course Bituminous Surfacings and Road Bases	233,012	235,342-256,313	1-10%	244,663-279,614	5-20%
Structures	19,401	21,923	13%	27,743	43%
Ancillary Works	16,181	16,343	1%	16,990	5%
Dayworks	5,041	5,041	0%	5,041	0%
Total Cost Increase Percentage	372,900	379,837-405,618 **2%-9%**		404,403-444,699 **9%-19%**	

Source: COWI

The values listed in Table 5-4 discuss the likely costs in adapting construction to make a climate resilient road taking into account the climate models for 2050. In general the actual prices for individual roads are expected to be on the order of plus or minus 50% depending on specific local conditions not related to climate change issues. The values show the anticipated cost of building or upgrading a road to meet the minimum requirements as stated in the ERA manuals in response to climate change. The true cost would need to also 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 (chapter 5.5).

All new paved road construction can be expected to require similar increases in cost. There is a large variability due to the variability 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 the realistic costs of increases to earthworks and subgrade stabilization as this is completely dependent on what is found during the site investigations for each different project.

It is not expected that climate changes in the near future will require large changes to the methodology of high standard roads in Ethiopia. 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. If it chosen to seal a larger portion of gravel roads, then the cost of a gravel road is expected to increase between 16% and 32%, or from a 2008 average construction cost of 365,000 USD/km to between 424,000 to 482,000 USD/km.

5.5 Economic costs of climate-related incidents

5.5.1 Approach and methodology

In a traditional analysis the costs and benefits (in the remaining of this chapter we use *costs* for *costs and benefits*[13]) 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.

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 behavior 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.

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

5.5.2 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 chapter 5 - 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 5-5 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 kilometer
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 kilometer 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 5-6 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 Ethiopia currently carried out by COWI A/S for the World Bank.

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 kilometer.

As described in chapter 3 there have been several known minor incidents (water overtopping) and major incidents (complete wash out) for both culverts and bridges in Ethiopia within the past years.

Also, there have been incidents of wash away of roads located near riverbanks (in the following "riverbank roads"), just as several roads have been partly flooded during periods with heavy rain due to inadequate drainage capacity of curb and gutter.

Figure 5-1 Road in Ethiopia partly washed away due to inadequate river bank protection

Source: Ethiopian Road Authority

Unfortunately, no statistical information about the recurrence of these incidents are available, but based on interviews of local authorities in Addis Ababa (among others ERA's Bridge Department), ERA's design manuals and the consultant's experience a best guess is that a typical culvert and a typical 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 bridges in a 50 year storm.

For riverbank roads it is assessed that it is washed away in a 25 year storm and that 2.5% of Ethiopia's roads are located next to rivers. For inadequate drainage the design manuals state that the drainage capacity should be sufficient for a 2 year storm so that the affected spots in the network are expected to be partly flooded every second year. It is assumed that for the Ethiopian road network there are 0.1 affected spots per kilometer.

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.

A description of the major and minor incidents is presented in the table below.

Table 5-7 Examples and description of typical traffic disturbances and effects on traffic

	Culverts	**Bridges**	**Roads located next to river banks**	**Surface drainage***
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%	Partial washout of road. The road is totally closed for 1 day until temporary solution is established. Length of detour is 100 km. For another few weeks the road has limited capacity. Yearly risk without climate changes - 4%.	Partly washout of the curb and gutter. No major effect on road users besides those included for minor events Yearly risk without climate changes - 5%.
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%	n/a	Water overtopping road due to low capacity of drainage ditches. 50% of the carriageway is closed for 4 hours until water is gone. The average delay time per incident is 30 seconds per vehicle. Yearly risk without climate changes - 50%.

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 the two tables above the cost of a major and minor incident can be estimated. The below table illustrates the costs for each category of incident on a road with an AADT of 1,000 vehicles.

Table 5-8 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**	**Bridges**	**Riverbank roads**	**Insufficient drainage**
Major incidents	198	925	132	
- of which VOC	188	879	126	
- of which VOT	10	46	7	
Minor incidents	29	29		0.0051*
- of which capital costs	12	12		0.0021
- of which time costs	17	17		0.0030

Note: The above values are for 2009. 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 due to water overtopping culverts and bridges for 8 hours are smaller but in the size of about 29,000 USD per incident.

When a riverbank road is washed away the total costs for road users are around 132,000 USD per incident. When water is overtopping a road due to inadequate capacity of e.g. drainage ditches the costs per incident are 5 USD.

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

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

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

Table 5-9 Expected road user costs on a road with an AADT of 1000 vehicles, no climate changes, 2009-prices

1,000 USD per year	**Culverts**	**Bridges**	**Riverbank roads**	**Insufficient drainage**
Total expected costs, 2009	3.2	9.8	5.3	0.003
Due to major incidents	2.0	9.2	5.3	
- of which VOC	1.9	8.8	5.0	
- of which VOT	0.1	0.5	0.3	
Due to minor incidents	1.2	0.6		0.0025**
- of which capital costs	0.5	0.2		0.0010
- of which time costs	0.7	0.3		0.0015
Total expected costs, 2050*	6.9	13.6	6.5	0.0096

Note: The above values are for 2009. 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 around 9,800 USD/year for a typical bridge.

For riverbank roads the expected costs are 5,300 USD/year for, while it is approximately 3 USD/year per critical spot for inadequate drainage.

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. For riverbank roads the cost is 6,500 USD/year in 2050 while it is 10 USD/year for inadequate drainages.

5.5.4 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 22% by 2050. As described in Chapter 4, much of the existing drainage infrastructure is built with excess capacity, and is not expected to fail for their corresponding ERA design storm in 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 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 5-10 Yearly risk of incidents with and without climate changes

	Culverts	Bridges	Riverbank roads	Insufficient drainage
Risk in 2009 (i.e. without climate changes)				
Major incidents	1.0% (100 year storm)	1.0% (100 year storm)	4.0% (25 year storm)	5.0% (20 year storm)
Minor incidents	4.0% (25 year storm)	2.0% (50 year storm)		50% (2.0 year storm)
Risk in 2050 (i.e. with full climate changes)				
Major incidents	1.06%-1,22%	1.06%	4.24%-4.88%	5.3%-6.0%
Minor incidents	4.24%-4.88%	2.12%-2.44%		53%-61%

Note: the range with full climate changes is the range in the four 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 increase in the risk of incidents were 6%-22% higher today. This is done in order to show the 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 5-11 Future expected road user costs with climate changes costs on a road with an AADT of 1000 vehicles, 2009-prices

	Culverts *1,000 USD per year*		**Bridges** *1,000 USD per year*		**Riverbank roads** *1,000 USD per year*		**Insufficient drainage** *USD per year*	
	Future expected cost	**Increase due to climate changes**	**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	3.3 - 3.8	0.2 - 0.7	10.4 - 12.0	0.6 - 2.2	5.6 - 6.4	0.3 - 1.2	2.7 - 3.1	0.2 - 0.6
Due to major incidents	2.1 - 2.4	0.1 - 0.4	9.8 - 11.3	0.6 - 2.0	5.6 - 6.4	0.3 - 1.2		
- of which VOC	2.0 - 2.3	0.1 - 0.4	9.3 - 10.7	0.5 - 1.9	5.3 - 6.1	0.3 - 1.1		
- of which VOT	0.1 - 0.1	0.0 - 0.0	0.5 - 0.6	0.0 - 0.1	0.3 - 0.3	0.0 - 0.1		
Due to minor incidents	1.2 - 1.4	0.1 - 0.3	0.6 - 0.7	0.0 - 0.1			2.7 - 3.1	0.2 - 0.6
- of which capital costs	0.5 - 0.6	0.0 - 0.1	0.3 - 0.3	0.0 - 0.1			1.1 - 1.3	0.1 - 0.2
- of which time costs	0.7 - 0.8	0.0 - 0.2	0.4 - 0.4	0.0 - 0.1			1.6 - 1.8	0.1 - 0.3
Total expected costs, 2050*	7.3 - 8.4	0.4 - 1.5	14.4 - 16.6	0.8 - 3.0	6.9 - 7.9	0.4 - 1.4	10.2 - 11.8	0.6 - 2.1

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 200-700 USD per year for a typical culvert and 600-2,200 USD for at typical bridge in Ethiopia 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 1,500 USD/year for a typical culvert and 3,000 USD/year for a typical bridge.

For riverbank roads the increased cost of wash aways due to the climate changes are expected to be about 300-1,200 USD per/year for a critical spot, while the increase is approximately 0.2-0.6 USD per year for spots with insufficient drainage. In 2050 the same costs could be as high as 1,400 USD/year and 2.1 USD/year respectively.

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.

5.5.5 Summary of conclusion on the user 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. The example illustrates that for a typical road with an AADT of 1000 vehicles the additional user costs of climate change - if no adaptation is made - could be as high as around 20% in the most dramatic of the four climate scenarios.

6 Economic assessment of adapting to the climate changes

6.1 Costs and benefits of adaptation

In section 5.5 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 as much as 20%. 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 cost of adapting is 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 5-11this means that if avoiding the increase in expected yearly costs in 2050 is lower than 400-1,500 USD per year for a typical culvert, the adaptation strategy is feasible.[14]

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 incident following the climate changes, the size of a typical culvert needs to be increased. The cost of increasing the size of a typical culverts are described in chapter 5 and are summarized in the table below just like the annualized costs are calculated based on the cost information.

[14] 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	6,000-7,500	1,000-2,500
Life time	50	50	0
Yearly risk of destruction (major incident)	1.06%-1.22%	1.0%	0.06%-0.2%
Repair costs (including removal costs)	6,000	7,200-9,000	1,200-3,000
Annualized costs			
Annualized construction costs	602	722-903	120-301
Annual expected repair costs	64-73	72-90	8-17
Total annualized costs	666-675	794-993	128-318

Note: The annualized costs have been calculated using a discount rate of 12%

The table above illustrates that the cost of adaptation are relatively low for the typical culvert. It is estimated that the increased risk of incidents can be eliminated for approximately 128-318 USD/year which is significantly less than the cost to road users in the "Do nothing"-scenario which is 400-1,500 USD/year (see Table 6-2 below).

Other examples

Similar calculations have been carried out for a typical bridge (20 m length by 9 m wide bridge). This showed that the cost of adaptation for a typical bridge can be estimated to 4,300-14,000 USD/year which is higher than the cost of no adaptation which was assessed to be 800-3,000 USD/year for bridges (see Table 6-2 below).

For strengthening of the protection of riverbank roads the adaptation costs has been estimated to 190-400 USD/year per km for affected road spots which should be compared to a cost of 400-1,400 USD/year per km for road users, if nothing is done to avoid climate changes.

For drainage ditches the increase in precipitation influences both the risk of water overtopping the road but also the speed of the water in the ditches. This has a larger impact on the road as materials are more likely to be washed away from the road. It is assessed that the increased risk of having material washed away due to inadequate drainage can be eliminated for approximately 21-172 USD/year for each affected spot in the road network.

Table 6-2 Overview of adaptation cost and road users costs

USD/year per unit	**Culverts**	**Bridges**	**Riverbank roads**	**Insufficient drainage**
Cost of adaptation	128-318	4,300-14,000	190-400	21-172
Road user costs if "do nothing", 2009	200-700	600-2,200	300-1,200	<1
Road user costs if "do nothing", 2050	400-1,500	800-3,000	400-1400	<2
Is adaptation feasible?	Yes	No	Yes	Maybe not

Table 6-2 illustrates that for culverts and riverbank roads the cost of adaptation is cheaper than the additional cost to road users without adaptation. This means that adaptation is cheaper than doing nothing in all cases.

For bridges, full adaptation is more expensive than doing nothing. In fact, the cost of adaptation is up to 7 times higher than the expected cost in the "do nothing" scenario.

Another interesting result is that the climate-related increase in expected road user costs are relatively low for incidents where water overtops the road due to inadequate size of drainage ditches. This suggests that an adaptation strategy is only feasible if the related maintenance savings are sufficient to finance the increase in construction costs.

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.

Ethiopia is planning to increase the size of it's road network substantially in the next many years and given the limited funds it seems to be unrealistic to assume that the reconstruction of an existing, well-working bridge will be prioritized to construction of new roads.

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. Note however that the devotion of resources to new roads will increase the network quality, and - presumably - by more than the decrease 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 new road infrastructure.

Whether it is the best strategy is not investigated further in this project[15], 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 the total cost of climate changes in Ethiopia 2010 - 2050

Section 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 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.

In section 6.1 it was argued that adaptation 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.

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

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 build climate resistant such that after a reconstruction there are no longer any costs to road users due to climate changes.

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 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 150% in 2050 due to the climate changes (see section 5.4.8). 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 150%.

Example: Cost item 1 to 3
According to ERA's bridge department there are currently 2,955 federal bridges in Ethiopia. In order to keep things simple, these bridges are divided into two categories: bridges less than 50 meters with a design life of 50 years and bridges over 50 meters with a design life of 100 years (design life corresponds to ERA's design guide). The basic information for these bridges can be seen from the table below.

Table 6-3 Summarized data for federal bridges

Bridge category	< 50 meters	>= 50 meters
Average bridge length	18	72
Life time	50	100
Number of bridges	2,735	220
Total construction costs (undiscounted)	870	284
Age	25	35
Rest life time	25	65

Note: The construction cost has been assessed using an average carriage width of 9 meters and an average construction cost of 1,600 USD/m^2

Based on these data the three cost components can be assessed for each bridge category. This is done in the table below. Note that since the remaining life time of the smaller bridges is less than to year 2050, the cost of climate changes due to losses in depreciated is zero since the depreciated value of these bridges is zero in 2050. Likewise, since longer bridges have a life time exceeding 2050, the cost related to building climate change resilient bridges when the current bridges are worn out are zero, as there are no worn out bridges.

Table 6-4 Net present value of cost of climate changes 2010-2050 for existing bridges in Ethiopia

NPV 2009, Million USD	**1) Reconstruction costs**	**2) Exceeded lifetime costs**	**3) Depreciated value**	**Total**
< 50 meters				
Without climate changes	60.8	28.2	0.0	89.0
With climate changes	69.2 - 89.5	31.7 - 39.5	0.0	100.9 - 129.0
Difference: cost of climate change	8.5 - 28.7	3.5 - 11.3	0.0	11.9 - 40.0
>= 50 meters				
Without climate changes	5.7	0.0	-0.5	5.3
With climate changes	6.5 - 8.4	0.0	-0.4	6.1 - 8.0
Difference: cost of climate change	0.8 - 2.7	0.0	0.0	0.8 - 2.8
All bridges				
Without climate changes	66.5	28.2	-0.5	94.2
With climate changes	75.7 - 97.9	31.7 - 39.5	-0.4	107.0 - 137.0
Difference: cost of climate change	9.3 - 31.4	3.5 - 11.3	0.0	12.8 - 42.8

The same calculations have been carried out for the three other types of typical infrastructure. The table below summarizes the cost of climate changes related to each type of infrastructure.

Table 6-5 Net present value of cost of climate changes 2010-2050 for infrastructure in Ethiopia

NPV 2009, Million USD	**Culverts**	**Bridges**	**Riverbank roads**	**Insufficient drainage**
1) Reconstruction costs	1.3 - 3.3	9.3 - 31.4	0.0 - 0.1	0.5 - 1.5
2) Exceeded lifetime costs	4.7 - 11.6	3.5 - 11.3	0.0 - 0.0	0.8 - 2.4
3) Depreciated value	0.0	0.0	0.0	0.0
Total	5.9 - 14.8	12.8 - 42.8	0.0 - 0.1	1.2 - 3.9

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.

In 2008 ERA spend approximately 156 million USD on federal road maintenance. However, this is perceived as far too little in order to keep the network in a condition corresponding to its initial design. It is roughly assessed that the total cost would be closer to 500 million USD per year if the maintenance was adequate to keep the originally designed service level.

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 490-1,228 million USD (net present value) in 2009.

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

Given the information above, the road agency's future increase in costs due to climate changes from 2010 to 2050 can be assessed to have a net present value of 511-1,290 million USD in total.

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 5-8, 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.

Table 6-6 Amount of infrastructure

	Number of affected infrastructure
Culverts	25,457
Bridges	2,955
River banks	511
Insufficient drainage	2,043

Source: ERA and own assumptions

Based on the figures from Table 6-6 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 6-7 Road user costs due to climate-related incidents 2010-2050, NPV 2009

NPV 2009, Million USD	Culverts	Bridges	Riverbank roads	Insufficient drainage	Total
Without climate changes	701.9	231.0	16.5	0.0	949.4
With climate changes	710.1 - 731.7	233.4 - 239.9	16.6 - 16.9	0.0	960.2 - 988.6
Difference: CoCC	8.2 - 29.8	2.5 - 9.0	0.1 - 0.4	0.0	10.8 - 39.2

The table above shows that the climate change related increase in road user costs on the existing network from 2010 to 2050 is around 10-40 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 100% higher.

The major contributor to the increased costs is the increased risk of culvert incidents due to inadequate size of the culverts currently 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 behavior 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

In the future the road network in Ethiopia will be expanded significantly. It is assumed 500 km new classified road will be build each year in Ethiopia in the period from 2010 to 2050 corresponding to a doubling of the current network.

Road agency
Due to the climate changes the new roads will be more expensive and require more maintenance than in the case of no climate changes.

If it is assumed that the future network will look like the current network with regard to number of bridges, culverts etc. per kilometer, the increase in costs related to building the road infrastructure can be assessed using the estimated yearly cost of making the infrastructure climate resilient (see Table 6-2)

If it moreover is assumed that the maintenance costs for the new network in the long run are similar to the existing network, the increase in maintenance costs can be also be assessed.

The below table illustrates the increase in road agency costs due to climate changes related to the expansion of the road network.

Table 6-8 Road agency costs related to the future expansion of the road network in Ethiopia, net present value in 2009

	Million USD
Increase in construction cost in order to make infrastructure climate resilient	29.6 - 90.7
- of which culverts	5.9 - 14.6
- of which bridges	23.0 - 74.6
- of which bank protection	0.0
- of which curb and gutter	0.7 - 1.5
Increase in maintenance costs	120.2 - 500.9
Total	**187.9 - 591.7**

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 behavior 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 Ethiopian road sector when adapting

The below table summarizes the information from section 6.2.1 and 6.2.2.

Table 6-9 Total Cost of Climate Changes, 2010 - 2050, NPV 2009, million USD

Million USD	**Road Agency**	**Road users**	**Total**
Existing network	**511.2 - 1,290**	**10.8 - 39.2**	**522.0 - 1,329**
Culverts	5.9 - 14.8	8.2 - 29.8	14.1 - 44.6
Bridges	12.8 - 42.8	2.5 - 9.0	15.2 - 51.8
Riverbank roads	0.0 - 0.1	0.1 - 0.4	0.1 - 0.5
Insufficient drainage	1.2 - 3.9	0.0	1.2 - 3.9
Maintenance	491.2 - 1,228	n/a	491.2 - 1,228
Future new network	**187.9 - 591.7**	**0.0**	**187.9 - 591.7**
Culverts	5.9 - 14.6	0.0	5.9 - 14.6
Bridges	23.0 - 74.6	0.0	23.0 - 74.6
Riverbank roads	0.0	0.0	0.0
Insufficient drainage	0.7 - 1.5	0.0	0.7 - 1.5
Maintenance	120.2 - 500.9	n/a	120.2 - 500.9
Total existing and future network	**661.0 - 1,881**	**10.8 - 39.2**	**671.8 - 1,921**
Culverts	11.9 - 29.4	8.2 - 29.8	20.1 - 59.2
Bridges	35.7 - 117.4	2.5 - 9.0	38.2 - 126.4
Riverbank roads	0.1 - 0.1	0.1 - 0.4	0.2 - 0.5
Insufficient drainage	1.9 - 5.4	0.0 - 0.0	1.9 - 5.4
Maintenance	611.5 - 1,729	n/a	611.5 - 1,729

As seen from the table above, the total costs of climate changes in the road sector from 2010 to 2050 is expected to be in the range of 670 to 1,920 mill. USD in 2009 net present value.

For comparison the total expenditures in Ethiopia in the road sector in 2008 was 1,200 million, thus the total net present value of the costs of climate changes in the road sector from 2010 to 2050 corresponds roughly to 1½ years budget. However, calculations show that the yearly costs by 2050 may be in the size of 1,000 million USD per year due to the enlarged network which suggests that the costs of climate changes is a significant problem in the future.

Clearly, these estimates are very uncertain for several reasons. Besides the uncertainties about AADT, change in risk etc. which has been mentioned above, 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 When to adapt?

In Table 5-9 the expected road user costs per year due to climate-related incidents was estimated for culverts, bridges, riverbank roads and insufficient drainage. This was the expected cost given the current climate without climate changes.

In section 6.1 the unit cost per year of improving culverts, bridges river banks and drainages were estimated for typical infrastructures in Ethiopia.

The table below summarizes the above mentioned findings.

Table 6-10 Cost of climate-related incidents in 2009 and climate change adaptation, 1,000 USD, 2009-prices

	Culverts	**Bridges**	**Roads located next to river banks (per km)**	**Drainage ditches (per km)**
Expected road user costs in 2010(1,000 USD/year)	3.2	9.8	5.3	0.003
Yearly cost of adaptation strategy (1,000 USD/year)	0.1 - 0.3	4.3 - 14.0	0.1 - 0.4	0.02 - 0.2

As seen from the table above - when it comes to culverts and riverbank protection - the costs of adapting to the future climate changes are estimated to be significantly lower than the costs of climate-related incidents *today* with *today's* climate.

This may suggest that the sizing of today's infrastructure may be insufficient seen from an economic point of view. If e.g. increasing the size of culverts today reduces the risk of incidents with just 4% (0.1 / 3.2 x 100) it is feasible to increase the size of culverts even with today's climate.

This suggests that adapting new infrastructure to the future climate changes may be feasible today.

6.4 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 100% 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 and riverbank protection. For structures the specific conditions decide if it is economic feasible to adapt fully to the 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.

- The proposed adaptation measures may be feasible today, as they will decreases the risk of incidents with today's climate.

- The total cost of climate changes in the road sector from 2010 to 2050 is estimated to be in the range of 670 to 1,920 mill. USD in 2009 net present value.

7 Policy implications, engineering measures and strategy for adaptation

7.1.1 Introduction

The total cost of climate changes in the road sector from 2010 to 2050 is roughly estimated to be in the range of 0.7 billion - 1.9 billion USD measured as net present value in 2009.

Ethiopia has a very large challenge in building climate resilient roads due to its difficult terrain and high amounts of rainfall, but a climate resilient road in the future in Ethiopia will be very similar to a climate resilient road right now. The climate changes predicted suggest that the problems in the future can be accommodated with today's engineering solutions provided that the solutions are reviewed and reconsidered regularly as more information on climate changes becomes available. Basically, Ethiopia has the knowledge and materials needed to design and keep their roads up to standard.

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 - 2% 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.

Design parameters for the standard design storm that is used for all drainage systems and structures 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. 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 economically feasible to adapt fully to the climate change.

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 around a 150% increase 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.

Scour damage to bridges and drainage structures is a serious threat to Ethiopia’s infrastructure that should be addressed. The Bridge Management System is an excellent start to monitoring Ethiopia’s road infrastructure and would benefit from adding a scour action plan, with countermeasures discussed in the FHWA scour countermeasure reports.

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.

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 used for all drainage systems and structures on every 5 to 10 years.
- 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 materials suitable for the climate and topography that are locally sustainable and economically feasible.
- New alignments need to consider likely future changes to environment considering increases in rainfall, groundwater, etc.
- Require 4 day soaked CBR testing for all soils materials tests.

Maintenance

- Develop a database for road maintenance
- Investigate the economics of Labor Based Technology
- 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.
- Prioritize paving maintenance in high rain areas.
- Allocate more funds for maintenance of the current roads.

Research

- Further research into more initially robust scour prevention compared to long term maintenance savings.
- Investigate the option of using different wearing courses other than gravel for areas with limited supplies.
- Expand methods for slope stabilization and protection.
- Append the design manuals with more low cost engineering solutions for community roads.
- Add a chapter to the design manuals focusing on climates impacts on roads and engineering solutions.

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 in the rapidly changing Ethiopian landscape.
- 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 feasible 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
- Establishment of more focused maintenance strategies followed by more resources for road maintenance
- Development of reliable and accurate hydrology models as it is a common problem that this is lacking

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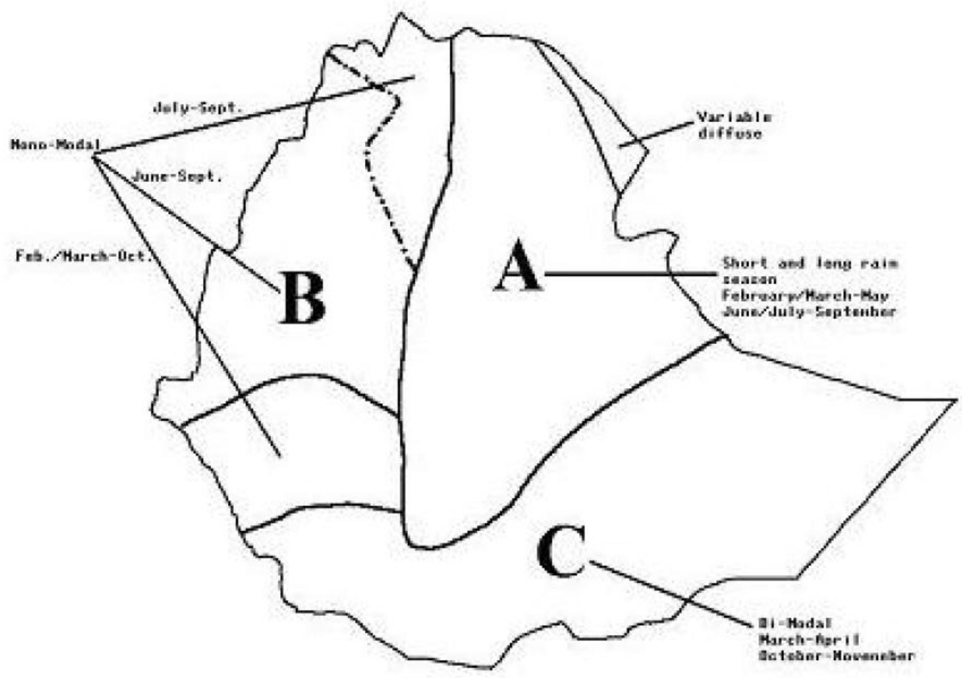
9 Appendix

9.1 Present precipitation seasons in Ethiopia

The following short description of the existing climate of Ethiopia is copied directly from the web page "RANET Ethiopia" from NMA, National Meteorological Agency, Federal Democratic Republic of Ethiopia:

In Ethiopia, the pattern and character of rainfall varies in different parts of the country. There are some regions, which experience three seasons (tri-modal type) with two rainfall peaks (where one peak is more prominent than the other), while some regions have four seasons with two distinct rainfall peaks (bi-modal type). There are still some regions, which have two seasons with single rainfall peak (mono-modal type).

Figure 9-1 Rainfall Regimes over Ethiopia (after Tesfaye Haile)



*Areas under **region A** are characterized by three distinct seasons and are locally known as Bega (October to January), Belg (February to May) and Kiremt (June to September). The rainfall pattern in region A has two distinct peaks during a year.*

*Areas under **region C** over the southern and south-eastern parts of the country are characterized by two distinct rainfall peaks with dry season in between, where the first wet season is from March to May and the second is from September to November.*

*Areas demarcated by **region B** are characterized by single rainfall peak during a year, where two distinct seasons, one being wet and the other dry are encountered. Mean monthly rainfall pattern shows that the south-western, western and north-western parts of the country are under their wet season during February/March to October/November, April/May to October/ November and June to September, respectively.*

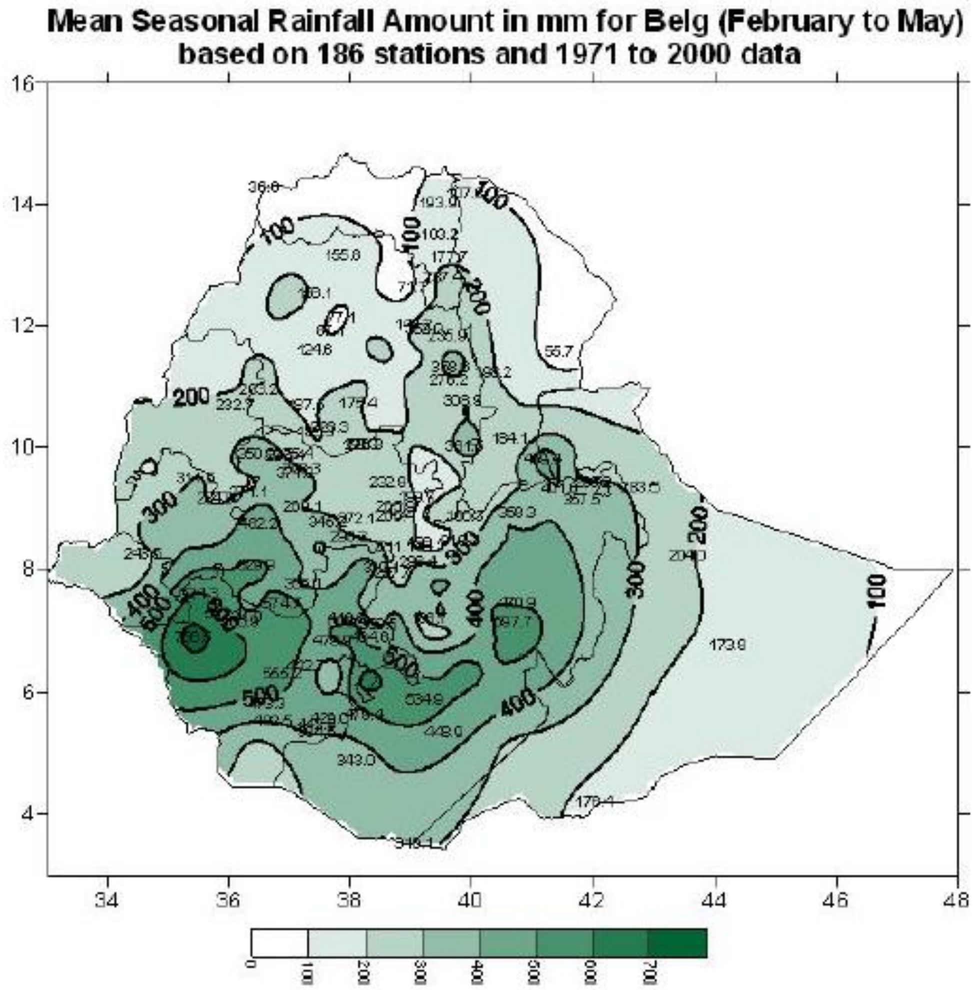
The National Meteorological Services Agency, considering the dominant regional atmospheric circulations and the rainfall patterns across the three major rainfall regimes over the country uses the following seasonal classification for operational monitoring and forecasting of the weather over the country.

***October to January (Bega) :**- Predominantly called Bega(dry season)over areas in Region A, also part of the long dry season over north-western parts of the country of region B, where as over the western and south-western parts of the country of region B, denotes the time when the long rainfall season comes to an end to be followed by a medium to short dry season during the same period. During the first half of this season, south and south-eastern parts of the country of region C get their short rain season due to the southward retreating Inter Tropical Convergence 2one. Year to year variabilities of the weather during this season are largely related to intensities of the occurrences of westward moving depressions over the Arabian Sea, intensities of the Siberian High pressure system and its extension and the Saharan high pressure system which may affect the variabilities in the cloudiness and minimum temperature values over the central, eastern, western, south-western and north-western parts of the country. North-eastern parts of the country and adjoining areas can sometimes get some rain during January due to the east ward moving northern hemisphere mid latitude systems coupled with the Red Sea convergence 2one. Moreover Global tele-connection patterns such as the ENSO also can have influences on abnormal weather conditions such as un-seasonal rainfall activities over areas where this season is considered normally as a dry season.*

***February to May (Belg):** - Predominantly called Belg or Small rainy season over areas in region A, where as over the south-western parts of the country of region B it denotes the start of the long rainy season. Over the western parts of the country of region B also the rainy season starts during March/April. However over the north-western parts of the country of region B, this season is predominantly dry except for the month of May. Southern and south-eastern parts of the country of region C are expected to get their long rainy season during this time starting in March and peaking in April.*

June to September (Kiremt):- *Predominantly called Kiremt season which is considered as the main rainy season in which about 85% to 95% of the food crops of the country are produced.*

Figure 9-2 Example: Mean seasonal precipitation in the Belg (Feb-May) season



Source: RANET

9.2 Climate impacts on road assets

9.2.1 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.

9.2.2 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.

ERA explained of a situation on road A 7-5 between Sodo and Omorate in the southern part of the country that has experienced an ongoing problem with the success of bridge construction. Originally, the road passed over this section of the Delbena river using 1.0 meter diameter pipe culverts as seen in Figure 9-3. After some time, this was washed away and replaced by a 30 meter long bridge. This replacement bridge was destroyed during a flood in 2000.

Figure 9-3 Original 1 meter pipe Delbena River Road A-75

Source: ERA BMS

And in 2002, a 60 meter replacement bridge destroyed during construction from a flood due to an abutment being washed away as seen in Figure 9-5. After this, a new 105 meter long bridge has been designed for a new alignment in a different location. This bridge is currently in construction.

Figure 9-4 Replacement bridge destroyed Road A-75

Source: ERA BMS

Figure 9-5 60 meter replacement bridge destroyed during construction,2002 Road A-75

Source: ERA BMS

ERA BMS explains that the river in this area has increased from being contained by small diameter pipes to now over a 100 meter long bridge. It is not clear what original design parameters were used, or how the river originally appeared.

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.

The above bridge example on Road A-7 is located in unstable flood plains where large floods have the power to move the main river channel out of its existing channel. The rate of the change of the geo-morphology of the rivers in Ethiopia will occur at a faster rate with more floods, causing more difficulty in choosing the most suitable location for a new bridge.

Culverts

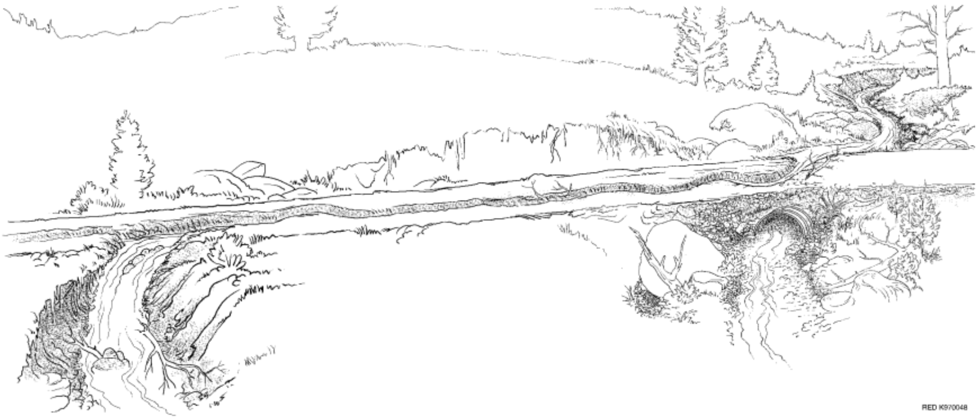
Precipitation affects culverts in similar ways as bridges. Culverts are susceptible to scour in the same ways as bridges, and are subjected to similar problems with siltation and aggradation.

Culverts can be more susceptible to sedimentation deposits as Figure 9-6shows. 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 9-6 is during the next storm, the water that is not able to pass through the culvert will overtop the road.

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 the figure below. 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.

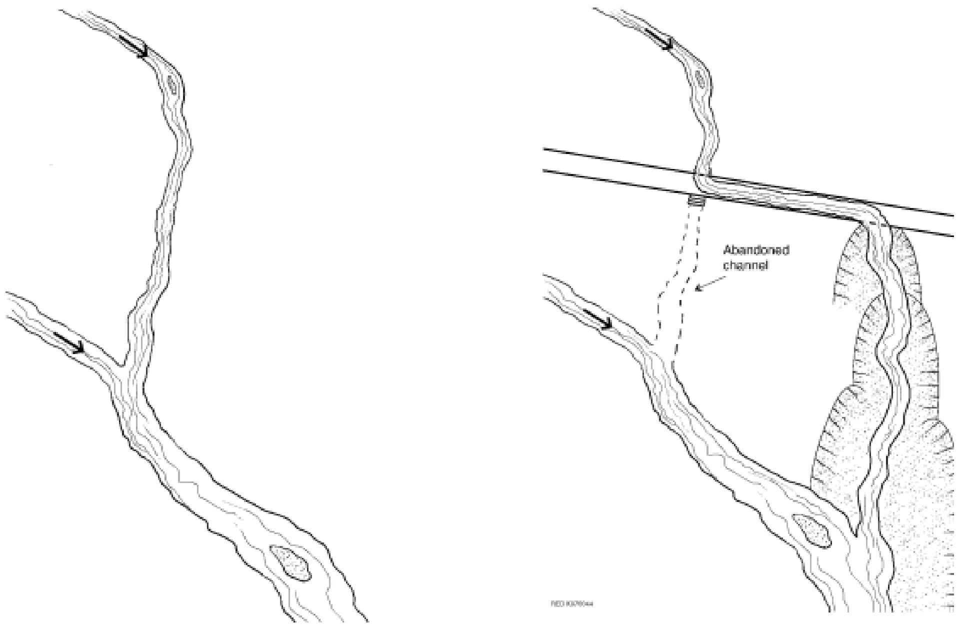
Figure 9-6 Diversion potential



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 9-7. 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 9-7 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) Subbase 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.

A large portion of Ethiopia receives over 1000 mm rain/year, and is a hilly to mountainous country with many of the gravel roads nearing or exceeding 4%. 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 Ethiopia.

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.

The figure below show the significant damage caused by floodplain scour on a section of road in the Dire Dawa region. The embankments of the road have been completely washed away leaving the carriageway exposed and the resulting road failure.

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.

9.3 Climate scenarios and prediction data

9.3.1 Introduction to scenarios and data

The World Bank has chosen 4 climate scenarios for Ethiopia 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":	CSIRO-MK3.0,	SRES A2
"Ethiopia Wet":	NCAR-CCSM,	SRES A1b
"Ethiopia Dry":	IPSL,	SRES B1

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 Ethiopia", 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[16] processing was done by:

Len Wright, Ph.D., P.E., D.WRE
Anthony Powell
Chas Fant
Alyssa McCluskey, Ph.D.
Kenneth Strzepek, Ph.D., P.E.

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.

9.3.2 Statistical analysis of historical and simulated future meteorological data for the purposes of quantifying potential changes to climate in Ethiopia

The purpose of this report is to provide The COWI Group with state-of-the-science information related to climate change predictions in Ethiopia 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:

[16] The report and spreadsheets with all data and results are available in electronic form at the World Bank office in Washington.

"Global Wet" : NCAR-CCSM, SRES A2

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

"Ethiopia Wet": NCAR-CCSM, SRES A1b

"Ethiopia Dry": IPSL-SRES B1

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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