USAID
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A GUIDE FOR USAID PROJECT MANAGERS

ROADS

INCORPORATING CLIMATE CHANGE ADAPTATION IN INFRASTRUCTURE PLANNING AND DESIGN

NOVEMBER 2015

ACKNOWLEDGMENTS

This guide was developed for the United States Agency for International Development (USAID) by AECOM as part of a series of sector specific climate change adaptation manuals prepared for the USAID-funded Global Climate Change, Adaptation, and Infrastructure Issues Knowledge Management Support Project.

COVER PHOTOS

The cover photo shows the MCC Vanuatu Transport Infrastructure Project (credit: AECOM). The second image shows a road in Haiti (credit: DeNatale, AECOM).

GLOBAL CLIMATE CHANGE, ADAPTATION, AND INFRASTRUCTURE ISSUES KNOWLEDGE MANAGEMENT SUPPORT

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A METHODOLOGY FOR INCORPORATING CLIMATE CHANGE ADAPTATION IN INFRASTRUCTURE PLANNING AND DESIGN

ROADWAYS

CONTENTS

ACRONYMS

CAPEX	Capital Expenditure
CBA	Cost-Benefit Analysis
MCA	Multi-Criteria Analysis
OPEX	Operational Expenditure
USAID	United States Agency for International Development

KEY TERMS

ADAPTIVE CAPACITY, as it relates to infrastructure and built assets, describes the degree to which the physical elements of a system can absorb, withstand, or respond to climate change impacts without incurring damage.

CLIMATE is an expression of the composite weather conditions (e.g., temperature, precipitation, wind), including both statistical averages and the occurrence of extreme events, over a given period of time. The World Meteorological Organization recommends a 30-year period to adequately describe the climate of a given area.

CLIMATE CHANGE refers to a statistically significant variation in climate data or patterns over a given period of time, due to either natural climate variability or as a result of human activity.

CLIMATE CHANGE ADAPTATION describes measures taken in response to actual or projected climate change in order to eliminate, minimize, or manage related impacts on people, infrastructure, and the environment.

CLIMATE CHANGE MITIGATION refers to actions that reduce the production of greenhouse gases that cause climate change. Although some adaptation strategies have mitigation co-benefits, they are not specifically referenced in this guide.

CLIMATE CHANGE IMPACTS on infrastructure are, for the purposes of this guide, the resulting influence of climate change effects on the structural form or function of an asset (e.g., the buckling of train tracks due to extreme heat).

CLIMATE CHANGE VARIABILITY is the short-term fluctuation in weather conditions, usually over a period of a year or a few decades.

CLIMATE DRIVER is the manifestation of a change in climatic conditions through one or more weather variables, such as a change in precipitation or sea level rise, to create an impact.

EXPOSURE refers to the extent to which a system comes into contact with a hazard.

LARGE-SCALE INFRASTRUCTURE SYSTEMS serve large populations and tend to be focused on urban areas.

RISK is the combined function of the likelihood that a hazard will occur and the resulting consequences.

SENSITIVITY is the degree to which a built, natural or human system is directly or indirectly affected by or responsive to changes in climate conditions or related impacts.

SMALL-SCALE INFRASTRUCTURE SYSTEMS service smaller populations, ranging from villages to clusters or communities of households, and are often more relevant to rural areas.

VULNERABILITY is the degree to which a system is susceptible to or unable to cope with adverse effects of climate change, including climate variability and extremes. It is often defined as a combined function of exposure and sensitivity to the effects of climate change, minus the adaptive capacity of a system.


DeNatale, AECOM

EXECUTIVE SUMMARY

Extreme weather events such as droughts, heat waves, dust storms, forest fires, floods, and landslides, which already disrupt the lives of millions each year, are expected to increase in frequency and intensity with climate change. The impact of these sudden events, in addition to the gradual change in climate effects over time, will put added stress on vital water, sanitation, flood management, transportation, and energy infrastructure. Responding to the impacts of climate change presents a major challenge for developing countries lacking adequate resources, and it is therefore an important focus of the United States Agency for International Development's (USAID) development assistance portfolio.

To help address this challenge, and consistent with Executive Order 13677 – Climate-Resilient International Development, USAID has developed the Global Climate Change, Adaptation, and Infrastructure Knowledge Management Support Project (a Task Order under the Architecture and Engineering Indefinite Quantity Contract or IQC) to articulate best practices in incorporating climate adaption in the planning and engineering design of USAID infrastructure activities.

Under this project, a suite of knowledge management products has been created, led by the *Overarching Guide: A Methodology for Incorporating Climate Change Adaptation Infrastructure Planning and Design*. The objective of the Overarching Guide is to support the consideration of climate change risks and adaptation in USAID infrastructure development activities. Serving as a technical companion volume to the 2014 USAID publication, *Climate Resilient Development: A Framework for Understanding and Addressing Climate Change*, the Overarching Guide provides engineering and non-engineering development professionals with a methodology to evaluate infrastructure vulnerability and select appropriate engineering design options to rebuild resilience.

As a part of the suite of tools for incorporating climate resiliency into engineering design, this particular guide focuses on roadway infrastructure, with the overall objective of supporting the consideration of climate change risks and adaptation in USAID roadway infrastructure development activities. The term "roadway infrastructure", in the context of this guide, refers to low-volume road infrastructure as most USAID's development activities focus on this scale of road that is multi-modal, carrying automobiles, buses, trucks, bicycles, as well as pedestrians. This guide will be useful for those considering engineering design options to make roadway infrastructure more resilient in a climate altered future. It provides engineering and non-engineering development professionals with an overview of potential impacts on roadways, adaptation options, and guidance for utilizing a risk assessment methodology to determine appropriate design measures.

While the focus of this guide is on engineering design; broader elements such as management of transportation infrastructure are also proposed as they are closely associated with the optimum performance of roadways infrastructure. The focus of this document is not on mitigation of greenhouse gas emissions related to transportation infrastructure construction or operation.

A SUITE OF TOOLS

Accompanying this roadways guide are additional primers that focus on flood management, potable water structures, sanitation, bridges, and irrigation, that provide more detail on climate change impacts and appropriate adaptation responses and strategies for these other important infrastructure sectors.

THE IMPORTANCE OF CONSIDERING CLIMATE CHANGE IMPACTS IN ROADWAY INFRASTRUCTURE

It is important for practitioners and stakeholders to consider the nature and extent of climate change impacts on investments and activities, including activities related to both new and existing infrastructure.

Climate change is likely to worsen issues related to extreme weather events that cause damage to roadways, reduce their performance or restrict access. Since most roadways are designed using historical climate data, the strength and capacity of existing roadways may not be adequate to handle the impacts of changing climate. The uncertain nature of climate change is likely to bring about additional challenges to the design, construction, and operation of new infrastructure.

When considering the impact of climate change on roadway infrastructure, it is important to understand the relevance and cost-effectiveness of climate change adaptation activities. If the infrastructure asset is a short-term or temporary solution, or if the project is small in scale, it may not be necessary to fully assess longer term climate change risks to the investment. If the asset is large or expected to last more than three decades, climate change risks should be considered. For example, the design and construction of a major highway with a design life of 100 years or more should consider climate change impacts. On the other hand, a small-scale secondary roadway that is expected to have little usage and can be repaired (cost effectively) following an extreme weather event may not need to be fully climate resilient.

A STEPWISE APPROACH TO CLIMATE RESILIENT DESIGN

Following a climate resilience framework when developing and evaluating roadway infrastructure design will help practitioners improve the effectiveness of these investments. USAID's Climate Resilient Development Framework promotes the adoption of development strategies and infrastructure activities that integrate risk considerations in order to create more climate resilient infrastructure and thereby enhance cost effectiveness of interventions. These goals can be realized by following a five-step approach to: 1) establish the context; 2) conduct a vulnerability assessment; 3) conduct a risk assessment; 4) develop an adaptation strategy; and 5) implement activities in support of climate resilient infrastructure (addressed in Chapter 3).

This framework should be used by practitioners to establish what climate change impacts existing, or future, infrastructure assets might be facing (e.g., sea level rise, flooding, drought, and more extreme heat days); whether or not the asset might be sensitive to those changes; and how such sensitivities impact the asset. The subsequent risk assessment will help identify those assets whose failure would have significant or severe impacts on buildings, economic activities, or public health. Adaptation strategies should then be defined and implemented.

ADAPTATION STRATEGIES AND RESPONSES

Responding to climate change impacts will require the selection of appropriate adaptation strategies. These strategies should be selected based upon the previous assessments conducted under the Climate Resilient Design Methodology (see Chapter 3) and take into consideration a country's priorities, availability of resources, and temporal-scale of the activities.

The diverse array of adaptation strategies and responses for enabling more climate resilient infrastructure design can be categorized under four types of strategic approaches: 1) accommodate and maintain; 2) harden and protect; 3) relocate; and 4) accept or abandon. Each approach has advantages and disadvantages that are expanded upon in Chapter 3. Examples of climate impacts and risks, and adaptation measures relevant to potable water infrastructure are provided in Table 1. A compendium illustrating adaptation strategies available to practitioners to address potential climate change-related risks to roadway infrastructure is also provided in the Annex.

CASE STUDY

A climate change resilient infrastructure design case study is also provided to demonstrate the application of the methodology presented in this guide.

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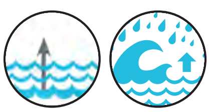
[1] USAID. 2014. Climate-Resilient Development: A Framework for Understanding and Addressing Climate Change. Washington, D.C., available at http://www.usaid.gov/climate/climate-resilient-development-framework

TABLE 1: EXAMPLES OF ROADWAY INFRASTRUCTURE RISKS AND ADAPTATION MEASURES

Climate Drivers	Climate Impacts and Risks	Adaptation Measures
 Extreme Heat and Heatwaves, Wildfires	• Higher temperatures and solar radiation can increase the rate of degradation of pavements leading to higher maintenance costs • Extreme heat can limit construction activities, which may increase the cost and duration of construction and maintaining activities • Wildfires may reduce vegetation cover contributing to increased run-off and the potential for flooding or landslides	• Confirm capability of current heat-resistant road materials and, if necessary, use more heat tolerant binders and materials • Use lighter color paving materials (i.e. concrete) or reflective coatings for asphalts • Maintain and implement vegetation management practices that minimize fire risk
 Extreme Precipitation Events, Less Frequent but Higher Intensity Storms, Flooding	• Damage to roads from landslides, flooding and ground movement can restrict access to essential emergency services, food supplies and access to markets and other economic opportunities • Most stormwater drainage systems have been designed based on historic precipitation data. It is possible that they will not withstand more intense and frequent events, thereby leading to road washouts and flooding of assets • Wet weather conditions make unpaved roads unsafe for motorists and may become inaccessible during extended wet weather	• Size drain and stormwater systems for new infrastructure with consideration of climate change projections • Retrofit existing stormwater infrastructure (i.e. culvert crossings, bridges) to accommodate increasing flow patterns • Harden or stabilize slopes subject to increased run-off from extreme weather events • Elevate electrical equipment in operations or maintenance facilities (i.e. traffic signals) to minimize risk of inundation and failure • Use waterproof materials to limit damage to assets • Alter maintenance regimes to target vulnerable sections of transport systems
 Sea Level Rise, Storm Surge	• Increased exposure to higher salinity levels causing roadway to deteriorate • Damage to roads from flooding and erosion restricting access • Sea level rise and coastal erosion may cause coastlines to shift exposing infrastructure that was not previously at risk to storm surge and wave damage	• Raise elevation of roadway or bridge touchdown on embankments or levees • Increase capacity of the stormwater drainage system and increase drainage maintenance in areas at greatest risk of flooding • Use corrosion-resistant or waterproof materials (adapting different pavement mixture design can improve resistance to water damage - compared with concrete pavement, asphalt pavement material is generally less resistant to water damage)

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CHAPTER I

INTRODUCTION

ROADWAY INFRASTRUCTURE

Roads are an integral part of the transportation system of a country. Only with an efficient, connected, well maintained road network and transportation services can a country maximize its economic potential. The extent and quality of roads are linked to a country's economic development. In countries such as India, Thailand, Ethiopia, and Uganda, investment in rural roads are found to have had a greater economic impact than any other investment – greater than education, agriculture, and health[2]. Investing in roads and increasing road coverage will make it easier for those located in remote areas to transport goods, travel long distances, and improve access to electricity and clean drinking water. Better-quality roads also support advancement in social infrastructure. In 2011, World Highways[3] reported that positive impacts have been documented in countries such as Morocco, where improved road access created safer traveling conditions, resulting in an increase of girls attendance in school. The same World Highways study also reported that improved road access substantially increased health care facility use and quality, and social impacts for women. In spite of these opportunities, reliable roadways with sufficient connectivity to jobs and community resources are still lacking in developing countries because of inadequate investment and poor maintenance.

CLIMATE CHANGE IMPACTS ON ROADWAY INFRASTRUCTURE

Climate change will likely exacerbate existing roadway issues and further deteriorate the condition of roadways in both developed and developing countries. In 2014, the Intergovernmental Panel on Climate Change (IPCC)[4] concluded the following:

- The effects of climate change will continue even if greenhouse gas concentrations were to stabilize at existing levels; average temperature increases and sea level rise will continue due to the timescales associated with climate processes and feedback effects.
- Global mean temperature may rise between 1.0°C to 3.7°C by the end of 2100, depending on the scenario and models.
- Sea level rise will most likely reach 40-63 centimeters during the 21st century.
- It is virtually certain that, in most places, there will be more instances of hotter, and fewer cold, temperature extremes as global mean temperatures increase.

Roadway infrastructure design standards will have to be adjusted to build resilience to direct and indirect impacts from climate change. Direct impacts include exposure to extreme heat, heatwaves, extreme weather events, strong surge and sea level rise. Changes in traffic patterns and more frequent road closure are examples of indirect impacts. While impacts associated with storm surge and sea level rise will be restricted to coastal roadways, changes in temperature (average and extremes), extreme rainfall events and storms may affect both inland and coastal roadways. If these risks are not carefully considered in new roadways construction activities, they could prevent emerging countries from continuing their economic and social development.

Climate change is a significant threat to poverty reduction activities and could jeopardize decades of development efforts. From the very beginning of the investment plans and the design process, development of new infrastructure and rehabilitation of existing infrastructure should be designed to be resilient to climate risks.

[2] World Highways. 2011. Rural Roads: as the wealth of Nations, available at: http://www.worldhighways.com/sections/world-reports/features/rural-roads-important-to-global-development/

[3] Ibid.

[4] Intergovernmental Panel on Climate Change (IPCC). 2014 Fifth Assessment Report http://ipcc.ch

The impacts of climate change will vary regionally. Future climatic conditions must be considered in planning and managing infrastructure activities, including developing the business case, defining levels of service and decision making related to location, design, operation, maintenance, renewal, and refurbishment.

HOW TO USE THIS GUIDE

The overall objective of this guide is to support the consideration of climate change risks and adaptation in USAID roadway infrastructure development activities. This guide provides engineering and non-engineering development professionals with a guidance document demonstrating a step-by-step method for assessments and supporting technical information, including an overview of potential impacts on roadway activities, adaptation options, case studies, and resources. This guide will be useful for those considering how climate change may require specific infrastructure projects to be altered to enhance resilience and meet service goals in a climate altered future.

This roadways guide accompanies an Overarching Guide that covers integration of climate change adaptation considerations into a broad range of USAID infrastructure activities. The overarching methodology offers a step-wise process for implementing a risk assessment framework. This guide is specific to roadway infrastructure. Note that some content is repeated in both guides to maintain readability of each document.

This guide addresses climate change adaptation rather than mitigation of greenhouse gas emissions. The focus of this guide is on engineering activities; however, broader elements such as changes in traffic management are included in this guide as a means to further protect transportation systems from climate change impacts.

Nairobi Kileleshwa Ring Road where pedestrians and motorists are separated by a drainage channel designed to help divert water away from the road surface.

ADB KENYA

DeNatale, AECOM

CHAPTER 2

CLIMATE IMPACTS AND RISKS

CLIMATE IMPACTS AND RISKS TO ROADWAY INFRASTRUCTURE DESIGN

The development of new infrastructure and the renewal and maintenance of existing assets will increasingly be impacted by climate change. Consequently, it will be critical that practitioners understand how natural hazards and the changing climate will likely impact infrastructure assets and services in order to assess risks and make informed decisions regarding asset design, operation and maintenance.

When considering the impact of climate change on roadway infrastructure, it is important to understand the relevance and cost-effectiveness of climate change adaptation activities. If the infrastructure is a short-term or temporary solution, or if the project is small, it is likely unnecessary to fully assess the climate change-induced risks to the investment. If the project is large, or if the asset has a longer service life, climate change should be considered.

The primary climate drivers referenced in this guide are identified below. Icons are provided for each climate driver and are used as visual aids throughout this guide. Additional natural hazards that are not explored in this guide but may affect infrastructure include tsunamis, earthquakes, volcanic eruptions, landslides and rockfalls. The following sections provide an overview of the risks that climate change may pose to roadways, and how to manage or minimize these risks in the development, maintenance or rehabilitation of roadway infrastructure. The range of risks discussed is not exhaustive; practitioners should conduct a detailed assessment at the project or program level to identify all relevant risks.

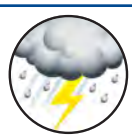
KEY CONSIDERATIONS IN IDENTIFYING IMPACTS TO ROADWAYS

Climate change is likely to impact roadway infrastructure assets through modification in the pattern of extreme climatic events, which includes storms and storm surge, floods, and drought; or through gradual changes in seasonal or annual patterns of temperature, solar radiation, precipitation, and sea level rise. When evaluating the impact of climate change and risk to bridge infrastructure there are two overarching concerns – the timeframe for the asset's productive lifespan and required capital

CLIMATE DRIVERS

EXTREME HEAT/ HEATWAVES: Extreme temperatures are location specific. Heatwaves are prolonged periods of excessively hot weather. Likely increase in extreme air temperature and heatwaves in most areas.

DRYING TREND/ DROUGHT: A prolonged dry period in a natural climate cycle which results in a shortage of water. Likely increase in drought conditions in some areas through a warming of air temperature and decrease in precipitation.



EXTREME PRECIPITATION/ FLOODING: Extreme precipitation events are location specific and can cause flooding when downpours exceed the capacity of river or urban drainage systems. Uncertain climate projections, expected to intensify in some areas.

STORM SURGE: The difference between the actual water level under the influence of a meteorological disturbance (storm tide) and the level which would have been attained in the absence of the meteorological disturbance (i.e. astronomical tide). Sea level rise exacerbate storm surge height.

SEA LEVEL RISE: Anticipated sea level changes due to the greenhouse effect and associated global warming. Leads to changes in erosion and accretion, long term inundation, exacerbate storm surge and tsunami height.

DAMAGING STORMS (WIND, LIGHTNING): Severe weather systems involving damaging winds and heavy rainfall downpour, including tornados, hailstorms, tropical cyclones and hurricanes. Uncertain climate projections.

WILDFIRE: A massive and devastating fire which destroys forests, grasslands and crops, kills livestock and wild animals, damages or destroys settlements and puts lives of inhabitants at risk. Uncertain climate projections.

costs. While engineering design always considers some measure of extreme weather conditions when designing or rehabilitating infrastructure, it is important to consider a temporal scale that is appropriate to the anticipated life of the asset as well as and cost-effectiveness of climate resilience options. For example, the design and construction of a coastal highway with a design life of 100 years or more should consider climate change impacts. However, a small access road that is relatively inexpensive to maintain or repair following an extreme climate event does not necessarily need to be climate-proofed.

KEY CONSIDERATIONS

In developing countries, climate adaptation measures will be required to reduce the costs and disruption caused by climate change. Keeping in mind the key aspects noted above, it will also be important when designing or rehabilitating roadway infrastructure systems to follow certain principles that will help create greater resiliency by planning not just for the current climate, but for the climate scenario projected for the entire design life of the infrastructure asset.

Impacts are a function of current and future climate variability, location, asset design life, function, and condition. Many characteristics of the asset and its location influence the likelihood and extent of climate impacts. These characteristics must be considered when establishing the context for the climate change risk and vulnerability assessment. Questions about the condition of the existing asset base (Has it been maintained? What is its current failure rate?) are important to evaluate as part of a comprehensive assessment.

Climate change can cause direct physical impacts to assets and indirect impacts including loss of service. Changes in the pattern of extreme events can directly impact the physical integrity of built structures in a variety of ways, causing loss of service. One way climate change impacts roadways is through flooding and washouts around crossing culverts due to increased intensity and frequency of heavy rainfall and increased runoff volumes flowing through existing drainage systems. In the future, flooding is expected to occur more frequently and be more destructive.

Current infrastructure design is based on historical data and experience. Most existing infrastructure assets were designed based on historical climate data, such as average rainfall and runoff in an area, or historic flood events. However, the pace of climate change means that historic data may no longer be relevant for longer-term infrastructure performance. Climate change may cause shorter asset life spans or require early rehabilitation as infrastructure degradation accelerates. These situations can be exacerbated in less developed countries, where design standards and climate information may be out of date or nonexistent.

Climate variability or increased frequency of extreme events may mean that infrastructure is no longer optimally designed for even short-term purposes. To illustrate, it is likely to be preferable to design culverts and drainage systems associated with roadways to a higher standard than current design guidance in anticipation of future extreme flood events. These situations are often exacerbated in less developed countries where design standards and climate data may be out of date or nonexistent.

For new assets, both the location of the asset and the functional classification of a roadway based on performance characteristics (e.g., traffic flow and performance of a roadway, as well as vehicular traffic and pedestrian usage) should take climate change into consideration. The associated impacts of climate change on transportation infrastructure will vary regionally, reflecting differences both in the magnitude of climate change, and in environmental conditions. Asset location is particularly relevant in coastal areas and floodplains. The capability of the asset to perform to its as-built condition and level of design may be impacted by changes in the environment.

Demand for transportation services can shift as a result of climate change. Warmer temperatures and more frequent heat waves can lead to physical damage for some roadways and consequently increase usage for other undamaged roadways that are in the vicinity. Demographic expansion or contraction, such as the relocation of coastal communities affected by flooding and sea level rise, may affect traffic levels and the demand for services.

Indirect impacts and cascading consequences can be more difficult to identify than direct impacts, but they should be considered. For example, inadequate power distribution services during an extreme weather event may impact traffic signals increasing the risk of accidents. Additionally, traffic on roadways may increase as a result of evacuation in the lead up to an extreme event placing additional stress on infrastructure.

COASTAL ROADWAY INFRASTRUCTURE

Coastal roadways are particularly vulnerable to climate change as they are located in close proximity to wave and tidal forces as well as corrosive salt water. Coastal erosion is a natural process that can cause significant impacts to coastal roadways. Coastal roadways in many countries have been flooded or damaged following storm surge events. Coastal roadways are important assets, and the demand for these types of roads is expected to remain high and possibly increase as populations continue to grow in coastal areas. Climate stressors can pose serious risks to coastal roads and their surrounding areas. Sea level rise, increased frequency of damaging storms, increasing average and extreme temperatures are some of the climate hazards outlined below that can have serious impacts on coastal roadway infrastructure.

SEA LEVEL RISE AND STORM SURGE

Climate change is expected to contribute to more rapid sea level rise. Although the rate varies between different regions of the world, on average sea levels worldwide have been rising at a rate of 0.14 inches (3.5 millimeters) per year since the early 1990s.[2] Sea level rise impacts coastal roadways through the increased frequency of flooding during high tides and strong winds creating high waves. Increased frequency of flooding can reduce the service life of roadway infrastructure and require more frequent and extensive repair. In addition, as sea levels rise, coastlines also change as a result of erosion and semi-permanent inundation. As a result, roadways that were not previously at risk may be exposed to storm surge and wave damage in the future. Higher sea levels can exacerbate storm surge and waves, as well as cause salinity levels to rise. Exposure to salinity can deteriorate road infrastructure.

Storm surge and waves. Occurring along the coast, storm surge is caused by strong storm winds and pressures, which lead to a rise in water level. Sea level rise contributes to larger storm surges which can reach heights over 20 feet during powerful storms or hurricanes which can cause significant damage to roadways as a result of wave impacts or inundation. Since most infrastructure design is based on historical data and experience, asset location or design may not be able to cope with projected risks associated with storm surge and wave impacts.

Increase of flooding frequency. Sea level rise will likely result in more frequent occurrences of coastal flooding which causes increases of moisture in the pavement systems. Increase in soil moisture content will cause soil to lose its firmness, and pavement seals may crack as a result of the increased moisture and repetitive load. Moisture can enter the pavement through the cracks, further degrading the pavement layer and allowing water in the pavement's structural soil and ultimately can cause severe degradation of the roadway.

Salinity level increase. Sea level rise may lead to the increased salinity in the water table which may interact with roadways. Once salt dissolves in water and enters the pore spaces of the aggregate used in the road, it reacts with chemicals within the aggregate, forming crystals that have a larger volume. The expanding volume causes cracks to develop and allow more moisture to enter the pavement layer. When moisture reaches those crystals, it creates a cycle of crystallizing; dissolving and re-crystallizing further deteriorating the pavement. Salinity can also cause corrosion to reinforced structures associated with the roadway including culverts.

INCREASE IN AVERAGE TEMPERATURE AND EXTREME HEAT

Current climate projections indicate that average temperatures are expected to continue to rise. Higher average and extreme temperatures will have direct impacts on roads causing a series of chemical reactions that weaken and deteriorate pavement.

- ***Frost heaves*** – An increase in average temperatures in colder climates will increase the frequency of the freezing and thawing cycle during the winter. Considerable damage can be done to the pavement if thawing of the ground is accompanied by heavy traffic loads. If temperatures in the winter months rise, then the frequency of the day-night freezing and thawing cycle may increase, causing frost heaves to break pavements.
- ***Rutting*** –This form of deformation is generally caused by heavy traffic, especially when moving at slow speeds. At higher temperatures, the asphalt binder is temporarily heated into a more plastic and malleable state. This has the effect of decreasing its binding strength. Over time, the asphalt binder will become thin and stretched due to repeated heavy traffic loading, which can lead to rutting. Once rutting occurs, it will negatively affect the performance of the roadway including reducing motorist safety and comfort.
- ***Cracking*** – With high temperatures and solar radiation, a series of chemical reactions occur where elements within the asphalt combine with oxygen molecules in the air. This process leads to a chain of physical and chemical changes that cause the onset of micro-cracking. Cracks not only reduce the life and performance of roadways, they also allow water to seep into the pavement and increase moisture content, which further degrades roadway infrastructure. Without inspection, cracking may go unnoticed until an extreme rainfall event washes out the road that has been weakened by the cracking.

SUMMARY OF IMPACTS

Climate drivers such as sea level rise, extreme rainfall and extreme temperatures could reduce the performance and service life of coastal road infrastructure by causing the following impacts (see Table 1):

- Increase frequency of traffic disruption. During major rainstorms, flooding may delay evacuation and emergency response activities.
- Deterioration in roadway conditions will diminish the effectiveness of emergency response from fire, health and safety services.
- Roads can be washed-away by coastal erosion.
- Increased resource requirements for maintenance and repair.
- If a major highway is damaged or destroyed, for example by an extreme weather event, it can significantly affect the economy and development of a country. Damage to roads from landslides, flooding and ground movement can block access to essential emergency services, food supplies and, in the longer term, disturb access to markets and other economic opportunities.
- Increased damage to roads, causing them to become unstable and unsafe for motorists and travelers. This may lead to communities becoming isolated or having to rely on secondary roads which can be unpaved and less safe for travel.


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TABLE 1: COASTALROADWAY INFRASTRUCTURE

Climate Drivers	Impacts and Consequent Risks
Coastal Roadways	
 Increased frequency of extreme precipitation events and floods	• Damage to roads from landslides, flooding and ground movement can block access to emergency services, food supplies and, in the longer term, disturb access to markets and other economic opportunities • Failure of drainage infrastructure leading to road washouts and flooding of assets
  Sea level rise and storm surge	• Coastal erosion reducing the stability of road foundations or causing the failure of roads • Damage to roadways from inundation or wave impacts • Increased exposure to salinity causing roads to deteriorate
 Extreme heat and heatwaves	• Increase in the rate of degradation of pavements leading to higher maintenance costs • Softening and expansion of pavements which can lead to rutting and pavement cracking • More frequent unsafe traffic conditions associated with climate related damage to road surfaces • Disruption of construction and repair activities as a result of extreme heat creating unsafe work conditions

INLAND ROADWAY INFRASTRUCTURE

Climate change affects inland roadways differently than coastal roadways. Unlike coastal roadways, some inland roadways remain unpaved and unsealed. This is especially the case in developing countries, where typically only major highways and urban roads are paved, with the majority of the secondary roads comprised of gravel or dirt. To differentiate the impacts and risks between coastal and inland locations, inland roadways are separated into two categories: paved and unpaved. Impacts and risks associated with each type of inland road are described in further detail in the following section.

PAVED ROADS

Inland paved roads are designed for different climatic factors than those located near the coast. Climate drivers likely to impact inland roads include extreme precipitation and flooding, extreme heat and variation in temperature.

- ***Increase frequency of extreme precipitation events and floods.*** Similar to coastal roadways, paved inland roads can be damaged by flooding. As the frequency of flooding increases, impacts will include washouts due to undersized and inadequate drainage; deforestation and changes in land use can contribute to increased impervious cover generating more runoff contributing to the stress on the existing drainage system. Furthermore, extreme precipitation events may cause landslides and mudslides along inland roadways that cause direct physical damage, and restrict access, to these roads.

- ***Increase in average temperature and extreme heat.*** Inland areas are generally more likely to experience a larger daily variation of temperature than coastal areas. Thus, the "freezing and thawing" cycle may be more severe for inland roadways causing cracking and rutting. Conditions will worsen if roads are not properly maintained.

- ***Increase in moisture content.*** Flooding will introduce additional moisture to inland roads. If accompanied by cracking pavement, water can leak below the pavement surface and degrade the base and sub-grade layer, which reduces the service life and driving conditions of roads.

- ***Salinity level increase.*** Salinity affects inland roads in a different way than coastal roads. Since inland roads are not in close proximity to sea water, salt does not come in contact with the pavement through the surface layer, but rather from the subsurface layers. As sea levels rise, groundwater becomes more commonly contaminated by saline water which may degrade roadway infrastructure.

UNPAVED ROADS

The performance and condition of unpaved roads are typically poor, even without the effect of climate change. Lacking pavement to stabilize the driving surface, unpaved roads are more susceptible to flooding and erosion. Climate changes will make these problems worse.

- ***Increase Frequency of Extreme Precipitation Events.*** The increased frequency of extreme precipitation events will cause a greater occurrence of flooding, where road washout and erosion will occur more often. The condition of unpaved roads may become impaired, causing them to be unstable and unsafe to drive on. Extreme precipitation events may also increase the risk of landslides and mudslides which may damage and restrict access to roadway infrastructure. The risk of flooding may be worsened in areas were wildfires reduce vegetation cover leading to higher volumes of runoff during storm events.
- ***Increase in Moisture Content.*** Since unpaved roads do not have the waterproofing layer that paved roads do, they are more susceptible to increases in moisture. Standing water and muddy conditions on dirt roads can decrease tire traction making the roads unsafe for travel. Unpaved roads can become inaccessible in wet weather. For roads that are near the groundwater table, increased frequency of extreme rainfall events may cause prolonged periods of high groundwater levels making the roads inaccessible for longer periods.

With the exception of sea level rise and storm surge, all other climate change impacts on coastal roads (as discussed above) can affect inland roads similarly. Specific climate change impacts on inland unpaved roads (Table 2) may include:

- ***Increased frequency of traffic disruption.*** During extreme rainfall events, flooding may cause roads to become inaccessible and consequently isolate rural communities. Most rural villages are only accessible through unpaved roads. Isolation may put lives at risk during emergency situations.
- ***Unpaved roadways are highly susceptible to erosion.*** Erosion of the road surface decreases the safety of motorists and travelers and increases the risk of accidents.

SUMMARY OF IMPACTS

TABLE 2: INLAND ROADWAY INFRASTRUCTURE

Climate Drivers	Impacts and Consequent Risks
Coastal Roadways	
 Increased frequency of extreme precipitation events and floods	• Increasing flooding, which leads to erosion of unpaved roads. Erosion can deteriorate and reduce the service life of roadways • Increased risk of landslides and mudslides damaging, and restricting access to, roads • Increase in the incidence of road washout • Wet weather conditions make unpaved roads unsafe for motorists and may become inaccessible during extended wet weather
 Increased in average temperature and extreme heat	• Similar to coastal roadways, extreme heat can cause rutting and cracking of pavements. • Damage of asphalt can be more common and severe for inland roadways, as temperatures may be higher inland than near the coast
 Increased moisture content of roads and soil	• Reduced access to, and safety of, roadways
 Wildfires	• Wildfires reduce the vegetation cover which lead to higher volumes of runoff during storm events and increased flooding conditions


Mozambique
DeNatale, AECOM

CHAPTER 3

A CLIMATE RESILIENT INFRASTRUCTURE METHODOLOGY

ENABLING CLIMATE RESILIENT PLANNING AND DESIGN OF ROADWAY INFRASTRUCTURE

This chapter provides a step-wise methodology to enable practitioners to include climate change considerations in the design of new roadway infrastructure or the evaluation of existing infrastructure (see Figure 2).

- **STEP 1** establishes the context of the assessment defining the asset and the climate impacts that will be the focus of the assessment.
- **STEP 2** considers the vulnerability (exposure, sensitivity, and adaptive capacity) of the assets screening those that require more detailed analysis.
- **STEP 3** identifies, analyzes and evaluates the subsequent risks (combining likelihood with consequences).
- **STEP 4** develops adaptation strategies to address the most significant risks.
- **STEP 5** guides the implementation, monitoring and evaluation of adaptation solutions.

In applying the methodology, the majority of the effort is focused on Steps 3 and 4. Risk assessment and adaptation to climate change impacts should be part of a multi-criteria decision-making process (along with other technical, socio-cultural, environmental, economic, and financial factors) that reviews solutions and options during engineering planning and design. While the capital costs of creating infrastructure assets that are more resilient to climate change impacts may guide the adaptation strategy selection and design, a pro-active approach when possible and affordable is often more cost-effective than being reactive. It will ultimately be more economical to build stronger and better located assets than to rebuild or repair structures following a disastrous event, in addition to other costs such as healthcare and clean-up that may result from failure of an asset.

If a risk management process is already in place for infrastructure activities, the following methodology can be used to assess the adequacy or identify gaps in the process. If there is no existing risk management process in place, this step-wise approach can be used to establish such a process.

STEPWISE APPROACH FOR CLIMATE RESILIENT INFRASTRUCTURE PLANNING AND DESIGN

The management of climate change risks in USAID infrastructure activities can be facilitated by the following five-step process including:

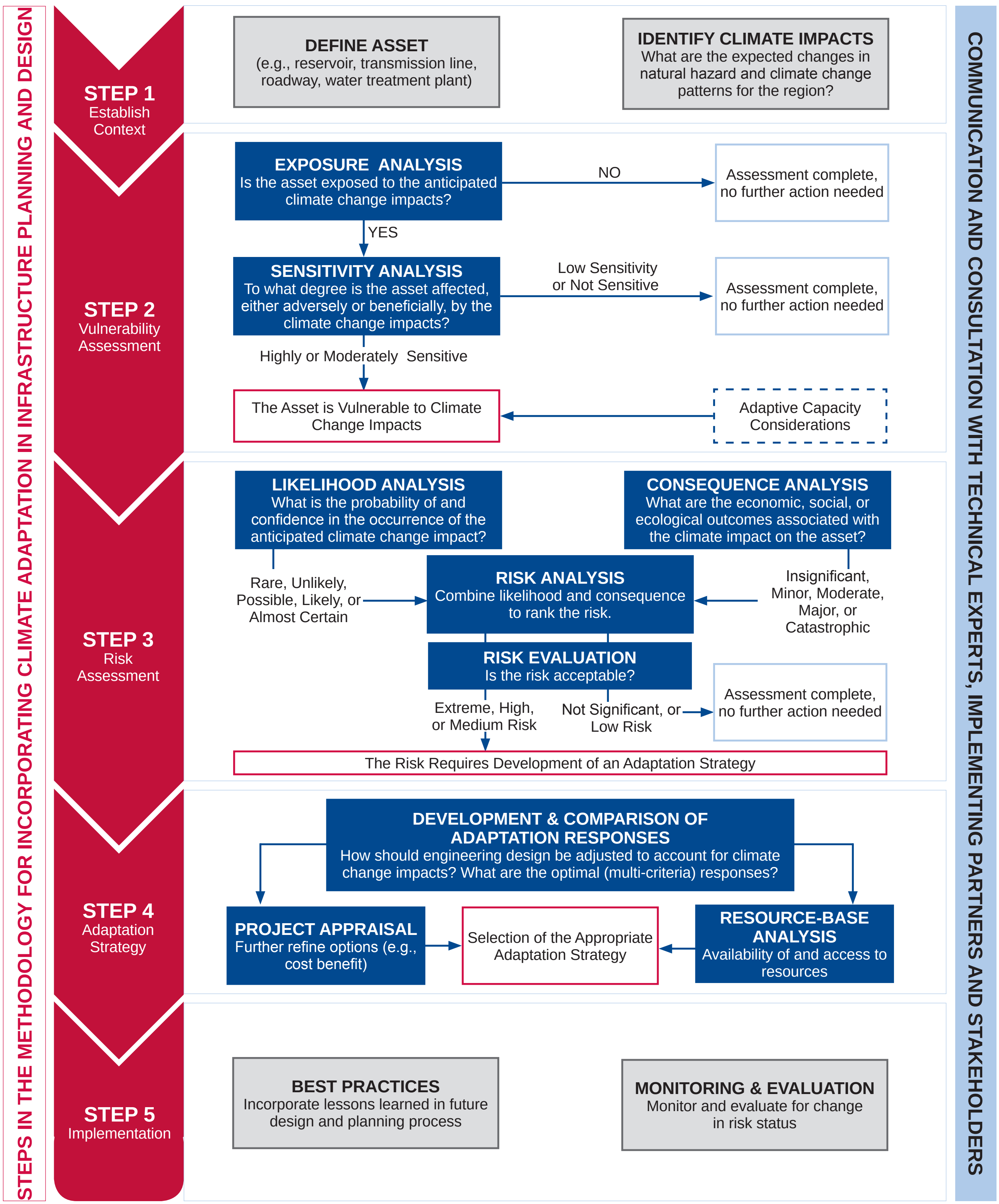
5 STEP PROCESS

1	Establishing the Context
2	Vulnerability Assessment
3	Risk Assessment
4	Development of Adaptation Strategies
5	Implementation

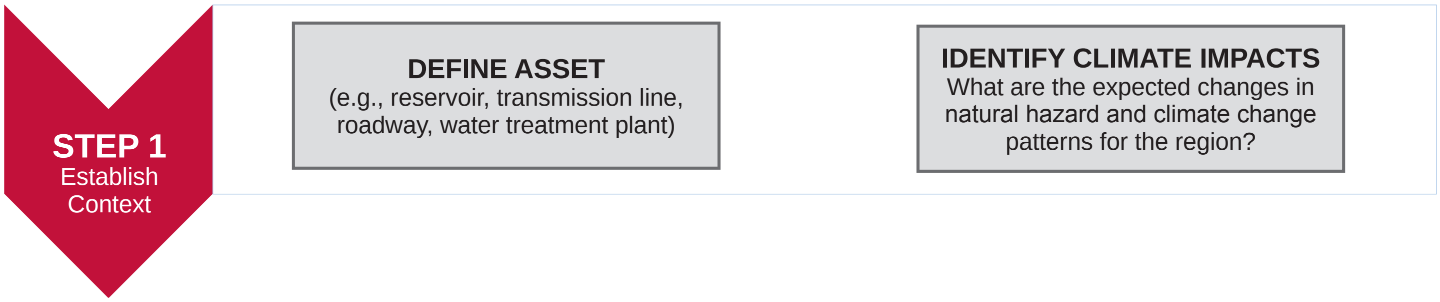
Collectively, these steps establish a climate resilient design methodology to be used when determining appropriate engineering design actions for more climate resilient structures.

This process will help establish whether or not an existing or future infrastructure asset is vulnerable and at risk from climate change impacts. Tools, in the form of checklists, worksheets, or matrices, can support practitioners in undertaking these steps and are provided in this chapter.

FIGURE 2: USAID'S CLIMATE-RESILIENT DEVELOPMENT FRAMEWORK



STEP 1: ESTABLISHING THE CONTEXT



The first step in the overall approach is to define the service to be delivered by the infrastructure activity in the face of future climate change. Establishing the context notably includes defining the service to be delivered by the roadway infrastructure within the context of future climate change.

DEFINING INFRASTRUCTURE OBJECTIVES

For roadway infrastructure, establishing the context notably includes gathering research and information to understand baseline and projected traffic conditions, travel patterns, and mode share usage (automobile, truck, bus, bicycle, and pedestrian). Understanding projected use can assist in determining if any changes to the target level of service may be required. Climate change can represent one of a number of influences that may affect demand for a particular service or asset, and practitioners should therefore assess the potential for changes in demand as a result of climate change risks. For example, coastal erosion or flood events may cause a gradual shift in population over time away from an area at risk due to sea level rise, and anticipated travel patterns will change accordingly.

Consideration should also be given to the broader system that the assets are integrated with. Once the scope of the assets is defined, information about the assets is needed to inform the later stages of the assessment. Typically an inventory or database is developed that contains information on each asset's criticality, function, condition, location, design and interdependences. This information may be sourced from existing asset management systems or operational staff. Site visits or physical surveys may also support this task.

UNDERSTANDING AND IDENTIFYING CLIMATE AND NON-CLIMATE STRESSORS

Gathering data and information via research will also help practitioners understand current hazards, how they may be affected by climate change, and identify relevant internal and external factors that are within or outside the control of the project team or organization.

Internal factors include objectives and criteria governing investment decisions, engineering specifications, or service delivery targets. External factors include socio-economic (financial resources, economic activities, culture and traditions, education, and socio-demographic conditions); biophysical aspects (biodiversity, geomorphology, hydrology, and soils); and institutional arrangements (governance, regulations, and stakeholder relationships among public, private, and voluntary sectors).

Most of these factors will be reviewed as part of typical planning infrastructure development activities. The additional element that must be integrated involves climate science modeling for the region to understand what the likely changes in climate variables such as rainfall patterns, extreme temperature, or storm events might be. For coastal projects, projected sea level rise and storm surge must also be reviewed.

SOURCING CLIMATE DATA

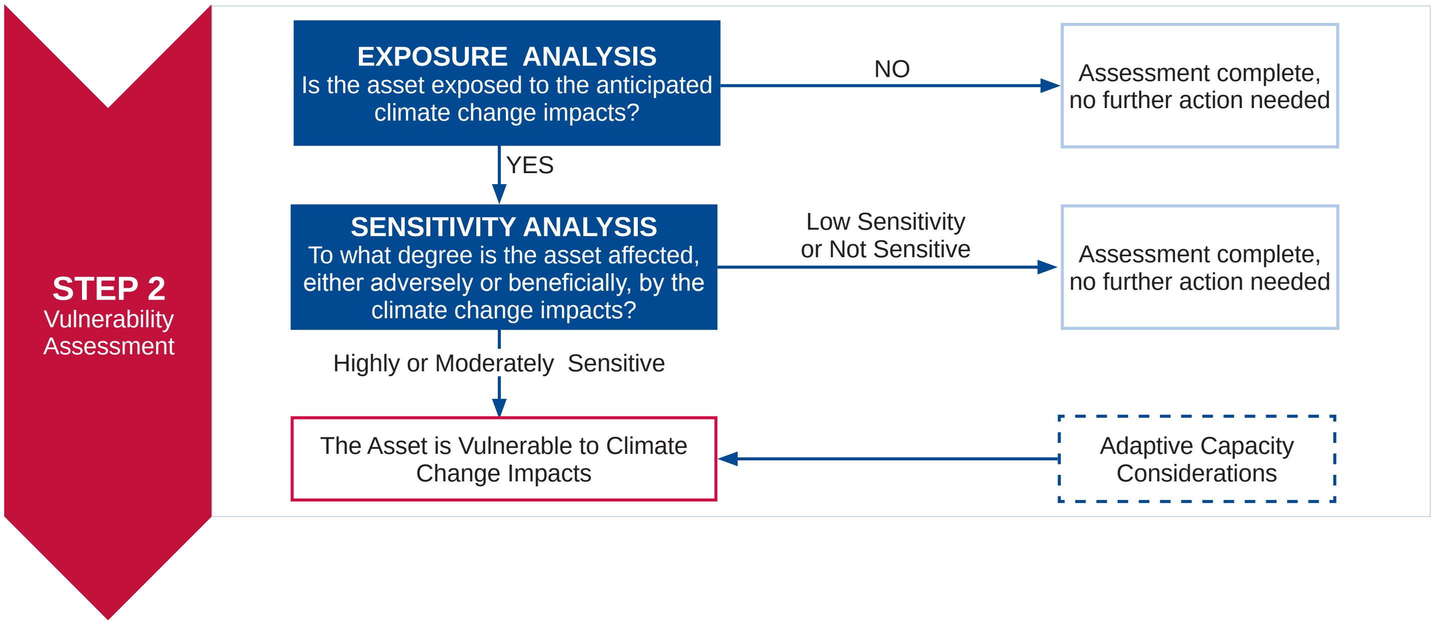
USAID development projects are undertaken in a variety of geographic settings and country contexts involving floodplains, coastal atolls, mountainous and arid regions. When evaluating climate impacts and risks to infrastructure assets, understanding the context by collecting climate data and projected trends for specific geographic locations will be a critical first step. In many developing country settings, detailed climate observations and projections may be scattered, inaccurate, incomplete, or not available. Lack of weather stations, difficulties in terrain, and inaccuracies from data collection (i.e., human error) are all factors that can create uncertainty. Practitioners can respond by making conservative estimates based on available data and source data at the regional and continental scales.

In some situations, lack of specific climate data may be overcome by consulting available data in similar parts of the region, traditional knowledge and mapping, drawing from studies conducted under similar conditions or by conducting new studies. The USAID *Overarching Guide: A Methodology for Incorporating Climate Change Adaptation in Infrastructure Planning and Design* contains additional information and guidance on climate data and trends as well as information sources that may assist with this step.


Road rehabilitation, Northwestern Rural Development Project Cambodia

AECOM

STEP 2: VULNERABILITY ASSESSMENT



CONDUCTING A VULNERABILITY ASSESSMENT

1. Analyze exposure of the asset to hazards using spatial information
2. Analyze sensitivity of the asset using a sensitivity matrix
3. Consider adaptive capacity

The second step in the overall approach considers the degree to which an infrastructure asset is susceptible when exposed to hazards identifying those that warrant more detailed investigation in Step 3. The vulnerability screening involves understanding an asset's vulnerability to specific climate change impacts over time. Climate-Resilient Development: A Framework for Understanding and Addressing Climate Change[2] defines vulnerability as a function of an asset's exposure, sensitivity and adaptive capacity to a specific climate hazard.

DETERMINING ASSET EXPOSURE

Exposure is the nature and degree to which a structure or asset is subject to a climate impact. For example, a road likely to be impacted by tidal flooding as a result of sea level rise at mid- century would be exposed to this climate impact, whereas a road that is not likely to be impacted by tidal flooding would be considered not exposed.

For each planned activity, determine whether or not it is likely to be exposed to the impacts identified in Step 1. Spatial information related to hazards will assist this process (e.g. flood hazard or other planning maps). Only those assets deemed to be exposed to particular climate change impacts identified in Step 1 should progress to the assessment of sensitivity. If an asset or project site is not exposed to climate change impacts, then the assessment is complete at this point.

DETERMINING ASSET SENSITIVITY

Sensitivity is the degree to which a system is affected, either adversely or beneficially, by climate stressors. For example, an unpaved road may be more sensitive to extreme rainfall

[2] USAID. 2014. Climate-Resilient Development: A Framework for Understanding and Addressing Climate Change, available at https://www.usaid.gov/climate/climate-resilient-development-framework.

than a paved road because it does not have the protection of a paved surface. Table 3 outlines the levels of sensitivity ranging from Not Sensitive to High Sensitivity. Using this scale, project elements that are rated as having a Moderate or High Sensitivity would be deemed vulnerable to the climate impacts associated with the relevant climate hazard and be the focus of the risk assessment. To help inform sensitivity assessments, Table 4 provides a summary of the likely sensitivity of different types of infrastructure to different climate hazards.

TABLE 3: LEVELS OF SENSITIVITY TO CLIMATE CHANGE IMPACTS

Level of Sensitivity	Definition
NOT Sensitive	• No infrastructure service disruption or damage
LOW Sensitivity	• Localized infrastructure service disruption; no permanent damage • Some minor restoration work required
MODERATE Sensitivity	• Widespread infrastructure damage and service disruption requiring moderate repairs • Partial damage to local infrastructure
HIGH Sensitivity	• Permanent or extensive damage requiring extensive repair

Moderate or high sensitivity impacts are considered vulnerable and should be the focus of the risk assessment.

TABLE 4: LIKELY SENSITIVITY TO CLIMATE CHANGE IMPACTS

THEME	PROJECT	Extreme Heat	Drying Trend/ Dought	Extreme Precipi-tation/ Flooding	Storm Surge	Sea Level Rise	Damaging Storms (wind, lightning, snow/ice)	Wildfire
Coastal Roadways	Paved Road Concrete			MODERATE	MODERATE	MODERATE		
	Paved Road Asphalt	LOW		HIGH	HIGH	HIGH		LOW
Inland Roadways	Paved Road Concrete			MODERATE				
	Paved Road Asphalt	LOW		HIGH				LOW
	Unpaved Road			HIGH				MODERATE

NOT Sensitive | LOW Sensitivity | MODERATE Sensitivity | HIGH Sensitivity

ASSESSING ADAPTIVE CAPACITY

Following the determination of an asset as vulnerable, practitioners may also consider the adaptive capacity of the infrastructure system. This step is not critical to the vulnerability screening process, however, it may provide useful information to inform the consequence discussion in Step 3.

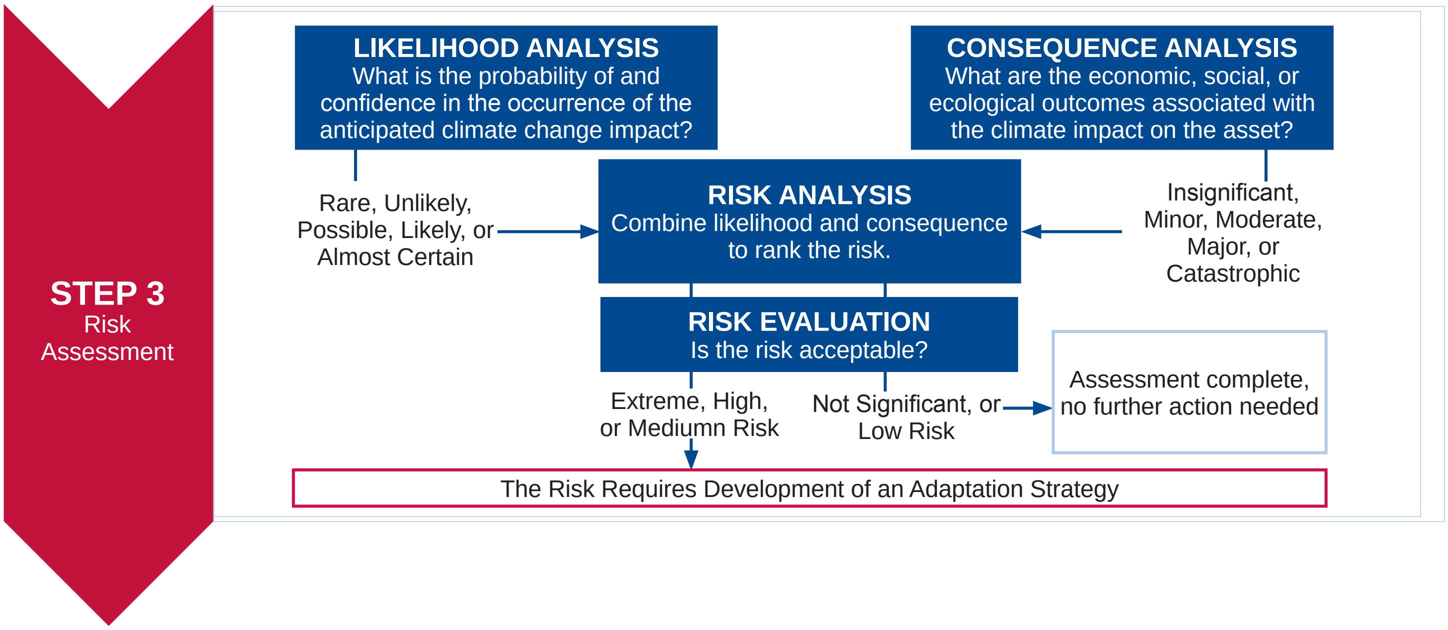
Adaptive capacity is generally considered as a social component when working with soft infrastructure. When working with built or hard infrastructure, adaptive capacity refers to the ability to anticipate, prepare, and recover from climate impacts.

From a system perspective, this may be assessed by looking at core economic drivers in-country (or in similar contexts if not readily available), such as access to health services and education, resource strength in terms of wealth and human, strength of networks, institutions leadership, and disaster response mechanisms. Focusing on specific infrastructure, consideration may be given to the potential for supplementary capacity (e.g. redundancy provided by alternative transportation routes), likely duration of a disruption to service or the duration of repairs to return an asset to operation.

A road rehabilitation project in Kiribati focused on rehabilitating the main road on Tarawa, but also used a coastal assessment to identify areas vulnerable to erosion where coastal protection structures would be required.

SCOPE GLOBAL DFAT KIRIBATI ROAD REHABILITATION

STEP 3: RISK ASSESSMENT



CONDUCTING A RISK ASSESSMENT

1. Define the likelihood of climate impacts occurring
2. Understand the consequences of climate impacts
3. Conduct a risk analysis and develop a risk rating matrix
4. Accept the appropriate level of risk and adaptation needs

The third step of the approach enables practitioners to consider risks once the vulnerability of an asset or project has been established. A risk assessment provides an analytical framework with qualitative descriptors for likelihood and consequences in a resulting risk matrix. Only those assets that have been identified as vulnerable in Step 2 need to be analyzed for risk.

Risks are often expressed as the combination of the consequences of an event and the associated likelihood of it occurring:

RISK = CONSEQUENCES x LIKELIHOOD

This approach is aligned with traditional risk management principles (e.g. ISO 31000:2009 *Risk management—Principles and guidelines*). Exposure and sensitivity data gathered in Step 2 can be used to inform the rating of likelihood and consequences.

LIKELIHOOD OF CLIMATE IMPACTS

Table 5 provides examples of qualitative definitions that can be used to characterize the likelihood of a risk occurring. The probability of a risk occurring is often described in qualitative terms. Only when there is sufficient data and capability can a quantitative description of likelihood be made, where the time horizon is the life of the asset.

The level of certainty in determining the likelihood of a climate impact largely depends on the scale and certainty that the climate modeling exercise will yield (e.g., more frequent heat waves), changes in hydrological patterns (e.g., recurring floods), variations in coastal environments (e.g., sea level rise), and climate-driven gravitational hazards (e.g., higher frequency of rock falls, mudslides and avalanches).

Regional models will likely yield more precise results with a smaller range of projections, providing greater certainty. Assumptions regarding uncertainties associated with the model, or a hypothesis when modeling is not possible, should be clearly articulated.

TABLE 5: EXAMPLE OF QUALITATIVE DEFINITIONS OF LIKELIHOOD

Level of Likelihood		Definition
5	**Almost Certain**	More likely than not, probability greater than 50%
4	**Likely**	As likely as not, 50 / 50 chance
3	**Possible**	Less likely than not but still appreciable, probability less than 50% but still quite high
2	**Unlikely**	Unlikely but not negligible, probability low but noticeably greater than zero
1	**Rare**	Negligible, probability very low, close to zero

CONSEQUENCES OF CLIMATE IMPACTS

It is important to understand the consequences associated with an asset being impacted by a climate hazard. In some instances, the consequences can be very specific and defined for each sub-component of a large infrastructure system. Defining consequences is ideally done in a workshop setting with key stakeholders to identify important criteria to be used to assess consequences. There may be one or several criteria used, depending on the project. Examples of consequence criteria which could be considered are listed below. Table 6 provides example definitions for rating each consequence criteria.

- **Asset Damage.** Damage Damage requiring minor restoration or repair may be considered minor while permanent damage or complete loss of an asset would be considered to be a significantly higher consequence.
- **Financial Loss.** A high repair or capital replacement cost would be of major consequence compared to a cheaper repair or replacement cost.
- **Loss of Service.** As an example, a water system serving a large-scale industry with high water use requirements would be of major regional consequence compared to one serving a small-scale industry using less water.
- **Health and Safety.** A system serving a large number of people would be of major consequence compared to a system serving a smaller number. Casualties or other acute public health consequences would weigh more heavily.
- **Environmental Considerations.** Damage to a wastewater system adjacent to a local drinking water source, for example, would be of major polluting consequence compared to a system isolated from a local water source.
- **Reputation.** Loss of service, health or environmental impacts may affect the reputation of the responsible agency.

TABLE 6: EXAMPLE DESCRIPTOR FOR CONSEQUENCES

Level of Likelihood		Definition
5	Catastrophic	• **Asset Damage:** Permanent damage and / or loss of infrastructure. • **Loss of Service:** Widespread and extended (several weeks) interruption of service of the agreed Level of Service; result in extreme contractual penalties or contract breach. • **Financial Loss:** Asset damage > annual maintenance budget or 75% of CAPEX value. • **Health / Safety:** Substantial changes to the health and safety profile; risk of multiple fatalities as a result of extreme events. • **Reputation:** Irreversible damages to reputation at the national and even international level / Public outrage.
4	Major	• **Asset Damage:** Extensive infrastructure damage requiring extensive repair / Permanent loss of local infrastructure services. • **Loss of Service:** Widespread and extended (several days) interruption of service for less than 50% of the agreed Level of Service; result in severe contractual penalties. • **Financial Loss:** Asset damage 50%+ of annual maintenance budget or 25% of CAPEX value. • **Health / Safety:** Marked changes in the health and safety profile, risk of severe injuries and even fatality as a result of extreme events. • **Reputation:** Damage to reputation at national level; adverse national media coverage; Government agency questions or enquiry; significant decrease in community support.
3	Moderate	• **Asset Damage:** Damage recoverable by maintenance and minor repair / Partial loss of local infrastructure. • **Loss of Service:** Widespread interruption of service for less than 20% of the agreed Level of Service; result in minor contractual penalties. • **Financial Loss:** Asset damage > 10% but < 25% of annual maintenance budget or 5% of CAPEX value. • **Health / Safety:** Noticeable changes to the health and safety profile, risk of severe injuries as a result of extreme events. • **Reputation:** Adverse news in media / Significant community reaction.
2	Minor	• **Asset Damage:** No permanent damage / Some minor restoration work required. • **Loss of Service:** Localized interruption of service for less than 10% of the agreed Level of Service. • **Financial Loss:** Asset damage > 5% but < 10% of annual maintenance budget or 1% of CAPEX value. • **Health / Safety:** Slight changes to the health and safety profile; risk of minor injuries as a result of extreme events. • **Reputation:** Some adverse news in the local media / Some adverse reactions in the community.
1	Insignificant	• **Asset Damage:** No infrastructure damage. • **Loss of Service:** Localized interruption of service for less than 1% of the agreed Level of Service (LoS). • **Financial Loss:** Asset damage < 5% of annual maintenance budget or negligible CAPEX value. • **Health / Safety:** Negligible or no changes to the health and safety profile or fatalities as a result of extreme events. • **Reputation:** Some public awareness.

CONDUCTING A RISK ANALYSIS

Once the likelihood and consequence are defined, the risk level is determined by multiplying the likelihood value by the consequences value to result in a score from 1 (Low) to 25 (Extreme). Generally, the resulting score will be assigned one of five levels of risk: Not Significant, Low, Medium, High, or Extreme (Table 7).

TABLE 7: RISK RATING MATRIX

Level of Risk		Consequence Level				
		Insignificant (1)	Minor (2)	Moderate (3)	Major (4)	Catastrophic (5)
Likelihood Level	Almost Certain (5)	Medium (5)	Medium (10)	High (15)	Extreme (20)	Extreme (25)
	Likely (4)	Low (4)	Medium (8)	High (12)	High (16)	Extreme (20)
	Possible (3)	Low (3)	Medium (6)	Medium (9)	High (12)	High (15)
	Unlikely (2)	Low (2)	Low (4)	Medium (6)	Medium (8)	Medium (10)
	Rare (1)	Not Significant (1)	Low (2)	Low (3)	Low (4)	Medium (5)

TABLE 8: EXAMPLE RESPONSES AND ACCEPTABILITY FOR DIFFERENT LEVELS OF RISK

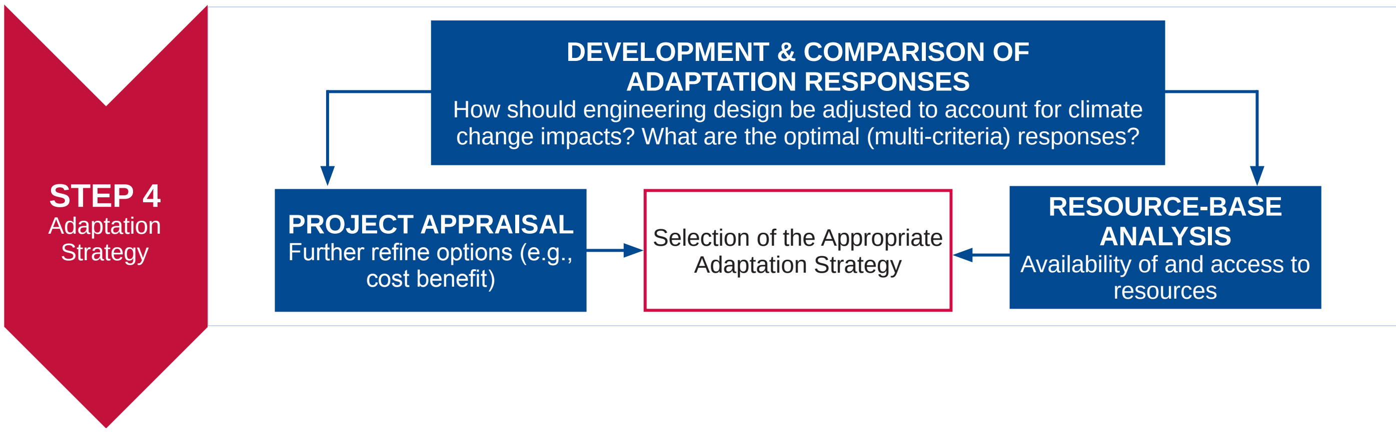
Level of Risk	Definition
EXTREME ≥ 20	• Extreme risks demand urgent attention at the most senior level and cannot be simply accepted as a part of routine operations • These risks are not acceptable without treatment
HIGH 12-16	• High risks are the most severe that can be accepted as a part of routine operations without executive sanction, but they are the responsibility of the most senior operational management and reported upon at the executive level • These risks are not acceptable without treatment
MEDIUM 5-10	• Medium risks can be expected to form part of routine operations, but they will be explicitly assigned to relevant managers for action, maintained under review and reported upon at the senior management level • These risks are possibly acceptable without treatment
LOW ≤ 4	• Low risks will be maintained under review, but it is expected that existing controls will be sufficient and no further action will be required to treat them unless they become more severe • These risks can be acceptable without treatment

DETERMINING RISK ACCEPTABILITY AND THE NEED FOR ADAPTATION

Based on the outcomes of the risk analysis, it is necessary to determine and prioritize those risks requiring treatment with appropriate adaptation measures. Risk acceptability criteria need to be defined (refer to Table 8) to guide the determination of which risks are determined to be acceptable and the most significant risks requiring treatment (i.e. adaptation planning).

Often the risk evaluation is led by a project funder or leader, rather than the technical staff who lead the risk analysis. Decisions on risk treatment should take into account the acceptability of external stakeholders that are likely to be affected.

STEP 4: DEVELOPING AN ADAPTATION STRATEGY



DEVELOPING AND SELECTING AN ADAPTION RESPONSE

1. Identify potential adaptation solutions

2. Conduct project appraisal (e.g., CBA) to further refine and generate a shortlist of adaptation options

3. Consider the availability and access to resources, human and material

4. Develop the adaptation strategy with the identified adaptation solutions

Once the degree of vulnerability has been established and the most critical risks have been identified, a decision can be made regarding how to address the risks. A range of appropriate adaptation strategies are available when preparing for and adapting to climate change impacts. Selection of a strategy is dependent on a number of factors, including location, temporal scale, and the specific impacts faced.

Understanding the available resource base to implement the infrastructure activity will also be important. While some adaptation options may require little resources (e.g., training or monitoring) others may prove more cost-intensive.

Four generally accepted types of adaptation responses that can be implemented include: 1) accommodate and maintain; 2) harden and protect; 3) relocate; and 4) accept or abandon. These strategies can help categorize various adaptation responses for new and existing infrastructure (Table 9) and understand the various advantages and disadvantages of selected responses (Table 10).

Examples of adaptive engineering design options specific to roadway infrastructure are provided in Table 11, with additional detail provided in the Annex.

SHORT-LISTING OF ADAPTATION SOLUTIONS

Once a range of possible adaptation options has been identified, they should be prioritized to create a shortlist of the most appropriate options for implementation. A number of approaches are available, including decisions strictly based on best judgment and not including detailed analysis and justification. Common approaches to shortlist options include the use of a Multi-Criteria Analysis (MCA) or applying an economic analysis, such as Cost-Benefit Analysis (CBA), to further refine and prepare for implementation. An example of a completed MCA is included in the companion document: *Overarching Guide: A Methodology for Incorporating Climate Change Adaptation in Infrastructure Planning and Design*.

TABLE 9: APPROACH TO ADAPTATION STRATEGIES

Strategic Approach		Adaptation Strategy	
		Existing Infrastructure	New Infrastructure
1	Accommodate and Maintain	• Extend, strengthen, repair or rehabilitate over time • Adjust operation and maintenance	• Design and build to allow for future upgrades, extensions or regular repairs
2	Harden and Protect	• Rehabilitate and reinforce • Add supportive or protective features • Incorporate redundancy	• Use more resilient materials, construction methods, or design standards • Design for greater capacity or service
3	Relocate	• Relocate sensitive facilities or resources from direct risk	• Site in area with no, or lower, risk from climate change
4	Accept or Abandon	• Keep as is, accepting diminished level of service or performance	• Construct based on current climate, accepting possibly diminished level of service or performance

TABLE 10: ADVANTAGES AND DISADVANTAGES OF ADAPTATION APPROACHES

Strategic Approach		Advantages	Disadvantages
1	Accommodate and Maintain	• Less costly • More pragmatic and flexible, allows adjustment over time as more climate change data becomes available	• Requires monitoring, possibly frequent repairs, adjustments, or more rigorous operations • Necessitates design for more flexible or upgradeable structure
2	Harden and Protect	• Proactive • Straightforward to implement and justify	• More costly • Assumes reasonably accurate climate forecasts
3	Relocate	• Proactive	• More costly • Sub-optimal location may decrease period of performance or service
4	Accept or Abandon	• No extra up-front cost	• Proper communications needed to inform decision-makers and beneficiaries to expect lower performance or service

TABLE 11: EXAMPLES OF ENGINEERING ADAPTATION OPTIONS FOR CLIMATE RESILIENT ROADWAY INFRASTRUCTURE

Climate Drivers	Adaptation Measures
 Extreme Precipitation Events, Flooding	• Alter maintenance regimes to target vulnerable sections of transport systems • Size drain and stormwater systems for new infrastructure with a consideration of climate change projections. If no projections are available, include a precautionary overestimation in the design to provide a safety buffer • Retrofit existing stormwater infrastructure (e.g. culvert crossings, bridges) to accommodate increasing flow patterns) • Harden or stabilize slopes subject to increased run off from extreme weather events • Elevate mechanical and electrical equipment in operations or maintenance facilities (e.g. traffic signals) • Use waterproof materials
  Sea Level Rise and Storm Surge	• Raise elevation of roadway or bridge touchdown on embankments or levees • Construct causeway • Elevate mechanical and electrical equipment in operations or maintenance facilities (e.g. traffic signals) • Increase capacity of stormwater drainage system and increase drainage maintenance at flooding hotspots • Use corrosion-resistant or waterproof materials (adapting different pavement mixture design can improve resistance to water damage - compared with concrete pavement, asphalt pavement material is generally less resistant to water damage)
 Extreme Heat	• Confirm capability of current heat-resistant road materials and, if necessary, use more heat tolerant binders and materials
 Wildfires	• Maintain and implement vegetation management practices that minimize fire risk

STEP 5: IMPLEMENTATION

IMPLEMENTING THE ACTIVITY

1. Provide on-going monitoring and evaluation to consider change in risk status.

2. Identify and develop best practice examples to integrate into future design processes.

3. Conduct consultation and transparent communication with all stakeholders involved to promote buy-in and better understanding of local context.

Implementation of climate change adaptation programs may be defined solely as an engineering program, but will likely be part of a larger program that includes planning and zoning, government and stakeholder buy-in, and many other complex factors.

MONITORING AND EVALUATION

Most projects and programs include monitoring and evaluation activities that can be adjusted to cover climate change risks. If feasible, embedding climate change risks in an existing monitoring and evaluation framework is the preferred approach, rather than developing a stand-alone climate change risk monitoring and evaluation framework.

Ongoing monitoring and evaluation activities can help consistently adjust the risk assessment and management approach, and support development of risk treatments that are effective, contribute to improvements in risk understanding, detect changes in external and internal conditions, and identify emerging risks.

Monitoring and evaluation should be based on robust and simple to measure quantitative and qualitative indicators. Careful consideration should be given to the cost efficiency and ease of measurement for the proposed measures. Information can be collected and analyzed through both participatory and external evaluation. Local communities can take a very active role in monitoring tasks.

IMPLEMENTING BEST PRACTICES

Monitoring and evaluation provides organizations with an opportunity to identify susceptible to climate change impacts and better inform future asset planning. For example, asset condition deterioration profiles may change where assets are exposed to more extreme conditions.

Climate change adaptation is an emerging field, so implementation is also experimentation in some cases. Both successes and failures should be reported and documented to build a community of practice so that climate change adaptation strategies improve over time and practitioners become more conversant in implementing such strategies.

COMMUNICATION AND CONSULTATION

Climate change risk communication activities should ideally form part of the overarching outreach and communications plan for each infrastructure asset.

Communication and consultation should ideally take place during all risk management activities. A robust and consistent communications plan including consideration of potential climate change risks and selected adaptation options should be developed in close collaboration with implementing partners and stakeholders. A communication plan should outline how the findings of the analysis will be made accessible to support decision making and general awareness raising for both technical and non-technical audiences.

Different target groups (e.g., government agencies, businesses, communities, and women and children) and different communication vehicles (e.g., workshops, reports, animations, summary sheets, and fact sheets) should be considered. Ongoing communication and consultation activities can support the development of appropriate objectives and understanding of the local context, help ensure that climate risks are correctly identified, and help build consensus among stakeholders on the findings of the risk assessment and the risk treatment selected for implementation.

DeNatale, AECOM


AECOM KIRIBATI

CLIMATE RESILIENT INFRASTRUCTURE DESIGN - TIMOR-LESTE AND THE REPUBLIC OF KIRIBATI

CASE STUDY

Roads are vulnerable to climate risks, and these risks will increase due to climate change. The main threats come through an increase in extreme rainfall and storm events (which can cause washouts or landslides that damage or destroy road sections), and from sea level rise (which will worsen damage from storm surge and coastal flooding and may eventually lead to permanent inundation). Other potential effects include increased damage to road surfaces through buckling from extreme heat, damage to road structures built in permafrost areas due to temperature changes, and accelerated corrosion and degradation of road infrastructure due to increased salinity, but these are likely of secondary concern. The largest impacts will be for roads in upland areas with steep topography, and for coastal roads in areas vulnerable to storm surge.

Managing climate risks has long been part of best practice in roadway design. Damage from storms and flooding can be reduced through physical measures (including structural drainage and protective measures, and bio-engineering options including vegetation of slopes to aid stabilization and run-off management) and through improved capacity (including road maintenance, land management, warning systems, and emergency response systems). The cost-effectiveness of particular measures may be challenging to quantify because the near- and long-term climate changes vary widely depending on topography, climate, and other factors.

Design features of roads have different operational lifespans, hence different sensitivities to projected changes in climate. Assets with short operational lives should be designed with current climate variability in mind. For instance, pavement standards or embankment height can be readjusted to reflect near time climate projections and traffic conditions when a road segment is rehabilitated (typically every 20 years). Longer lived and more inflexible assets include drains, culverts, and bridges. These assets require consideration of longer-term climate change projections that reflect their operating lifetime. Planning decisions should also consider climate risks, for example decisions regarding routing of roadway systems can affect the location and scale of development patterns for many decades and can therefore lock in exposure to climate risks.

Adaptive management and targeted improvements may be more efficient than immediate or blanket techniques. For example, an analysis of road options in Mozambique that accounted for climate change compared and contrasted a strategy of adaptive management—gradually rehabilitating existing roads and building new roads to higher standards as climates changes—to a strategy of immediate and general upgrading, and found that the adaptive option is more cost-effective. Targeted upgrading for particular flood-prone areas was more efficient than a blanket increase in standards. An adaptation policy of gradual evolution towards road designs that accommodated higher temperatures and followed rainfall trends (wetter or dryer) improved outcomes. At the same time, a generalized policy of upgrading all roads did not appear to be effective. For more information refer to the 2011 case study titled *Climate Change and Infrastructure Investment in Developing Countries: The Case of Mozambique*[6].

The following two case studies highlight additional examples of how climate resilience has been considered in road projects in Timor Leste and the Republic of Kiribati.

TIMOR-LESTE

Timor-Leste is a small and mountainous island country surrounded by Indonesia, with a population of about 1 million. It has a dramatic topography dominated by the Ramelau Mountains stretching across the middle of the island from the east to the west. About 44 percent of the Timor-Leste's total land area lies between 100 and 500 meters in elevation, and 35 percent above 1,000 meters[7].

[6] Arndt, Chinowsky, Strzepek and Thurlow. 2011. Climate Change and Infrastructure Investment in Developing Countries: The Case of Mozambique. UNU-WIDER Working Paper 92, available at http://www.wider.unu.edu/publications/working-papers/2011/en_GB/wp2011-092/
[7] World Bank, 2010. Building Climate Resilience into Timor Leste's Roads, available at: http://blogs.worldbank.org/transport/building-climate-resilience-into-timor-leste-s-roads

A climate resilient road project in Timor-Leste emphasized the need for sufficient drainage, noting that 80 percent of roads were in poor or very poor condition, largely due to landslides, floods, and insufficient maintenance and drainage capacity[8]. A climate change impact assessment study found that there would likely be fewer but more extreme rainfall events[9], which would increase the stress on already insufficient road infrastructure. The primary component of the project supported urgent road repairs followed by a program of road improvements involving construction of slope stabilization structures and drainage structures.

Traditionally, the response to hazards such as flooding and landslides has been to design and provide additional or reinforced engineering structures such as enhanced drainage, culverts, higher bridges and re-aligned road sections. However, it is recognized that re-vegetation and bioengineering measures for water courses and road slopes are key to implementing a lasting solution.

Bio-engineering improves slope stability, controls stormwater and sediments, and helps absorb pollutants through natural processes. There are a variety of measures that can be applied including tree and shrub planting on unstable slopes, and the use of vegetated erosion control blankets which are natural fibers able to retain soil and sediments while providing a medium for planting shrubs. The goal is to increase water retention capacity and infiltration through natural or bio-engineered systems.

There is a need for civil engineering measures—such as providing sufficient capacity longitudinal and transverse drainage, as well as improved retaining walls, gabions (i.e., stone filled nettings)—but without bio-engineering measures they are only partial solutions. The Timor-Leste government is taking steps to address the issues. Several projects have been constructed that incorporate durable gabions.

The photos illustrate the types of issues in the country. With the likelihood of more rain, with higher intensity, it is necessary to take steps to build some resilience into Timor-Leste's roads.

[8] AUSAID, 2012. Roads for Development – Project Document, available at: http://www.ilo.org/jakarta/whatwedo/projects/WCMS_184617/lang--en/index.htm
[9] World Bank, 2010. Building Climate Resilience into Timor Leste's Roads, available at: http://blogs.worldbank.org/transport/building-climate-resilience-into-timor-leste-s-roads

A major benefit from constructing stone retaining walls, gabions and stone drainage is that it creates work for local communities. This can provide much needed stimulus and support to the local economy. The International Labor Organization has been working on labor-based methods for road construction in Timor-Leste.

Timor-Leste is an example of building resilience into road networks to better cope with rainfall and the potential future climate changes. Relatively modest investments yielded major benefits not only in keeping roads open, but in saving on potentially large future maintenance or rehabilitation investments.

REPUBLIC OF KIRIBATI

Kiribati is at the front line of climate change with its highest point just three meters above sea level[10]. Based on current climate change projections, Kiribati may be uninhabitable by 2030 as a result of coastal erosion, sea level rise and saltwater intrusion into drinking water[11].

The East Asia Pacific region's communities in the atoll of South Tarawa (the capital of the Republic of Kiribati) are linked by a single main road and four causeways. As a result, nearly the entire population depends on the main road. The road system consists of about 36 km of sealed roads and causeways, 20 km of secondary roads – only half of which are sealed – and 40 km of unsealed feeder roads. Around 29km of paved roads have not received any sort of major maintenance for more than 20 years[12]. Kiribati's Road Rehabilitation Project helps to restore South Tarawa's main road so that it can be maintained more easily, including development of proper drainage systems. Plans have been established to manage the impact of natural disasters on the road. A restored road results in better access to schools and hospitals, and communities are better connected to one another.

Access to safe drinking water, and safe access to power are other immediate concerns for the people of Kiribati. Several kilometers of damaged water mains and installation of supporting infrastructure are being implemented parallel to the roadway rehabilitation projects.

Recognizing that it is not realistic to avoid all road damage, the project design included performance-based contracts for long-term road maintenance, and supported design and pilot implementation of emergency response systems to undertake rapid repairs after a storm. The road rehabilitation project in Kiribati focused on rehabilitating the main road on Tarawa, but also used a coastal assessment to identify areas vulnerable to erosion where coastal protection structures would be required. New roads in South Tarawa have also been designed to be more resilient to rising sea levels and tidal flows.

For further information see:

http://aid.dfat.gov.au/countries/pacific/kiribati/Pages/initiative-road-rehabilitation.aspx; and http://www-wds.worldbank.org/external/default/WDSContentServer/WDSP/IB/2014/09/26/000371432_20140926131515/Rendered//910240ISDS01400Box385335B00PUBLIC0.pdf

Example of gabion structure made of natural materials

[10] The Brooking institution – London School of Economics, 2011. On the Frontline of Climate Change and Displacement: learning from and with Pacific Island countries, available at http://www.brookings.edu/~/media/research/files/reports/2011/9/idp-climate-change/09_idp_climate_change.pdf

[11] Pacific Climate Change Science (PCCS), 2011. International Climate Change Adaptation Initiative: Current and Future Climate of Kiribati, available at: http://www.pacificclimatechangescience.org/wp-content/uploads/2013/06/11_PCCSP_Kiribati_8pp.pdf

[12] World Bank, 2011. *Kiribati Road Rehabilitation Project: Project Information Document*, available at: http://www-wds.worldbank.org/external/default/WDSContentServer/WDSP/IB/2013/07/25/000001843_20130726103021/Rendered/PDF/130070250P1440990KRRP0AF0PID0Final.pdf

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ROADWAY CLIMATE CHANGE ADAPTATION STRATEGIES

ANNEX

INTRODUCTION

This Annex, *Roadways Climate Change Adaptation Strategies*, is a companion to *Roadways: A Methodology for Incorporating Climate Change Adaptation in the Engineering Design of Infrastructure*. More details, including the advantages and disadvantages of various adaptation strategies, are discussed in this document. Practitioners, engineers and other stakeholders will find the components to develop a preliminary cost estimate that is valid for a proposed project. Other aspects, such as technical feasibility and schedule, are also discussed in this Annex.

There are many comprehensive solutions and adaptation options that address climate change. Some involve technology or innovative and detailed design, while others involve the use of different materials. All options have their advantages and disadvantages, for instance: concrete is less sensitive to climate change effects, but harder to maintain. Some adaptation options may involve a substantial one-time, capital expenditure (CAPEX), whereas a number of solutions require incremental increase in normal business operational expenditures (OPEX). Some adaptation options may involve a substantial one-time, capital cost, whereas a number of solutions require incremental increase in normal business operational expenditures. Nonetheless, all strategies are intended to assist with decision-making for climate-proofing roadway infrastructure.

Climate change adaptation strategies are an evolving and dynamic domain, with best practices and as-built case study examples being refined globally in multiple environments and contexts. This Annex is not intended to be exhaustive. If there is a strategy or approach that you think merits more discussion in this Annex, please send your ideas to climateadapteddesign@usaid.gov. We would like to consider user comments and recommendations in our next revision.

CONTENTS

INFRASTRUCTURE DESIGN AND MATERIALS

TABLE A.1: MAKE GREATER USE OF CONCRETE

Overview	
	Concrete (a cement-based material) is a versatile and commonly used construction material that has many benefits, which include the ability to resist high temperatures. With the appropriate aggregate type included in the mix, concrete pavements provide thermal stability and are able to withstand extreme hot climatic conditions, and generally have the advantages of being durable and having a long service life. Since concrete pavement mixture can be made with a wide range of materials, including different aggregates and cement binders, this feature makes it an adaptable material suitable for use in hot climates. The use of roller-compacted concrete uses less cement as a binding agent.
Advantages	• Ability to resist high temperature • Longer service life • Requires less maintenance and repair compared to asphalt, which results in lower operational cost • By reflecting sunlight rather than absorbing it, it reduces “heat island” effect experienced in urban areas
Disadvantages	• More difficult to perform maintenance and repair than for asphalt pavements • Longer road closure if maintenance and repair are required, due to longer cure time for concrete • Higher capital, up-front cost
Indicative Costs	• Purchase of concrete pavement material including aggregates and binders
Timing for Implementation	• Several days to weeks will be added to the construction schedule if asphalt is replaced by concrete
Governance	• None
Acceptability	• High
Feasibility and Technical Requirement	• To produce a correct concrete pavement mixture, knowledge of local conditions, concrete, cement material properties, supply vendors in the area that can provide the material, and knowledge in road design is needed. A trained engineer is preferred

TABLE A.2: CONCRETE PAVEMENT, REDUCE THE AMOUNT OF WATER IN MIXTURE

Overview	
	If concrete is chosen as the pavement material, changing the design of the concrete pavement mixture to reduce the amount of water required can strengthen the pavement, and increase resistance to weathering. However, too little water can destroy the chemistry of the mixture. Reducing the amount of water in the mixture increases the density and durability of the material but lowers its permeability properties.
Advantages	• Stronger and more durable concrete pavement
Disadvantages	• Reduce workability • Lowers permeability
Indicative Costs	• No direct additional cost
Timing for Implementation	• No additional time needed compared to typical pavement construction schedule
Governance	• None
Acceptability	• High acceptability for lower trafficked roadways
Feasibility and Technical Requirement	• Trained worker and vendor supplier of material available in the area to ensure the right amount of water and aggregate is contained in the concrete mixture

TABLE A.3: USE OF WATER RETENTION PAVEMENTS

Overview	
	Water retention within a permeable surface pavement was initially developed in Japan as a solution to reduce the “heat island” effect. However, it has proved to have the ability to resist rutting, which is a common form of pavement degradation in hot climates. This type of pavement is porous asphalt pavement with the voids filled with water-retaining materials. Because water is retained within the pavement, when water is evaporated, water draws heat from the surrounding materials and therefore reduces pavement temperature. For more information refer to Namikawa,Y., A Small-scale Field Experiment of Continuous Water Retaining Pavement System available at www.recwet.t.u-tokyo.ac.jp/furumailab/crest/workshop05/june10am_3.pdf
Advantages	• Self-cooling system utilizing the mechanism of evaporation • Effective in lowering pavement temperature and resisting rutting, as well as reducing “heat island” effect in urban areas • Reduce surface runoff, which can reduce the frequency of flooding
Disadvantages	• Traffic restrictions may be needed • Possibly higher CAPEX because of the required water- retention material • Possibly higher OPEX from more frequent maintenance
Indicative Costs	• Cost of water-retention material plus typical cost for road pavement
Timing for Implementation	• No additional time to typical pavement construction schedule
Governance	• None
Acceptability	• High level of acceptability due to limited disturbance to road users
Feasibility and Technical Requirement	• Requires understanding of the proper design and application of water retention pavements

TABLE A.4: IMPROVE THE REFLECTANCE OF THE PAVEMENT SURFACE

Overview	
	Improve solar reflectance of pavement surface for roadways or surface parking lots can be done by using lighter color pavement materials such as concrete, instead of asphalt, or by applying a spray-on or isothermal protective coating. An innovative technology, which is currently fairly widespread, utilizes a spray-on coating that has a higher reflectivity for near infrared rays and lower reflectivity for the visible rays. The spray-on coating helps reduce the ability of the pavement surface to absorb infrared rays and consequently reduces pavement temperature.
Advantages	• Can be applied on existing infrastructure • Provides ultraviolet weathering resilience • Can cover a large area, such as a parking lot
Disadvantages	• Limited to smaller scale application (e.g, a parking lot) and not for entire roadway • Increase in CAPEX • Technology is fairly new, therefore cost may be prohibitive • Increased in OPEX, as may need to reapply periodically to maintain effectiveness
Indicative Costs	• Cost for spray-on coating
Timing for Implementation	• Immediately
Governance	• Consultation with responsible government to discuss financial feasibility of technology as it may not be cost-effective in all circumstances
Acceptability	• High acceptability if application is cost-effective; otherwise, low acceptability to the public and government
Feasibility and Technical Requirement	• Vendor access of right materials, and technical expertise needed for application and maintenance

TABLE A.5: CONVERT UNPAVED ROADS INTO PAVED ROADS

Overview	
	Unpaved roads are constructed of a variety of native and sub-grade materials. These roads are very common as secondary roads and circulator roads in developing countries. They generally have lower construction cost than paved roads, but they may require higher maintenance costs. If left unmaintained, damages will eventually result in unstable roads that perform very poorly. Unpaved roads often become inaccessible after extreme weather events. Converting unpaved roads into paved roads will improve their performance and stability, which will increase their ability to withstand extreme weather events and remain accessible during emergency situations.
Advantages	• Paved roads are more reliable and stable than unpaved roads • Safety is improved and better access provided for emergency vehicles • May maintain accessibility during extreme weathers events • Requires less maintenance
Disadvantages	• High CAPEX cost to convert unpaved roads to paved roads • May not be economically justified for low usage roads • Stormwater management required as the extent of impervious surface area increases
Indicative Costs	• Cost associated to construct paved roads, including labor, materials and time
Timing for Implementation	• Time-frames highly dependent on the urban context, length, elevation, and soil conditions of specific road • Can take several months to years
Governance	• Consultation with local government and community to understand the need for paved roads as improvement to travel origins and destinations • Conduct comparative cost-benefit and life-cycle analysis to determine if unpaved roads should be converted into paved roads; or simply schedule more frequent maintenance
Acceptability	• High acceptability to public as paved roads are safer and more comfortable for walking or bicycling • Low to moderate acceptability to government, primarily due to cost
Feasibility and Technical Requirement	• Engineering expertise to design and skilled and unskilled labor to undertake construction and maintenance

TABLE A.6: ADJUSTMENT OF PAVEMENT DESIGN

Overview	
	There are a number of design adjustments that can be incorporated into a pavement to improve its resistance to water and moisture damage. Concrete pavement materials are generally expected to be more resistant to water damage than asphalt. However, if asphalt pavement is preferred over concrete pavement, the use of different additives and fillers can increase water resistance in bituminous pavements, for example: • Liquid anti-stripping, such as latex polymers along with amines and polyamines agents, can be used to resist stripping damages caused by water or moisture. Latex polymers are chemical compounds that will tend to bond with water and keep it from disrupting the binder-aggregate bond; and • Hydrated lime is also a commonly used additive to resist water damages. The gradation of an asphalt mixture can also have a significant impact on how a pavement handles moisture. Pavement can be impermeable to water if a dense-graded mix is used and compacted to a sufficient density. Alternatively, if an open-graded mix is used, then pavement can be designed to absorb water and infiltrate it in the subgrade. Permeable pavements have the benefits of reducing splash and standing water in wet conditions. However, a drainage system must be incorporated into permeable pavement design to ensure proper drainage if the native soils below the permeable pavement system does not have sufficient hydraulic capability to recharge the entire volume of precipitation.
Advantages	• Some design adjustments may not require additional funding, for instance, using concrete pavement materials instead of asphalt pavement materials do not require increased CAPEX or OPEX for the subgrade materials. Concrete pavements are slightly more costly than asphalt pavements • Relatively easy to implement as some options are already commonly used best-practices • Adjustments generally increase or sustain the service life of a pavement and reduce the frequency of maintenance need
Disadvantages	• Some adjustments may be costly, such as the use of liquid anti- stripping agents
Indicative Costs	• Cost of additives if used
Timing for Implementation	• Can be incorporated into design immediately
Governance	• Consultation with government needed if adjustments involve increases in cost
Acceptability	• Moderate-High acceptability as CAPEX is expected to be minimal
Feasibility and Technical Requirement	• Technical expertise in pavement design needed to understand the chemical and physical properties of pavement

TABLE A.7: INCREASE THE DEPTHS OF FILLS DURING CONSTRUCTION TO RAISE THE INFRASTRUCTURE

Overview	
	Another option to protect roads against sea level rise is to increase the depths of fills and raise the elevation of the affected infrastructure. This strategy allows roads to be built and located upon an encroaching shoreline or in a vulnerable area, with lower risk of flooding. Since this strategy involves the use of fill, a protection measure should be used to prevent erosion. Structural fill is screened earthen material that creates a strong and stable base This option may not be feasible for areas where there is a shortage of natural material. Depending on the grade, compactness, and characteristics, fill materials are generally expensive, particularly if not available locally and needs to be transported over long distances. If natural material is readily available, this option can be effective in protecting roads. Protection can also be improved with a wide setback.
Advantages	• A more protective solution than using a vertical shoreline wall alone • Allow infrastructure to be built on low-lying areas • Addresses sea level rise
Disadvantages	• Can be expensive if fill material is not available locally, depending on the volume and quality of structural fill • A short-term solution – does not completely protect roads from storm surge • Most likely still require additional protection (e.g. constructing a shoreline wall)
Indicative Costs	• Cost per volume of fill material. This cost will be higher if it is not available locally
Timing for Implementation	• Several days to weeks to increase depths of fill for new infrastructure
Governance	• Public-Government-Private consultation to determine availability of fill material; if not available, discuss the cost and feasibility of importing material
Acceptability	• Highly acceptable as this strategy causes minimal disturbance • Moderately acceptable if material is not rapidly available
Feasibility and Technical Requirement	• Requires multi-discipline technical expertise including civil, geotechnical, and structural engineering

INFRASTRUCTURE PROTECTION AND DRAINAGE

TABLE A.8: IMPROVE OR UPGRADE STORMWATER MANAGEMENT SYSTEM

Overview	
	More intense precipitation events lead to greater amounts of moisture contacting pavements and pavement subgrades. Improper or insufficient drainage system can cause flooding, which can damage pavement. One way to reduce flooding and minimize impacts on pavements is to retrofit the stormwater drainage system using green stormwater infrastructure, which maximizes infiltration within the watershed and therefore reduces the amount of runoff coming in contact with pavements or needing to be drained through road crossings and culverts. Below is a list of examples that can be used for stormwater management: • Retrofitting green spaces such as grassed center medians of roads with bioretention systems, street planters or tree box filters can reduce flooding by infiltrating road runoff rather than directing it to the drainage system. Maximizing infiltration can minimize the frequency and intensity of flooding; and • Increase temporary water storage of existing stormwater systems such as retention and detention basins, and design new infrastructure using design storms based on hydrologic and climate change models that project future climate conditions. If a design is based on historical data and experience, the size of the stormwater systems may not be adequate to manage the increased amount of runoff caused by the increased frequency and peak intensity of extreme weather events.
Advantages	• Prevent flooding and lessen contact between water and pavement to prevent damages • Can be integrated into existing roadways • Minimize surface runoff, which helps prevent erosion
Disadvantages	• Increase in both the CAPEX and OPEX • Need careful planning and may not be suitable in all locations; for instance, a retention pond is not suitable in highly developed areas, or steep sites • Maintenance is required to maintain proper drainage
Indicative Costs	• One-time capital and installation costs • Recurring maintenance costs
Timing for Implementation	• For retention or detention basins, 6 months to 1 year
Governance	• Consultation with government entities to discuss funding for required CAPEX and OPEX
Acceptability	• Moderate acceptability from government regarding higher cost and required maintenance • High acceptability from public as stormwater management systems generally cause limited disturbance provides benefits beyond drainage
Feasibility and Technical Requirement	• Engineers and stormwater specialists to design and install retention and detention pond or green infrastructure • Unskilled labor to perform maintenance

TABLE A.9: INCREASE SLOPES OF ROADWAYS TO DIRECT WATER AWAY FROM PAVMENTS

Overview	
	Once a stormwater management system is established, water drainage can be encouraged by increasing the cross-fall or cross-slope of the road. Depending on soil conditions and geotechnical data, cross-slope of greater than 1.5 percent is preferred, but should not be greater than six percent as it would present an uncomfortable transition.
Advantages	• Relatively easy change to make at the design stage of a project • No additional CAPEX and OPEX needed
Disadvantages	• May cause an uncomfortable driving surface
Indicative Costs	• No additional CAPEX and OPEX needed
Timing for Implementation	• Immediately
Governance	• No necessary governance needed
Acceptability	• High acceptability from both the government and public expected as changing in road geometry creates limited disturbance
Feasibility and Technical Requirement	• Moderate technical expertise needed to ensure design modifications can be incorporated into design plans and bid documents

TABLE A.10: IMPROVE STORMWATER DRAINAGE SYSTEM TO PREVENT FLOODING

<table>
<tr><th colspan="2">Overview</th></tr>
<tr><td></td><td>The drainage function of a pavement structure is a key factor in preventing water from causing damages. As sea level continues to rise, coastal flooding will occur more frequently resulting in increased contact between pavement and water. Therefore, it is important for roadways to be equipped with proper drainage to allow water to flow as quickly as possible to a resilient collection system.

There are a number of ways to improve pavement surface drainage, including:
• Permeable pavement;
• Increasing the cross-slope; and
• Improving the road verge.

In addition to those listed above, culverts can be used to channel water under the roadway from one side to the other, which can reduce the impact caused by “weir-flow” damage mechanism. Over-washing or “weir-flow” damage mechanism occurs when water flows across the paved road and down the landward shoulder or slope.</td></tr>
<tr><td>Advantages</td><td>• Reduction in the frequency and severity of maintenance, as most of the damage on roadways are caused by water
• Can be implemented in segments or corridor-wide
• Can prevent flooding and reduce contact between water and pavement
• An indirect benefit – stormwater management is a best practice that addresses multiple impacts to roadways
• OPEX reduces over time</td></tr>
<tr><td>Disadvantages</td><td>• Will increase CAPEX and OPEX in the beginning, as stormwater drainage systems generally require maintenance; however, OPEX may be reduced overall due to less damage to roadways</td></tr>
<tr><td>Indicative Costs</td><td>• Moderate increase in CAPEX</td></tr>
<tr><td>Timing for Implementation</td><td>• Timing for the installation of new drainage system depends on the size of the project</td></tr>
<tr><td>Governance</td><td>• Requires government support, local stakeholder coordination, and ongoing investment in maintenance</td></tr>
<tr><td>Acceptability</td><td>• Highly acceptable at the community and government levels</td></tr>
<tr><td>Feasibility and Technical Requirement</td><td>• Moderate technical expertise needed in civil and roadway engineering, and knowledge of existing hydrogeological conditions. Most systems are easy to implement</td></tr>
</table>

TABLE A.11: STABILIZE ADJACENT STREAM BANKS TO PREVENT EROSION AFTER EXTREME RAINFALL

Overview	
	A washout is the result of the combination of flood and erosion. For roads that are near stream banks or run across streams, severe erosion may cause a washout of the road. Extreme rainfall events can cause washouts to occur more frequently as they generally introduce a heavy downpour of rain within a short period. The stabilization of stream banks can prevent washout from occurring through installing adequate drainage or the use of structural containment of stream banks. A culvert should be installed for roads that cross non-perennial streams[13] to accommodate flows during wet weather. Stream banks can be stabilized through the use of gabion, riprap or increased vegetation.
Advantages	• Relatively easy to implement and inexpensive • Stream bank stabilization can have numerous environmental benefits • Minimizing erosion can indirectly reduce the risk of flooding
Disadvantages	• Some level of maintenance needed to ensure that the infrastructure (culvert, gabion, etc.) or vegetation are not destroyed after rainstorms
Indicative Costs	• Cost of material and labor
Timing for Implementation	• Immediately
Governance	• Coordination with local government to perform bank stabilization and discuss maintenance plan
Acceptability	• High acceptability if vegetation is used as it is visually pleasing and has environmental benefits • Otherwise, moderate acceptability, as physical structure is generally associated with higher cost, is less visually pleasing and has limited environmental benefits
Feasibility and Technical Requirement	• Minimal technical expertise required – as stream banks stabilization techniques are very common

[13] A non-perennial stream is a stream that does not flow all year round; instead it requires 'rainy seasons' or heavy rainfall to flow.

TABLE A.12: STABILIZE SOIL ON ADJACENT SLOPES TO PREVENT LANDSLIDES OCCURRING AFTER EXTREME RAINFALL EVENTS

Overview	
	Landslides generally do not cause physical damage to roads; however, damages can be created if large-scale landslides occur. Regardless, landslides will create disturbance to traffic or cause a road to become inaccessible. Therefore, stabilization of slopes should be considered. Similar to protection of stream banks, there are multiple different techniques to stabilize slopes, including: • Physical supporting structures using various types of retaining wall – timber crib, steel bin wall, reinforced earth wall, gabion walls, or soldier piles and lagging. Water drainage will be important for these types of structures as water pressure can build up behind them and lead to failure; and • Stabilizing slopes with vegetation, cut brush layers, or buttress fill can be used in combination with synthetic fabrics or polymeric geogrids for the purpose of stabilization. This is known as biotechnical slope protection. Hydroseeding is a common type of seeding used for slope stabilization purposes. This type of stabilization method is generally preferred to physical structures, as the use of vegetation is more visually pleasing and environmentally friendly. In addition, this method generally requires minimal access for equipment and workers causing relatively minor disturbance. For more information refer to http://pubs.usgs.gov/circ/1325/pdf/Sections/AppendixC.pdf.
Advantages	• If using vegetation, this method is easy to implement and inexpensive • Creates safer road conditions for motorists and travelers in wet weather • Protects accessibility of road during and after rainstorms
Disadvantages	• If physical structures are used, it may not be visually pleasing and have less environmental benefits • Procedures for the harvesting, handling, storage, and installation of vegetation requires careful handling for successful biotechnical construction
Indicative Costs	• Cost of labor and materials, which can be minimized if vegetation method is used
Timing for Implementation	• Immediately • If physical structure is used, 1-3 months depending on the size of the slope
Governance	• Coordination with local government and community to perform stabilization and discuss maintenance plan
Acceptability	• High acceptability if vegetation is used as it is visually pleasing and has environmental benefits • Otherwise, moderate acceptability, as physical structure is generally associated with higher cost, is less visually pleasing and has limited environmental benefits
Feasibility and Technical Requirement	• If physical structures are chosen as a solution, a level of technical expertise is needed depending on the scale of the project, size of slope, and hydrogeologic conditions • Otherwise, moderate technical expertise is required

TABLE A.13: CONSTRUCT SEAWALLS, REVETMENTS, DIKES OR LEVEES TO PROVIDE PROTECTION TO ROADS

Overview	
	Sea level rise will almost certainly have an impact on coastal roadways. A direct coastal structure protection measure is to construct vertical, curved or stepped shoreline walls. There are three principal forms of shoreline walls to protect upland areas from storm surges and high tides: seawalls, bulkheads, groines, and revetments. The distinction between seawalls, bulkheads, and revetments are in their protective function, for example: • Bulkheads are typically constructed of structural material such as concrete, stone, earth or steel that is designed to retain the fill behind a vertical wall in a location with less wave action. This type of structure is common in areas where wave heights and fetches are very small; • Groines are a rigid hydraulic structure that interrupts water flow and limits the movement of sediment and water, thereby minimizing erosion and protecting shorelines. Made of concrete or rock piles, the groine can be entirely submerged or the surface can be exposed. They are often used in tandem with seawalls; • Revetments are a structural layer of protection on the top of a sloped surface to protect the underlying soil against erosion and absorb energy of incoming water associated with light waves. Revetments are common in areas where wave heights and fetches are moderate, such as bays or lake shorelines; and • Seawalls are designed to resist the force of storm waves, typically located near an ocean or large water body; they can be rigid structures or rubble-mound structures. Rubble-mound structures can be relatively inexpensive as some of the oldest coastal structures on the world are rubble-mounds. Furthermore, rubble-mound walls have the inherent ability to survive storms in excess of their design storm, which is very valuable in coastal environment. However, the design for these types of shoreline wall structures can be challenging, as the design is sensitive to wave height and the structures require routine maintenance. Wave heights are becoming harder to predict as sea levels continue to rise and storm surge events become more powerful.
Advantages	• Proven to be successful in protecting shoreline against erosion • Can be inexpensive depending on the type of structure used
Disadvantages	• Increase in CAPEX and OPEX regardless of the type of structure • Can be visually unpleasing • Structure may begin to erode over time – Require maintenance which increases OPEX • A short-term solution – a large storm can cause failure of the structure
Indicative Costs	• Mostly upfront cost depending on the scale of the system and type of structure
Timing for Implementation	• Seawalls and large-scale revetments structures may take up to several years • Small-scale (e.g. bulkheads, revetments) systems may take several months to a year
Governance	• Public and private consultation regarding funding for large-scale projects
Acceptability	• Moderate acceptability – cost of some of these structures may not be cost-effective; access to shoreline and aesthetic might be affected
Feasibility and Technical Requirement	• The level of technical expertise needed is dependent on the type of structure selected and the size of installation; however, knowledge in designing surface and submerged shoreline walls will be needed

TABLE A.14: UTILIZE PERMEABLE PAVEMENTS

Overview	
	In areas where green spaces or temporary water storage is not feasible, permeable pavements can be used to minimize the risk of flooding, as well as to control stormwater runoff. Permeable pavements allow water to enter into the pavement structure through the surface layer. Pavement blocks, porous asphalt or porous concrete can be used to allow water to pass through the surface of the pavement. Water that has entered the pavement is then stored at the bottom of the pavement structure, generally in the sub-base layer. Water is then discarded from the sub-base layer either through infiltration or by underdrains, or by a combination of both. Infiltration into soil is desirable from an environmental perspective; otherwise, a formal drainage system needs to be installed to remove water from pavement. Design considerations for permeable pavements include: • They are highly suitable for parking lots or residential driveways, or roads with light traffic; • In heavy traffic areas, the use of permeable pavement shoulder can be beneficial, especially in highly urbanized areas; • Frost protection of the soil beneath the structure has to be provided, if the road is located in a colder region; • Permeability of the entire structure, storage capacity of the sub-base layer and the infiltration or drainage at the bottom of the structure are important for good efficiency; and • Proper maintenance should be incorporated as clogging may affect the performance of the pavement. For more information refer to: www.cement.org/for-concrete-books-learning/materials-applications/pervious-concrete/pervious-concrete-durability; and http://www.wbcsdcement.org/.
Advantages	• An alternative for areas that cannot integrate bioretention areas or temporary water storage • A durable and ecological solution to minimize the risk of flooding • Improved road safety because of improved skid resistance
Disadvantages	• Full-depth permeable pavement cannot be used in heavy traffic roads and lengthy roadway segments • Restriction of traffic may be required on hot days • Many pavement engineers and contractors lack expertise with this technology • Become clogged relatively easy without proper maintenance • Risk of failure
Indicative Costs	• Recurring maintenance costs which can be significant for a large-scale project
Timing for Implementation	• Can be incorporated into design without additional time added to typical schedule
Governance	• Consultation with responsible government bodies to discuss implementation plan for increase in road maintenance
Acceptability	• Moderate-low acceptability as high level of maintenance required and risk of failure exists
Feasibility and Technical Requirement	• Knowledge of permeable pavement design is needed to ensure adherence to standards • Skilled laborers may also be needed to unclog pavement without damaging it

TABLE A.15: SUMMARY OF ALL OPTIONS TO MITIGATE IMPACTS CAUSED BY MOISTURE CONTENT

Overview	
	Increase in moisture content is not an immediate and severe problem compared to other climate change effects; however, it should not be ignored and appropriate prevention and mitigation strategies should be considered. A list of options includes: • Extensive planting of trees and other vegetation around roadways to lower the water table – plants and trees can act as a water absorption mechanism to draw down the water table. It is also a common practice to reduce runoff; • Raise new or existing pavement level. This is a similar concept to the strategy described in Table A.7: Increase the Depths of Fills During Construction to Raise the Infrastructure; • Design the sub-layers of the pavement to break the capillary barrier and prevent contact with groundwater table, or moisture accumulation immediately below the pavement layer; and • Design subsurface drainage system. A properly designed drainage system is critical in maintaining the optimum functionality of roadways.
Advantages	• All options reduce OPEX over time • Improve the service life of pavement by reducing moisture content • Minimal CAPEX required
Disadvantages	• No significant disadvantages except possibly increase in OPEX in the initial stage
Indicative Costs	• Costs for planting of trees and vegetation, mostly labor costs and plantings • Some material cost would be needed if the chosen option is to raise pavement level
Timing for Implementation	• Immediately
Governance	• Planting of trees and other vegetation may require local or municipal government approvals, and approval from abutting property owners if outside of the public right-of-way
Acceptability	• High acceptability as all options create minimal disturbance to community
Feasibility and Technical Requirement	• Investigation would be required to determine the need for adaptation strategies. Determining the level of the groundwater table may require extensive engineering and hydrogeology inputs • To raise the pavement level and design a subsurface drainage system, some technical expertise would be needed • No technical expertise needed for planting trees; only unskilled labor needed

OPERATION AND MAINTENANCE

TABLE A.16: PERIODIC COOLING OF PAVEMENTS, LARGELY USING WATER

Overview	
	For asphalt pavements, damage can occur during extreme hot weather, when the cement binder phase (chemical cohesion) loses stiffness due to increased temperature. To reduce the temperature of the pavement surface, water can be sprayed on pavement to act as a cooling agent. Practitioners should consider using treated wastewater or gray-water as the source of cooling water. Use of potable drinking water should be avoided.
Advantages	• Treated wastewater or gray-water is usually discharged into water bodies. Using it as a cooling mechanism can be a useful re- application for non-drinking water. • Easy to implement if infrastructure is available to centralize wastewater or gray-water conveyance • Usage can be selective or automatic depending on the system installed • Can help to reduce heat-island effect • Can be applied to existing infrastructure
Disadvantages	• Access to centralized wastewater or gray-water can be a challenge if infrastructure is not already available • A fleet of specialized vehicles are typically needed to apply water to roadways • Roads must be equipped with proper drainage system • May increase degradation of roadways if cracking or potholes exist on pavement prior to applying water • Effectiveness can be limited if high surface roadway heat causes rapid evaporation
Indicative Costs	• Installation piping or water spraying system by fleet of trucks (or retrofit, for example container mounted on pickup truck) • Installation of water catchment design solution including capturing water on-site • New piping needed to transport water from centralized system to site, if treated wastewater or gray
Timing for Implementation	• Several months depending on the size of the system and source of water
Governance	• Consultation with responsible government body • Public consultation if road is near residential area or if treated wastewater or gray-water is used
Acceptability	• Concerns regarding sustainability of resource especially if drinkable water is used, and this resource is limited
Feasibility and Technical Requirement	• A certain level of technical background needed as this technology has not been used commonly thus far • Communication with experienced engineers, designers and material suppliers should be the first step

TABLE A.17: CHANGES IN MAINTENANCE PLAN

Overview	
	More frequent maintenance can help to mitigate future damages, such as cracking, potholes, and rutting, directly or indirectly caused by increased temperature. Scheduling more frequent maintenance can sustain and possibly improve the performance and durability of pavement, especially for asphalt based pavement. More frequent surfacing can prevent cracking and rutting from worsening.
Advantages	• Can sustain the service life of pavements; therefore reduce the CAPEX for rebuilding roads
Disadvantages	• Increases OPEX– Labor and the cost of material needed for maintenance • More frequent road closures will occur as a result. Can minimize disturbance to traffic by scheduling maintenance to avoid peak traffic hours
Indicative Costs	• Cost of labor and material needed for maintenance
Timing for Implementation	• Immediately
Governance	• Consultation with responsible government bodies to discuss implementation plan for increase in road maintenance associated traffic management
Acceptability	• Medium to high acceptability, depending on availability of funding
Feasibility and Technical Requirement	• No additional technical expertise required

POLICY AND PLANNING

TABLE A.18: TRAFFIC MANAGEMENT

Overview	
	In addition to the adaptation strategies selected to improve the resiliency of roadway infrastructure, adaptation to climate change should include coordinated traffic management across all types of roadway functions to efficiently and safely maintain traffic flow for all travel modes (e.g., truck, bicycles, buses, walking, etc.). Climate change is likely to intensify climate extremes, such as severe storms, storm surge and intense precipitation, requiring more frequent and coordinated emergency response from transportation officials in multiple jurisdictions. Therefore, transportation or traffic officials should be pro-active in preparing for, and responding to climate extremes, for instance: • Map vulnerable travel routes by usage and destination matrix, such as those that are more susceptible to flooding or slope Failure • Establish an emergency plan for maintaining communications to divert traffic to alternative routes when a primary route becomes Inaccessible • Create and maintain an emergency operation budget that can immediately be used for emergency response purposes Having an emergency response plan established before a disruptive event occurs can improve the preparedness of officials to deal with the impacts of such climate extremes. In addition, emergency response planning, traffic policies can be applied to further protect roadways from damage. A number of reasonable policies can be adopted to deal with the different types of climate extremes. These include: • For asphalt pavement, traffic officials should consider encouraging heavy vehicular traffic to travel exclusively at nighttime, when temperatures are generally lower, which causes asphalt surfacing to be stiffer and more rut resistant; • If permeable pavement is used, introduce load restrictions on vehicles to improve durability of this type of road; and • Increase frequency of temporary road closures to perform maintenance on roads and repair minor damages before damage is made worse.
Advantages	• Low CAPEX • Further protects roads and roads users
Disadvantages	• Requires government coordination across multiple sectors and agencies • Does not address potential impacts to roadways from extreme events
Indicative Costs	• No direct material related costs, but can increase labor and maintenance cost
Timing for Implementation	• Immediate or near-term implementation, if policy is already in place
Governance	• Community, provincial and national government coordination and input
Acceptability	• High acceptability where government communication is good
Feasibility and Technical Requirement	• Knowledge and reoccurring training in emergency or incidence response and traffic management planning are needed

TABLE A.19: RELOCATION OF ROADWAYS

Overview	
	While other coastal options discussed previously in this Annex are shorter-term solutions, a longer-term solution is to consider the relocation of coastal roadways to inland locations away from the potential effect of water induced damage. Much of the coastline worldwide is experiencing erosion with varying magnitudes of recession. When a roadway is near a receding shoreline, it is gradually subjected to wave attack and continuous erosion. These impacts can be mitigated by strategies stated above; however, those mitigation methods can be costly and will require maintenance. More importantly, the protection is only temporary and roads can still experience wave impacts if the magnitude of the storm is too large. Under these circumstances, it may be best to consider relocating infrastructure to safer ground: farther inland away from the coastline; to higher elevation; or generally to a less vulnerable area. These alternatives could be used when coastal armoring and other shoreline protection efforts become too expensive, less productive or are expected to be a losing battle. Relocation involves planning and construction of new route, as well as abandoning or demolishing existing roadways. Careful planning is needed to ensure that the new route will be protected from wave impact and continuous erosion, but still within reasonable distance from the coastline. Shoreline protection strategies can be used in addition to relocation to further protect roadways.
Advantages	• A more enduring solution to sea level rise than other options • Usually less expensive than constructing vertical shoreline walls, especially since these structures are temporary • OPEX reduces over time
Disadvantages	• High CAPEX to construct new roadway and acquire new property for right-of-way • It may be difficult to locate a suitable alternative as inland areas may already be developed or have significant environmental values
Indicative Costs	• Cost for constructing new road including design, labor and materials • Cost for site remediation if existing roadway is demolished
Timing for Implementation	• Several years – considerable amount of time to plan and construct the new route before existing roadway can be abandoned or demolished
Governance	• Consultation with government and general public to discuss potential funding needs, the feasibility of relocation, and plan to address existing assets (e.g. removal and rehabilitation of land)
Acceptability	• Moderate acceptability, high CAPEX and the location of the new route may be less convenient
Feasibility and Technical Requirement	• Careful planning needed to ensure the new route causes minimal disturbance to the environment • Otherwise, construction of the new roadway does not require extensive technical expertise

TABLE A.20: DEVELOPMENT OF Water Sensitive Urban Design (WSUD) GUIDELINES

Overview	
	WSUD guidelines typically address issues around water supply and demand management with a strong focus on green infrastructure, while also considering the risks associated with non-potable water sources. The guidelines would include sections to guide practitioners on green infrastructure benefits, alternative water sources, risk management, site analysis and water balance assessment and end use and treatment required. More detailed information would be developed for specific green infrastructure elements such as rainwater tanks, stormwater biofiltration and constructed wetlands. The guidelines would not provide detailed technical information but, rather, a general description of the key WSUD fundamentals. The guidelines would be a relatively short document with a strong emphasis on graphic display of the information and easy to understand principles. The guidelines would represent the cheapest and easier to implement options from a WSUD perspective. The benefits from an improved water management perspective would be more limited than the development of WSUD strategy.
Advantages	• Enhances the current level of understanding of WSUD • Provides a framework for consistent implementation and integration of WSUD in new developments • Provides design guidance on WSUD details • Identifies issues that should be considered when evaluating strategies to achieve WSUD • Supplements (but not replaces) existing WSUD regulations and detailed design and implementation guidelines • Directs readers to more detailed technical WSUD literature on specific issues and for location specific advice
Disadvantages	• WSUD guidelines would be more limited than a WSUD strategy due to their general nature • Do not take site specific conditions into account, including topography, soils, landscape, services and other relevant site features and structural elements • Not a stand-alone design resource
Indicative Costs	• The cost of developing WSUD guidelines would be minimal as it would not involve any specific investigations or site-specific details
Timing for Implementation	• The development of WSUD guidelines can be achieved in weeks to months
Governance	• WSUD is mandatory for certain scales and types of developments • WSUD would require involvement from relevant water utilities and their engineering divisions (or external procurement) • Stakeholder consultation is key
Acceptability	• High acceptability – usually WSUD does not result in significant disturbance to local communities • Little public opposition against, and considerable support for, the use of WSUD • Some aversion to new technology
Feasibility and Technical Requirement	• Some WSUD technologies are simple to install and operate. Local people can be easily trained and construction materials are usually readily available • Primarily requires common engineering practices; however, some specific engineering inputs are required for design and construction as well as for specific materials that may not be local • Existing local skills associated with current facilities can be used for operational purposes • May require advanced plumbing work

TABLE A.21: DEVELOPMENT OF A WSUD STRATEGY AND IMPLEMENTATION OF WSUD OPTIONS

Overview	
	A detailed site analysis and water balance assessment would be the first step of a WSUD strategy. The following site characteristics should be considered as part of a detailed site analysis: • Climate (rainfall - annual average, seasonal variation); • Topography (steep slopes, vicinity to natural waterways); • Soils and geology (suitability for infiltration); • Groundwater (depth to water table); • Salinity (acid sulphate soils); • Space (potential areas for water treatment and storage); • Services (conflicts with existing and proposed); • Environmental (significant species); and • Heritage (retrofitting plumbing on heritage listed buildings). Secondly, an assessment of the end use and treatment required should include at least a general water breakdown in terms of internal water use (e.g., drinking, showers, toilets and laundry), external water use (e.g., irrigation, industrial plant, cooling towers), and an assessment of the suitability of alternative water sources (rainwater, stormwater, groundwater and recycled water). Finally the strategy should determine the right balance of green infrastructure to be implemented to ensure the long term efficiency of the WSUD measures.
Advantages	• A WSUD strategy allows for the integration of all WSUD elements within the development • A WSUD strategy would be site and development specific as each site has specific environmental conditions that influence implementation of WSUD, such as rainfall, topography, soils, creeks and receiving waters
Disadvantages	• WSUD upgrade requirements will vary between households and developments, increasing project complexity • WSUD will only have an effect with widespread uptake
Indicative Costs	• The cost of developing a WSUD strategy and implementation of WSUD options would vary on a site by site basis
Timing for Implementation	• The development of a WSUD strategy and implementation of WSUD options can be achieved in months to years, depending on site specific details and requirements
Governance	• WSUD is mandatory for certain scales and types of developments • WSUD would require involvement from relevant water utilities and their engineering divisions (or external procurement if they don’t have internal capacity), participation of the general community is not required • Stakeholder consultation is key
Acceptability	• High acceptability – usually WSUD does not result in significant disturbance to local communities • Little public opposition against, and considerable support for, the use of WSUD • Some aversion to new technology
Feasibility and Technical Requirement	• Some WSUD technologies are simple to install and operate. Local people can be easily trained to implement such technologies, and construction materials are usually readily available • Primarily requires common engineering practices however, some specific engineering inputs are required for design and construction as well as relevant materials that may not be local • Existing local skills can be used for operational purposes • May require advanced plumbing work

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