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» PIEVC GREEN PROTOCOL «

Integrating Ecosystem-based Adaptation into Infrastructure Climate Risk Assessments

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What is PIEVC?

PIEVC CVIIP

In 2005, Engineers Canada established a national committee called the Public Infrastructure Engineering Vulnerability Committee (PIEVC) to oversee development and delivery of a Protocol for the evaluation of risks related to the impacts of climate change on physical infrastructure in Canada. The PIEVC Protocol has been used in over 100 assessments of various types of individual infrastructure, larger infrastructure systems, and infrastructure portfolios.

The PIEVC Program is owned and operated through a partnership consisting of the *Institute for Catastrophic Loss Reduction (ICLR)*, the *Climate Risk Institute (CRI)* and *Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH*. This manual is one member of the growing family of PIEVC resources to help organizations achieve climate resilience.

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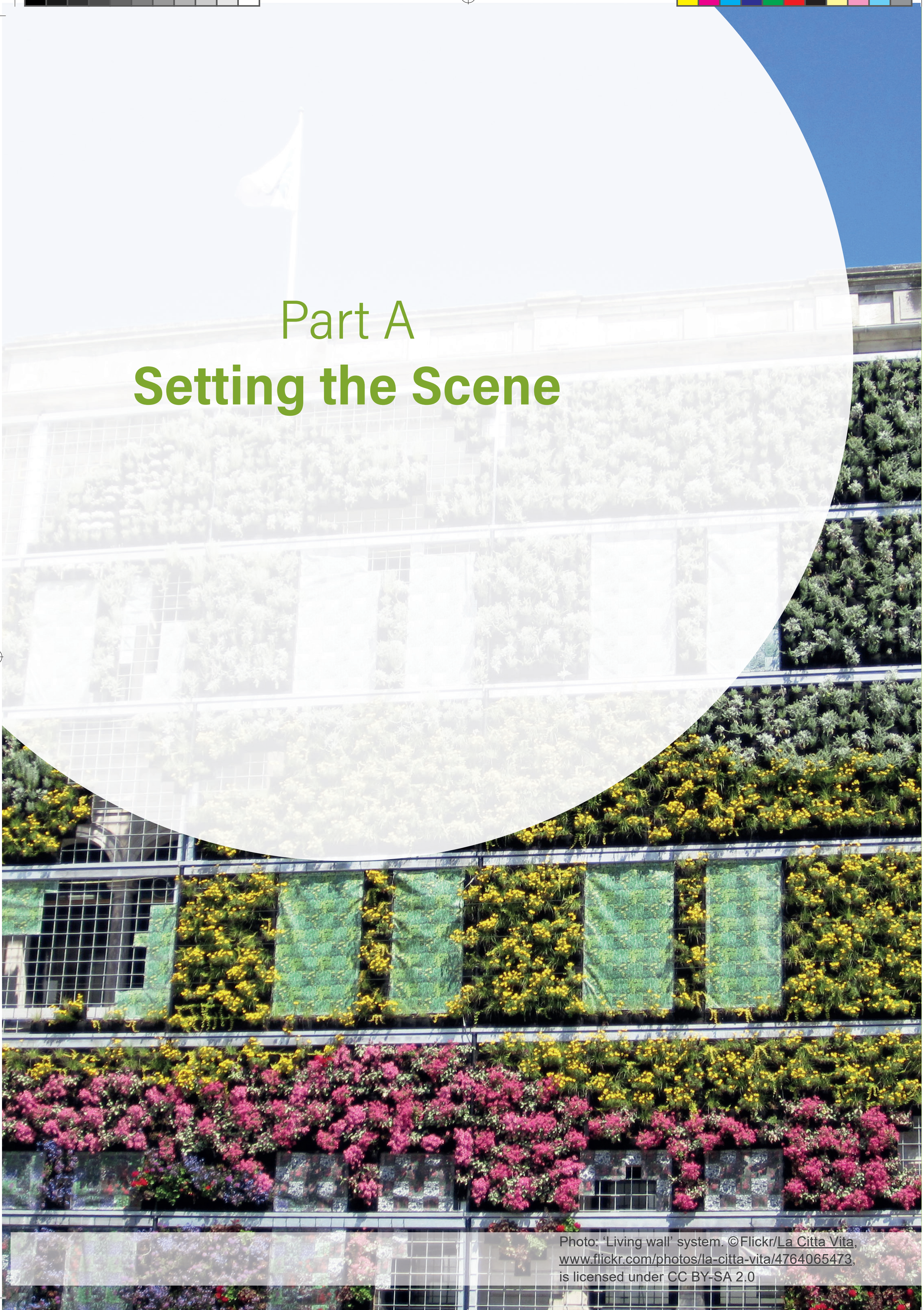


Photo: 'Living wall' system. ©Flickr/La Citta Vita, www.flickr.com/photos/la-citta-vita/4764065473, is licensed under CC BY-SA 2.0

1 Introduction

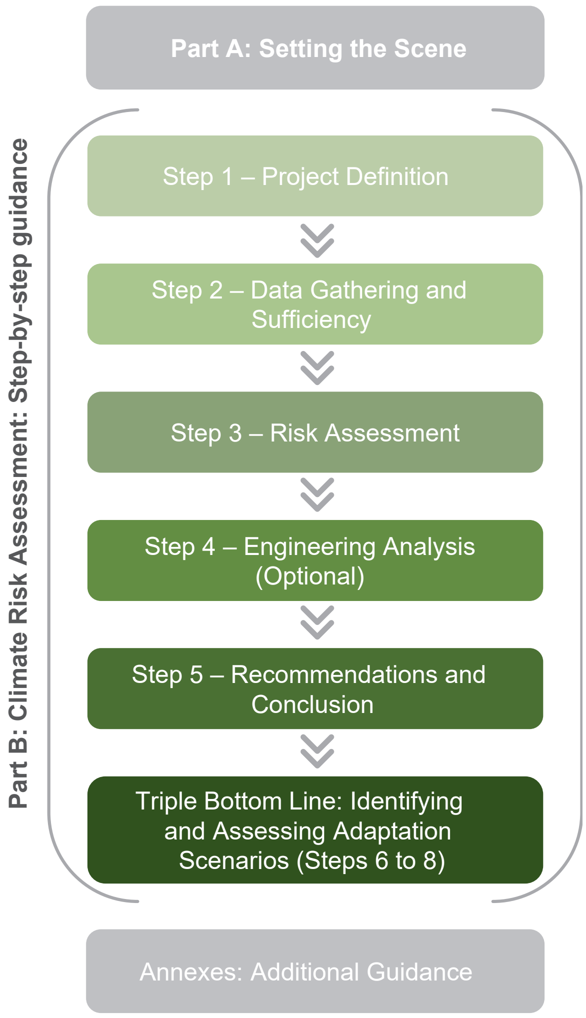
The PIEVC Green Protocol outlines a process to assess infrastructure component responses to climate change impacts, while considering the broader social and environmental systems within which the infrastructure component is situated. Information developed through the assessment process will assist owners, operators and other professionals, to effectively incorporate climate change adaptation into design, development and management of existing and planned infrastructure and its surrounding environment, including ecosystems.

Traditionally, engineers have relied on historic climate data records to design infrastructure. With climate change, this historic data may no longer be appropriate alone to inform infrastructure design, as it does not capture how the climate is changing. This can translate to a more challenging operating environment for which the infrastructure was never designed. As a result, infrastructure may be vulnerable and may not have sufficient resiliency. New infrastructure may not be designed with sufficient load bearing capacity. The process set forth by the PIEVC Green Protocol is designed to aid practitioners in characterizing the risk of the infrastructure due to climate change while considering the influence of the broader social-ecological system, and potential subsequent impacts to the social-ecological system should the infrastructure be disrupted or damaged. Climate risk assessment is within a broader context of climate proofing (a methodological approach aimed at incorporating climate change into project planning and development).

By applying a systems thinking approach to climate risk assessments for infrastructure and thereby including social-ecological aspects, the intrinsic value of surrounding ecosystems can be harnessed to optimize “grey” infrastructure projects’ structural integrity as well as service reliability. In addition, possible climate change impacts on the surrounding natural environment, which may in turn exacerbate some of the vulnerabilities of the built environment, can also be accounted for at an earlier stage of the PIEVC process. If you were assessing the climate risk of your house for example, you would also want to consider the tree next to the house and how this tree could increase the house’s climate risk (e.g., potential to fall onto the house due to a storm) or decrease the house’s climate risk (e.g., potential to cool surrounding air during a heat wave). The PIEVC Green Protocol enables a holistic planning approach, where a project is seen as embedded in a larger system. Thereby, it provides a catalyst for addressing systemic risk of social-ecological systems in pursuit of risk-informed development.

The PIEVC Green Protocol describes a step-by-step methodology of risk assessment and optional engineering analysis for evaluating the risk of climate change on infrastructure. Considering also the system beyond the infrastructure itself in a holistic approach, this process entails some added complexity and need for wider stakeholder engagement. The observations, conclusions and recommendations derived from the application of the PIEVC Green Protocol provide a framework to support effective decision-making about infrastructure operation, maintenance, planning and development.

Figure 1 Structure of the PIEVC Green Protocol



The core of this PIEVC Green Protocol document is the five-step methodology for climate risk assessment of infrastructure (with consideration of the broader social-ecological system) and three additional steps for identifying and assessing adaptation. This procedural information is bookended with conceptual information and additional guidance (Figure 1). The PIEVC Green Protocol begins by setting the scene with an explanation of key concepts, including an introduction to the fundamentals of climate risk assessment and considerations for communication in interdisciplinary teams. The annexes of the document include additional details and guidance on the methodology, along with reference material such as a glossary.

The core steps of the PIEVC Green Protocol are (Figure 1):

- **Step 1: Project definition** – defining the project parameters and boundary conditions for the climate risk assessment.
- **Step 2: Data gathering and sufficiency** – further defining the infrastructure and particular climate trends and projections that are being considered in the evaluation by developing an impact chain, conducting data acquisition, and assessing data sufficiency.
- **Step 3: Risk assessment** – combining information on vulnerability, exposure and likelihood to assess climate risk.
- **Step 4: Engineering analysis (optional)** – conducting focused engineering analysis on climate/infrastructure interactions requiring further assessment.
- **Step 5: Recommendations and conclusions** – providing recommendations and conclusions based on the climate risk assessment results.

- **Needs-based Triple Bottom Line Module: Identifying and Assessing Adaptation Scenarios**
  - **Step 6: Identifying adaptation scenarios** – generating different adaptation scenarios to address the risks identified in Steps 1-5.
  - **Step 7: Assessment of adaptation scenarios** – comparing and assessing adaptation scenarios generated in Step 6.
  - **Step 8: Recommendations and conclusions** – making recommendations for adaptation scenarios preparing final documentation and presenting results.

Evolution from the Original PIEVC Protocol

The PIEVC Green Protocol builds upon the original PIEVC Protocol[1] by mainstreaming systems thinking and integrating Ecosystem-based Adaptation (EbA) concepts as a tool for holistic climate risk assessments in the green-grey working context.

The structure of the PIEVC Green Protocol is the same as the original PIEVC Protocol, with the same five core steps plus Triple Bottom Line analysis steps.

Compared to the original PIEVC Protocol, the main differences in the PIEVC Green Protocol are:

- Broadened scope from the infrastructure system to include the social-ecological system and additional associated guidance.
- Integration of Ecosystem-based Adaptation (EbA) and ecosystem services concepts.
- Update of climate risk concepts and terminology to align with the Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report.
- One-stop-shop: Key methodological information from the PIEVC Vulnerability Assessment Module and Triple Bottom Line Analysis Module are integrated into the PIEVC Green Protocol.
- Content is shortened for ease of use.
- Integration of recent PIEVC methodology, such as from the PIEVC High Level Screening Guide.
- Broadened applicability to regions outside of Canada.
- Less description of climate data and information.
- Greater emphasis on co-benefits of adaptation options.

[1] The original PIEVC Protocol was developed with funding contributions from Natural Resources Canada under the direction of the Public Infrastructure Engineering Vulnerability Committee (PIEVC). PIEVC was a national steering committee established by Engineers Canada in 2005. The committee consisted of senior representatives from federal, provincial and municipal levels of government in Canada along with several non-government organizations. It oversaw the first National Engineering Vulnerability Assessment project, a long-term initiative of the Canadian Engineering profession to assess the vulnerability of public infrastructure to the impacts of changing climatic conditions. This Protocol is one key product of PIEVC's work. Effective March 30, 2020, the PIEVC Program is operated jointly by the Institute for Catastrophic Loss Reduction (ICLR), the Climate Risk Institute (CRI), and Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ).

The primary changes to procedural activities are:

- In Step 2: Data Gathering and Sufficiency:
  - Development of impact chains
  - Identification, selection, and normalization of vulnerability indicators
- In Step 3: Climate Risk Assessment:
  - Weighing and aggregating vulnerability indicators

PIEVC Family of Resources

The PIEVC Family of Resources[2] includes a variety of resources that cover the development of climate information, high-level screening, detailed assessment, training and certification (PIEVC Program, 2021a). Three examples of resources are described below.

The **original PIEVC Protocol** outlines a process to assess infrastructure responses to climate change. Information developed through the assessment process helps owners and operators incorporate adaptation into design, development, and management of existing and planned infrastructure. The **PIEVC Green Protocol** has a similar objective but with a broader scope, additional mainstreamed guidance on considering the broader social-ecological system, and updated to IPCC 6th Assessment Report concepts, along with other differences discussed above.

The **PIEVC High Level Screening Guide (HLSG)**, meanwhile, is designed to help infrastructure owners gain a high-level assessment of the potential risks posed by climate change to their infrastructure and related elements (PIEVC Program, 2021b). Generally, the distinction between the PIEVC HLSG and the PIEVC Protocol is the level of detail pursued at each step. The PIEVC HLSG process is written such that information can be obtained from readily available sources and based on a high degree of professional judgement. The PIEVC HLSG process may also be the initial screening step before other processes or further detail assessment.

The PIEVC Portfolio Screening Manual details general approaches to use the PIEVC Process (PIEVC Protocol, PIEVC High Level Screening Guide) on a portfolio of assets (PIEVC Program, 2022). A portfolio is controlled by a single entity. This addresses issues that could confound assessments of a range of similar assets owned by different entities. One key factor of portfolio assessment is the control established by one governing body applying consistent scope, context, and criteria.

2 For more details and resources, see pievc.ca.

2 Key Concepts

We provide a brief explanation of key concepts in the following sub-sections. A glossary of terms used in the Protocol is presented in Annex A.

Social-ecological Systems Approach

A systems approach to infrastructure climate risk assessment (also referred to as systems thinking) recognizes and considers how the broader social-ecological system within which the infrastructure project is located interacts with the infrastructure's climate risk.

Social-ecological systems can be defined as complex "systems of people and nature, emphasising that humans must be seen as a part of, not apart from, nature" (Berkes and Folke 1998). By considering complex systems of people and nature, social-ecological systems approaches pay particular attention to the dependency of people (socio-economic-cultural context) on ecosystem services (ESS). Ecosystem services are the benefits of nature for human well-being, including:

- Provisioning services (e.g., food, raw materials, water supply)
- Regulating services (e.g., preventing soil erosion, wetland water treatment, climate regulation, extreme weather event buffering)
- Habitat or supporting services (e.g., maintaining genetic diversity)
- Cultural services (e.g., tourism, recreation)

Ecosystem services, and in particular regulating services, provide the backbone for EbA and are of central importance in the context of risk reduction and adaptation. Ecosystem services are a useful lens to apply in considering the relationship between the infrastructure being analyzed in a climate risk assessment and its surrounding social-ecological system.

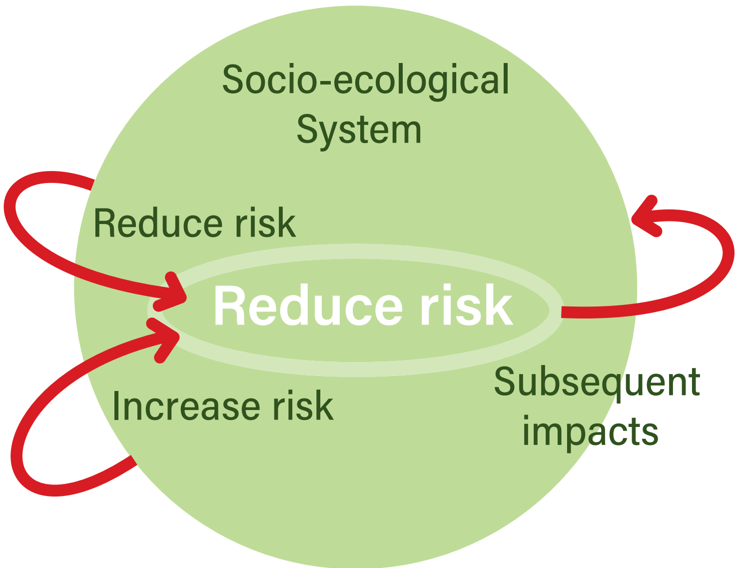
A social-ecological systems approach considers both human-induced and biophysical drivers of risk and helps to pursue adaptation strategies that make use of the multiple benefits provided by ecosystems. The geographical boundary of the system for the purpose of the climate risk assessment may be administrative (e.g., a local jurisdiction) or environmental (e.g., a water catchment area).

Key risks of climate change result in severe impacts for a social-ecological system due to the interaction of climate-related hazards (including hazardous events and trends) with the vulnerability and exposure of human and natural systems (IPCC, 2022a).

The interaction between the climate risk of the infrastructure and the social-ecological system may include (Figure 2):

- **How the system reduces the climate risk of the infrastructure** by protecting, assisting or replacing it. For example, vegetation stabilizing a slope next to a road protects the road as the risk of slope collapse from extreme rainfall events is reduced.
- **How the system increases the climate risk of the infrastructure**, recognizing that a vulnerable and maladapted ecosystem may contribute to infrastructure disruption, damage, or failure. For example, degrading mangrove forest ecosystems providing limited or reduced protection to coastal infrastructure increases the climate risk of the infrastructure to storm surges. In another example, vulnerable tree species with low survival rates during droughts and fires may lead to hydrophobic soils and further additional erosion or landslides.
- **If the climate risk of the infrastructure project is realized (i.e., an impact occurs), how it may have subsequent impacts for the broader social-ecological system**. For example, economic disruption and public safety risks from a bridge or road being washed out due to flooding (see additional examples of infrastructure response considerations in Annex B).

Figure 2 Relationship between infrastructure and the broader social-ecological system for climate risk



Ecosystem-based Adaptation

Ecosystem-based Adaptation (EbA) is "the use of biodiversity and ecosystem services as part of an overall adaptation strategy to help people to adapt to the adverse effects of climate change" (CBD, 2009, p.9). EbA has been recognized as being cost-effective and generating social, economic, health and cultural co-benefits (such as for health and well-being, additional sources of income, water purification, carbon storage, pollination, and recreation services), while contributing to the conservation of biodiversity (CBD 2009). In recent years, EbA measures have increasingly been promoted and piloted to help people adapt to climate change and reduce climate-related disaster risk. See examples of EbA for water infrastructure in the Nile Basin context in Box 1.

Box 1 Examples of EbA for water infrastructure in the Nile Basin context

In the Nile Basin, the most relevant EbA options for climate-proofing water infrastructure are those that minimize the impacts of increased sedimentation due to erosion, flood damages, low flow conditions, evaporation, and concentration of pollutants, since these stressors pose the greatest risk to water infrastructure and the services they provide.

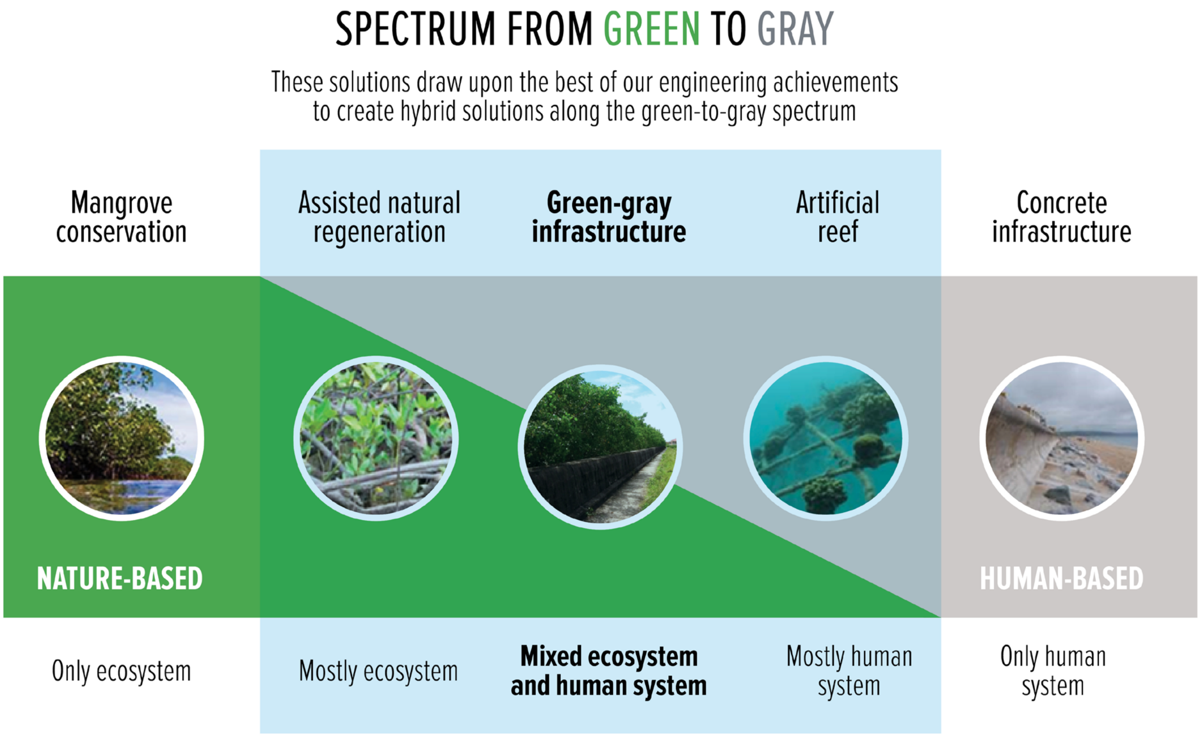
Example EbA alternatives that can assist in managing these impacts include re-meandering of rivers, creation or restoration of side-channels, flood plain widening, installation of green embankments, riparian planting and forest restoration, altered land use practices, wetland restoration, and the creation of bioswales for urban drainage.

Source: Nile Basin Initiative Climate Proofing Hub, 2022.

Nature-based Solutions (NbS), meanwhile, is an umbrella concept for various ecosystem-related approaches that is defined as "actions to protect, conserve, restore, sustainably use and manage natural or modified terrestrial, freshwater, coastal and marine ecosystems, which address social, economic and environmental challenges effectively and adaptively, while simultaneously providing human well-being, ecosystem services and resilience and biodiversity benefits" (UNEA, 2022, p.2). Ecosystem-based adaptation measures (EbA) are under this umbrella considered as NbS for climate change adaptation. In the PIEVC Green Protocol we use the term EbA.

In the context of infrastructure, EbA (or "green" measures) can also be combined on a spectrum with physical "grey" infrastructure, resulting in so-called "green-grey infrastructure" or "hybrid infrastructure" (Figure 3). It is important to note that this kind of infrastructure might be at risk under climate change as well.

Figure 3 General spectrum of "green" to "grey" infrastructure



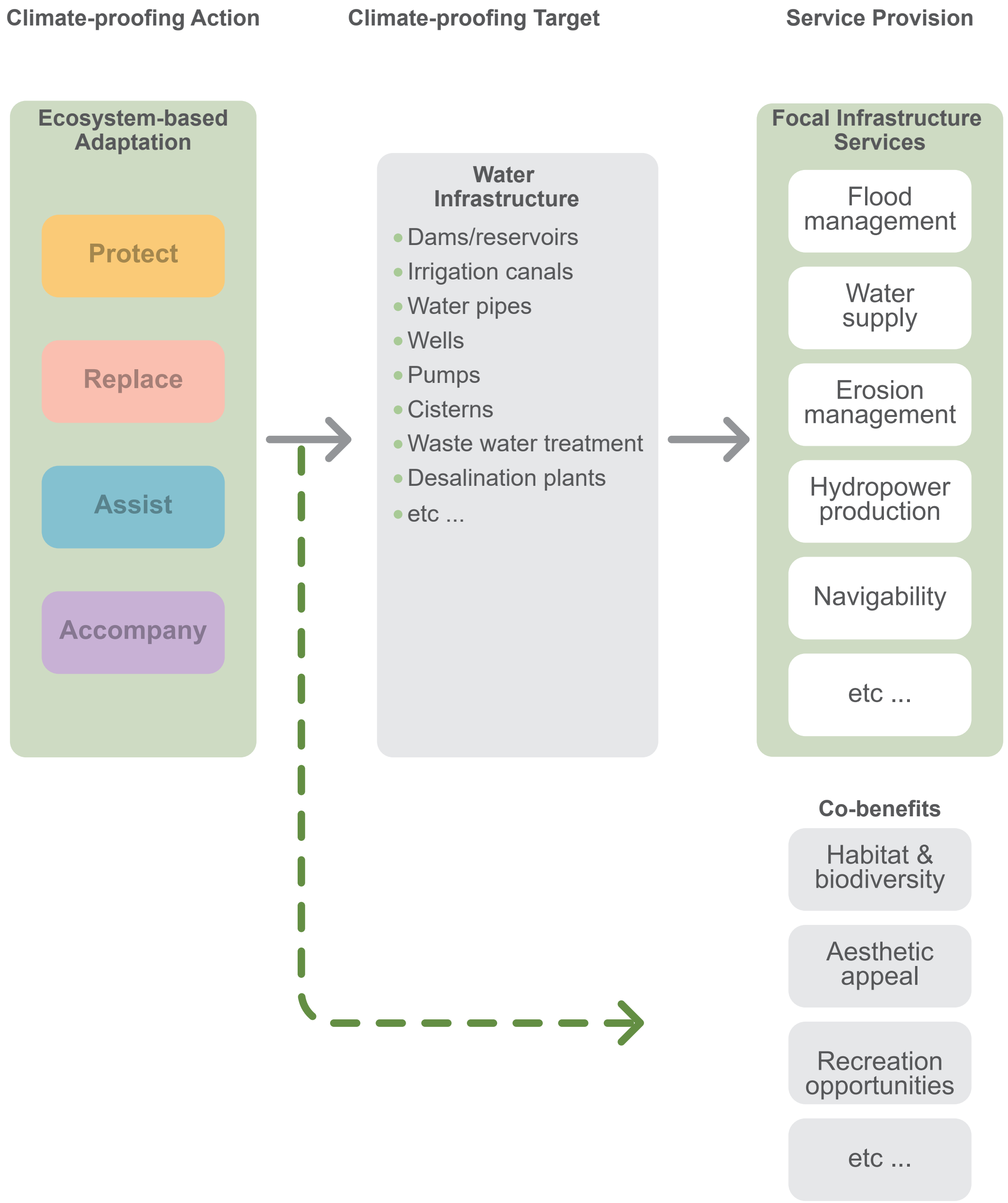
Source: Green-Gray Community of Practice, 2020.

As Figure 4 illustrates, several ecosystem-based adaptation actions can be applied in relation to infrastructure, each of which supply different ecosystem services. These actions can be organized into different types (see coloured ovals in Figure 4) based on how they interact with hard/grey infrastructure projects:

- **Protecting options s**upply ecosystem services that directly protect a hard/grey infrastructure project from climate hazards, increasing its lifespan and reducing operating/maintenance costs, while also providing co-benefits.
- **Replacing options** supply ecosystem services that completely replace the need for a hard/grey infrastructure project and are more resilient to climate hazards, while also providing co-benefits.

- **Assisting options** supply ecosystem services that complement a hard/grey infrastructure project by increasing focal service provision beyond what could be provided by the project alone, thereby improving capacity to continue service provision when impacted by climate hazards, while also providing co-benefits.
- **Accompanying options** provide no services that directly or indirectly improve the adaptive capacity of a hard/grey infrastructure project or its focal services but can be implemented as part of the project to provide co-benefits that increase overall adaptive capacity of society to climate hazards.

Figure 4 EbA and water-related infrastructure



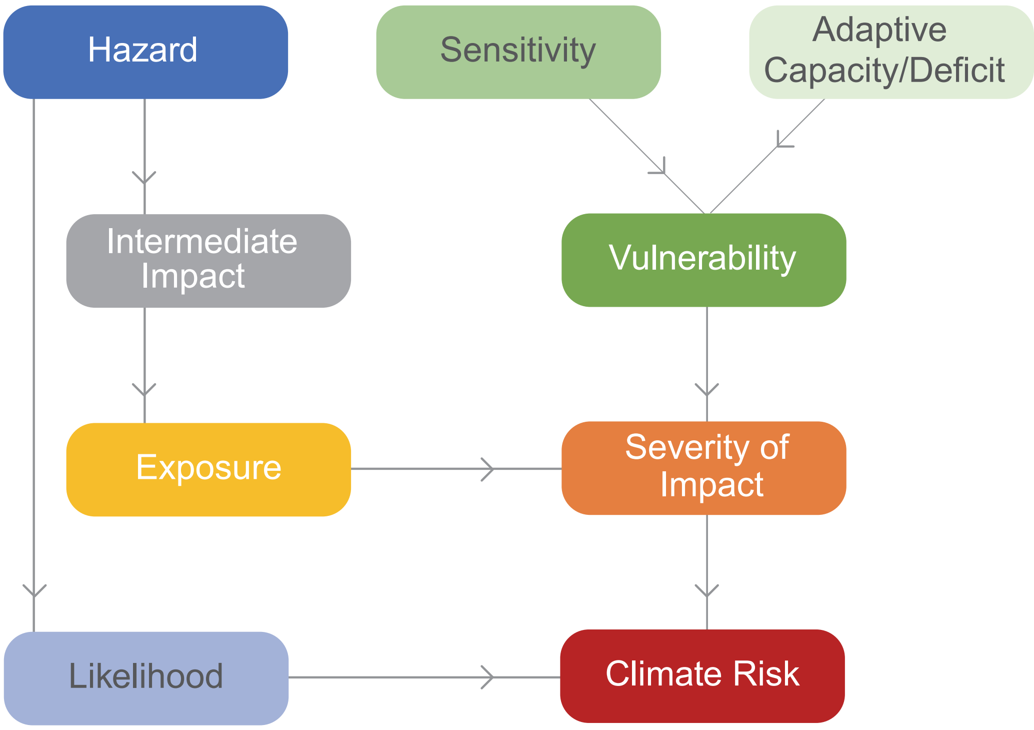
EbA and hybrid solutions might not be an optimal solution in all cases and different criteria should be used to identify and prioritize the best climate proofing options. For example, if the only management objective is to protect water infrastructure against a 10,000-year flood, many EbA alternatives would not be viable because they would have a negligible effect against such an extreme event. Decision criteria such as feasibility, relevance, costs, benefits, and many others can be applied and EbA's contribution to cumulative benefits should be considered (World Bank 2017, ADB 2019).

Climate Risk

Risk in a climate change context is defined as "The **potential for adverse consequences** for human or ecological systems, recognising the diversity of values and objectives associated with such systems. […] In the context of climate change impacts, risks result from dynamic interactions between climate-related **hazards** with the **exposure** and **vulnerability** of the affected human or ecological system to the hazards […]" (IPCC, 2022b, p.2921).

The following sub-sections and Figure 5 demonstrate the interactions between key concepts to form risk. Hazard, exposure, and vulnerability (sensitivity and adaptive capacity/deficit) are called components and each element of a risk component is a risk factor.

Figure 5 Relationship between risk concepts



Hazard

Hazard is defined as "The potential occurrence of a natural or human-induced physical event or trend that may cause loss of life, injury or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, ecosystems and environmental resources" (IPCC, 2022b, p.2911).

A hazard is not necessarily an extreme weather event (e.g., tropical storm, flooding), but can also be a slow onset trend (e.g., less water from snow melt, increase in average temperature, sea-level rise, salinity intrusion).

Myth: "Hazard is risk." It is very common to confuse the conceivability of a hazard occurring with its risk. There is a distinction between the likelihood of a hazard occurring and the risk, which is a combination of both the likelihood of the hazard occurring AND having a severe impact.

Exposure

Exposure is defined as "The presence of people; livelihoods; species or ecosystems; environmental functions, services, and resources; infrastructure; or economic, social, or cultural assets in places and settings that could be adversely affected" (IPCC, 2022b, p.2908).

'Exposure' refers to relevant elements of the system (e.g., infrastructure components, people, livelihoods, assets, species, ecosystems) that could be adversely affected by hazards.

Vulnerability

Vulnerability is defined as "The propensity or predisposition to be adversely affected. Vulnerability encompasses a variety of concepts and elements, including sensitivity or susceptibility to harm and lack of capacity to cope and adapt" (IPCC AR6 WGII p.2926).

The PIEVC Green Protocol includes guidance on both engineering vulnerability (considering aspects that are within infrastructure owners' direct management and budgetary control) and vulnerability in the broader sense that also considers social-ecological systems.

Though there are several ways to conceptualize vulnerability, here it is considered as a composite of sensitivity and adaptive capacity/deficit.

Sensitivity

Sensitivity is defined as "The degree to which a system or species is affected, either adversely or beneficially, by climate variability or change. The effect may be direct (e.g., a change in crop yield in response to a change in the mean, range, or variability of temperature) or indirect (e.g., damages caused by an increase in the frequency of coastal flooding due to sea level rise)" (IPCC, 2022b, p.2922).

Sensitivity may include ecological or physical attributes of a system (e.g., water retention capacity for flood control, building material of infrastructure, state of ecosystems to deliver their services) as well as local social, economic and cultural attributes (e.g., age structure, income structure) that constitutes the degree of robustness, protectiveness and the responsiveness to hazardous events.

Adaptive Capacity and Adaptive Deficit

Adaptive capacity is defined as "The ability of systems, institutions, humans and other organisms to adjust to potential damage, to take advantage of opportunities or to respond to consequences" (IPCC, 2022b, p.2899). Adaptive capacity may include the capacity to prepare, prevent, cope or adapt.

Adaptive capacity may include those features and capacities of the system in focus that reduce vulnerability through transformational processes to reduce hazard magnitudes and reduce vulnerability (increasing robustness, protection and residual risk management such as preparedness, warning, response and recovery of the system). For example, indicators of adaptive capacity may include having a well-functioning warning and business continuity management system, or having relief and recovery mechanisms (e.g., contingencies, insurance). Considering the broader social-ecological system as well, adaptive capacity can also include the ability of societies and communities to prepare for and respond to current and future climate impacts. It does not cover the capacity of ecosystems to respond to impacts but might include the capacity to manage ecosystems.

Adaptive capacity is a positive trait. Sensitivity, the other vulnerability component, is a negative trait. For consistency, it is necessary to consider only positive or negative attributes. This ensures that the analysis during the climate risk assessment does not pull in different directions and generate inconsistent results. For this reason, the analysis in Steps 2 and 3 of the PIEVC Green Protocol looks at the negative attribute of adaptive capacity, the inability to adapt or lack or resilience in the system. This is called adaptive deficit. For example, while an indicator of adaptive capacity may be "percentage of river line aligned by buffer strips," an indicator of adaptive deficit that would be used here instead is "percentage of river line not aligned by buffer strips."

Impact

Impacts are defined as "The consequences of realized risks on natural and human systems, where risks result from the interactions of climate-related hazards (including extreme weather/climate events), exposure, and vulnerability" (IPCC, 2022b, p.2912). Examples of impacts might be damage to infrastructure, economic losses, loss of life, ecosystem degradation.

In the PIEVC Green Protocol we also use two additional impact-related terms:

- ‘Severity of impact’ refers to the combination of exposure and vulnerability (if that impact were to occur).
- ‘Intermediate impact’ refers to effects triggered by climate parameters causing a sequence of intermediate impacts (e.g., erosion upstream, contributing to flooding downstream). Intermediate impacts are not a risk component by themselves, but merely an auxiliary tool to fully grasp the cause-effect chain leading to the risk.

Myth: “Severity of impact is risk.” The severity of impact of an event is sometimes confused with its risk. Impacts that would have high severity are considered to be high risk regardless of their likelihood. Similarly, impacts that would have a low severity are considered to be low risk even though they may occur quite frequently. By neglecting one key factor of risk the actual risk may not be properly assessed or managed.

Likelihood

Likelihood, sometimes also referred to as probability, is defined as “The chance of a specific outcome occurring, where this might be estimated probabilistically” (IPCC, 2022b, p.2914).

In the climate risk assessment process, you will assign the likelihood of a climate hazard occurring. This can be done by defining hazards as critical events or critical physical impacts (e.g., ‘heavy rain events’ instead of ‘rain’ or ‘heat days’ instead of ‘temperature’).

There will inherently be some uncertainty in assessing likelihood, given that we don’t know how society will reduce its greenhouse gas emissions in the future, and therefore how climate change will evolve. These can be cascading uncertainties, whereby uncertainty in future socioeconomic changes feed into emissions scenarios (i.e., Shared Socioeconomic Pathways), which in turn inform climate models, then risk assessments then adaptation planning, meaning there is uncertainty at each of these levels. Collaboration with a climate scientist on the team can support understanding and management of this uncertainty.

Myth: “Likelihood is risk.” Likelihood is only one factor that constitutes risk. When likelihood is confused with risk, the severity of an impact is neglected. It is possible to label high-likelihood – low-severity of impact as high risk. This can lead to unnecessary management action. Conversely, it is possible to label high-severity of impact – low-likelihood events as low risk, resulting in little or no mitigative action when action is actually necessary. For example, the likelihood of a flood-control dam experiencing a 1-in-200-year rainfall event may be small, but the severity of the event could lead to catastrophic failure of the dam. Based on likelihood alone, this event may be identified as a very low risk whereas a more thorough analysis would reveal a much more significant level of risk.

Key Concepts in Practice Example: 2021 British Columbia, Canada floods and extreme weather

The key risk concepts described above are applied to an example from British Columbia, Canada, to further illustrate these concepts.

Figure 6 Damage to Highway 1 Tank Hill Underpass in British Columbia, Canada, due to extreme rain event in November 2021

Source: BC Ministry of Transportation and Infrastructure / flickr

In November 2021, intense precipitation known as an atmospheric river in south-western British Columbia, Canada, resulted in floods and landslides that washed out or severely damaged highway and rail infrastructure (Figure 6). There was a small possible contribution from recent wildfires in the region on increasing potential for runoff. Five people lost their lives, and the City of Vancouver was completely cut off from the rest of Canada by road and rail, leading to massive economic losses and supply chain disruptions (the Port of Vancouver is Canada's gateway to the Asian market). Subsequent research found that human-induced climate change has significantly increased the likelihood of such events (Gillett et al. 2022).

If a climate risk assessment of highway infrastructure was being conducted prior to the intense precipitation event occurring, the assessment may have found (in a highly simplified example):

- The **hazard** is an atmospheric river (intense precipitation)
- The **intermediate impacts** are flooding and landslides
- The highway infrastructure may be **exposed** to potential flooding and landslides.
- The **vulnerability** includes both:
  - **Sensitivity**, such as the lack of forests on some slopes due to recent wildfires, which could reduce ground stability or reduce infiltration
  - **Adaptive deficit,** such as missing warning and monitoring systems
- The **severity of impact** would be the highway infrastructure being disrupted, damaged or completely washed out
- The **likelihood** of such an event is increased due to climate change
- There could be high **climate risk**, given the high severity of impact and high likelihood
- The **subsequent impact** of the highway infrastructure being disrupted, damaged or completely washed out is potential morbidity or mortality, and economic disruptions

Taking a systems thinking approach would consider how the social-ecological system could increase or decrease the highway infrastructure's climate risk (e.g., loss of ecosystem services due to forest fires increases risk) but also the subsequent impact on the system if the highway infrastructure is damaged (e.g., economic and supply chain disruptions).

Consideration of vulnerability would take into account sensitivity and adaptive capacity/deficit factors related to both the social-ecological system and the infrastructure itself.

3 Fundamentals of Risk Assessment

Climate risk assessments are a crucial component to guide, design and operate infrastructure and systems that are resilient to the effects of extreme weather and climate change. Climate risk assessment is a process of identifying how assets would respond to and recover from the impacts of a variety of climate hazards. Many governments and organizations are using or requiring climate risk assessment to inform adaptation action.

In a risk assessment you will answer three questions (Bedford and Cooke, 2006):

1. What can happen and what are causes / why it can happen? (climate hazard, vulnerability)
2. How likely is it to happen? (likelihood)
3. If it were to happen, what would be the impact? (severity of impact)

Typically, infrastructure will be exposed to more than one climate hazard. When starting a climate risk assessment, it is thus necessary to specify the risk(s) the study focuses on, to identify factors contributing to the risk(s) and to clarify who or what may be affected. Especially when incorporating a social-ecological system approach to infrastructure risk assessment, drivers of risk are searched beyond the physical or operational configuration of the infrastructure. The question is then, how characteristics of the social-ecological system (and its ecosystem services) contribute to the infrastructure's risk of functionality or loss of physical integrity. Examples of risks include risk of reduced operability of a dam due to sedimentation because of erosion (i.e., loss of protecting function of the soils) in the catchment and risk of damage to transport infrastructure due to heavy rains causing landslides and floods. Extreme heat on the other hand can contribute to forest fires causing road closures. But in many cases, we are experiencing also combined hazards and intermediate impacts, for example, forest fires leading to hydrophobic soils unable to retain water and additional torrential rains leading to even stronger landslides and so on.

Risk is something where the 'outcome is uncertain'. Climate change impacts are uncertain, for example, since the future of socio-economic pathways and greenhouse gas emission pathways are uncertain. In a climate risk assessment, this uncertainty can be addressed in different ways. Scenario approaches are commonly applied, for instance, different climate impacts for different greenhouse gas emission scenarios (i.e., IPCC Shared Socioeconomic Pathways). We present climate risk as a function of hazard, exposure, vulnerability, and likelihood as proposed by the IPCC in its AR6 report (IPCC 2022), but and recommend making uncertainty explicit wherever possible (see Corner et al. 2015, for guidance on communicating uncertainty).

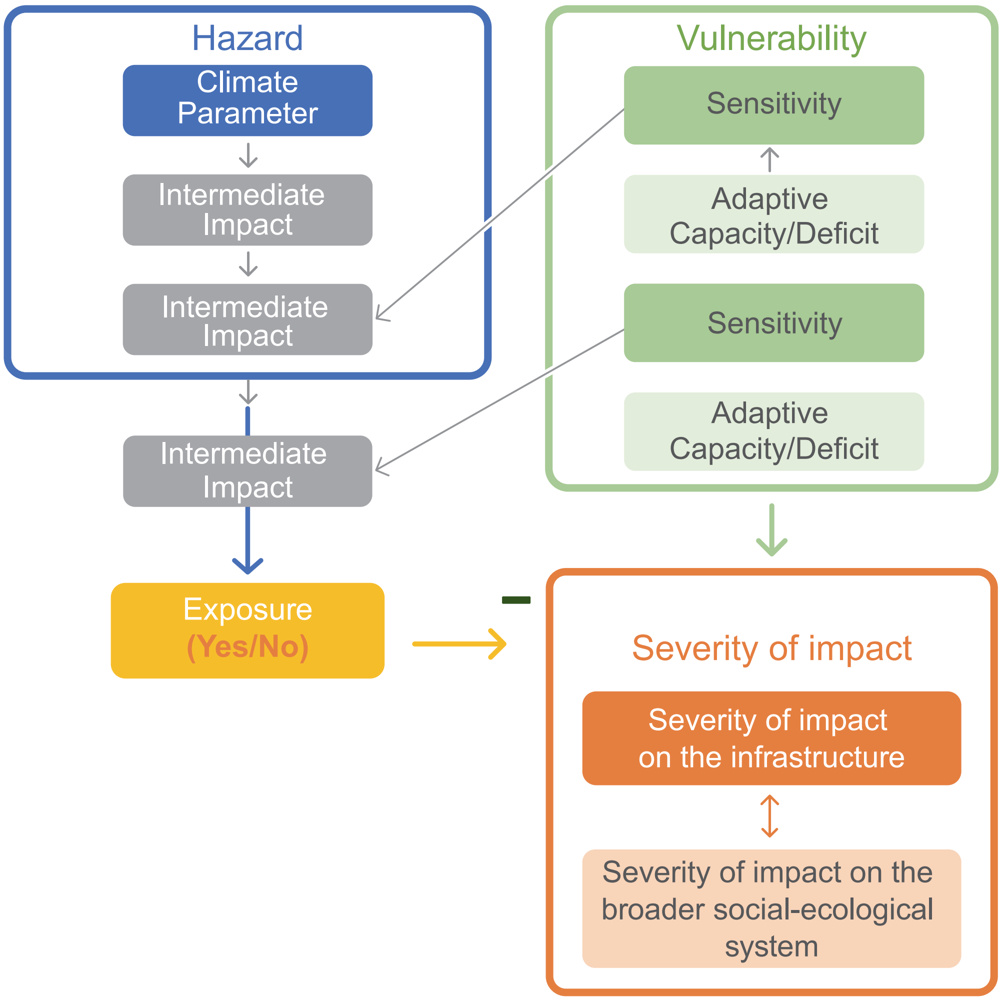
Under the PIEVC Green Protocol, the primary focus of the climate risk assessment is the infrastructure, including the interactions of the broader social-ecological system with the infrastructure in the context of climate risk. Note that the purpose of the PIEVC Green Protocol is not to conduct a climate risk assessment for the entire social-ecological system. Conducting a climate risk assessment for the entire social-ecological system requires a slightly different approach with an emphasis on spatial aspects. For further guidance, see the GIZ guidebook "Climate Risk Assessment for Ecosystem-based Adaptation: A guidebook for planners and practitioners" (2018).

Impact Chains

The development of an impact chain, or cause-effect chain, can be used as an analytical tool that helps you better understand, systemise and prioritise the factors that drive risk in the system of concern, such as a social-ecological system where infrastructure is perceived as being coupled with its surrounding ecosystem and its services (Figure 7). Impact chains always have a similar structure: a climate parameter (e.g., a heavy rain event) may lead to a direct physical impact, causing a sequence of intermediate impacts (e.g., higher run-off contributing to flooding downstream impacting the water-level of the reservoir), which – due to the vulnerability of exposed elements of the infrastructure or social-ecological system – finally lead to a risk (or multiple risks) when the severity of impact is combined with likelihood. This process is not linear. For example, internal loops can lead to changes in the impact chain pathways and one link doesn't always lead to the next. Rather, the impact chain depends on the dynamics at a given point in time in a given system.

Impact chains are composed of risk components (hazard, exposure, vulnerability) and underlying factors for each of them and intermediate impacts as a supporting tool. The hazard component includes factors related to the climate parameters. The vulnerability component comprises factors related to the sensitivity of the social-ecological system and the adaptive capacity/deficit. Vulnerability factors can include sensitivity and adaptive capacity/deficit of the infrastructure itself and of the social-ecological system, as the system contributes to the vulnerability of the infrastructure being assessed. You can also add additional boxes to the impact chain to consider the drivers of sensitivity. In contrast to hazard, exposure and vulnerability, intermediate impacts are not a risk component by themselves, but merely an auxiliary tool to fully grasp the cause-effect chain leading to the risk. By definition, intermediate impacts are a function of both hazard and vulnerability factors. This means that all impacts identified which do not only depend on the climate parameter, but also on one or several vulnerability factors, need to be placed here. As opposed to a climate parameter, an intermediate impact can be influenced by measures.

Figure 7 Structure and key elements of an impact chain



Using the risk terminology based on the IPCC AR6 definitions, the impact chain as described here would in fact be a chain examining the severity of impact rather than impact itself since it does not take likelihood into consideration. We nonetheless use the term 'impact chain' since the development of impact chains is a well-known analytical methodology term.

Impact chain development: key steps and basic principles

The development of impact chains comprises four sequential steps:

1. Identify severity of impact(s) if they were to occur.
2. Determine hazard(s) and intermediate impacts.
3. Determine exposed elements of the social-ecological system.
4. Determine the vulnerability of the social-ecological system.

By assessing hazard, exposure, and vulnerability, you develop an analysis of the drivers that make up severity of impact.

A sound understanding of the system of concern and the incorporation of expert/local knowledge through a participatory process (e.g., workshops, focus group discussions) form the basis for the development of impact chains. Building such impact chains is an iterative process. New relevant aspects can emerge during the development process.

There are several basic principles to consider when you brainstorm on the various factors (elements within a risk component) to generate an impact chain:

- To avoid double counting, a factor should be allocated to one risk component only.
- Factors allocated to one component should (as much as possible) be independent of factors of other components.
- Factors representing potentially hazardous events can either be allocated to the hazard component (preferably when these events are external triggers, which can hardly be influenced by adaptation within the system) or classified as intermediate impacts (preferably when they are influenced by the vulnerability and can be reduced by adaptation).

The Risk Matrix

In risk assessments it is common to present risk results within the context of a risk matrix.

The risk matrix is a Cartesian chart with likelihood score listed on the **x-axis** and severity of impact score listed on the **y-axis**. The severity of impact score includes both vulnerability and exposure and is scored in Step 3 of the PIEVC Green Protocol. Risk scores are presented within the body of the chart. Within the chart, areas of low, medium and high risk can be denoted with colour coding (Figure 8).

The risk matrix is a visual representation of the risk profile of the infrastructure and its components, including relevant physical grey and green components. It can be used as a risk evaluation tool through stakeholder engagement and consensus building in the course of executing risk calculations and evaluation. It clearly denotes the circumstances leading to high-risk interactions of priority concern and low-risk interactions of little immediate concern, indicating the priority areas for adaptation. This is a useful tool that can help you to identify interactions that are potentially very sensitive to the assumptions underlying professional judgment.

For example, in the case outlined in Figure 8, interactions receiving risk scores of 15 or 16 might merit closer attention. In these cases, very minor shifts in the assumptions leading to likelihood and severity scores may result in shifting an interaction from medium risk to high risk.

Figure 8 Example risk matrix

Severity of impact		Likelihood 1	Likelihood 2	Likelihood 3	Likelihood 4	Likelihood 5
5		5	10	15	20	25
4		4	8	12	16	20
3		3	6	9	8	10
2		2	4	6	8	10
1		1	2	3	4	5

low risk; medium risk; high risk

4 Interdisciplinary Communication

The language and practices from the climate, natural sciences (e.g., biodiversity practitioners, ecologists), risk management, social sciences (e.g., economists, social safeguard experts) and engineering communities can differ, resulting in occasional challenges in communication, expectations and timelines during a climate risk assessment (see Annex C for a comparison of terminology interpretation in the engineering and climate communities). More broadly, before the various team members (e.g., the engineer, the climate scientist, the ecologist, the planner) even come to the table they may hold potentially divergent views (or framing) about what climate change is, why it's happening, the factors contributing to vulnerability and risk, and what role adaptation can play (Fünfgeld & McEvoy, 2011). See Annex D for team composition considerations.

Practitioners may have completely different interpretations of the same risk terms, leading to potential miscommunication and misunderstandings that could compromise the climate risk assessment results. For many climate change practitioners, the most recent IPCC assessment reports represent the most important source for climate risk concepts and definitions, based on a rigorous approach and scientific consensus. Meanwhile, for many risk management practitioners, international standards such as ISO 31000, ISO 14090 or ISO 14091, may be the core reference for a consistent approach amongst practitioners. The PIEVC Green Protocol follows the definitions and conceptualization of risk terms as described in the IPCC 6th Assessment Report, thus it's important to consider how team members from other practitioner, sectoral or disciplinary communities may use these terms differently when following this Protocol.

For example, to a scientist, being "conservative" means essentially not drawing conclusions beyond what can confidently be inferred from scientific analysis. For example, in sea-level rise, being conservative could mean using "low estimates" (e.g., 0.5 metres) to a scientist. However, to an engineer, largely interested in protection, being "conservative" would normally mean the exact opposite (i.e., using high estimates, such as 1 metre).

Even defining the boundaries of the social-ecological system can be challenging in an interdisciplinary team and requires deliberate discussion. A planner may consider the system to be defined by jurisdictional boundaries, for example, while an ecologist may consider the system to be defined by a watershed. These differences in framing need to be addressed head-on.

> To protect the validity of the risk assessment, it is helpful to conduct early discussions to identify team terminology issues and other differences in approach such that the precise terminologies and project guidelines are explicitly understood by all members of the team.

Tensions can be avoided by encouraging team members to initially discuss concepts, language, principles, practices and timelines as applied to the project. In particular, it is important that team members be explicit about their expectations regarding the scope, accuracy and level of detail necessary for them to professionally execute their assigned tasks. Teams must actively avoid making assumptions that all members possess the same understanding of technical jargon, professional language, context, and scope of information necessary for their work. These perspectives on a project may vary considerably between professional groups, and discussions regarding what each professional requires to ethically deliver their element of the project are essential and should be sustained throughout the assessment.

> Don't underestimate the impact that differences in language usage between different disciplines may have on the effective execution of an interdisciplinary assessment (see examples in Annex C).
>
> These differences can often lead to confusion and avoidable conflict unless practitioners are particularly sensitive to the nuances of language and professional culture as they manage their team and work with other stakeholders.

Part B

Climate Risk Assessment: Step-by-step guide

This part provides step-by-step guidance on how to complete a climate risk assessment for infrastructure that also considers the broader social-ecological system.

The PIEVC Green Protocol includes 5 main steps, with an additional 3 steps in a needs-based Triple Bottom Line Module for identifying and assessing adaptation options (Figure 9):

- **Step 1: Project definition** – defining the project parameters and boundary conditions for the climate risk assessment.
- **Step 2: Data gathering and sufficiency** – further defining the infrastructure and particular climate trends and projections that are being considered in the evaluation by developing an impact chain, conducting data acquisition, and assessing data sufficiency.
- **Step 3: Risk assessment** – combining information on vulnerability, exposure and likelihood to assess climate risk.
- **Step 4: Engineering analysis (optional)** – conducting focused engineering analysis on climate/infrastructure interactions requiring further assessment.
- **Step 5: Recommendations and conclusions** – providing recommendations and conclusions based on the climate risk assessment results.

- **Needs-based Triple Bottom Line Module: Identifying and Assessing Adaptation Scenarios**
  - **Step 6: Identifying adaptation scenarios** – generating different adaptation scenarios to address the risks identified in Steps 1-5.
  - **Step 7: Assessment of adaptation scenarios** – comparing and assess adaptation scenarios generated in Step 6.
  - **Step 8: Recommendations and conclusions** – making recommendations for adaptation scenarios preparing final documentation and presenting results.

Figure 9 Overview of the climate risk assessment process

The steps in the PIEVC Green Protocol are aligned with the original PIEVC Protocol steps, with mainstreamed guidance on considering the social-ecological system, some new methodological tools (e.g., impact chains) and updated to the IPCC Sixth Assessment Report risk concepts. See further comparison between the PIEVC Green Protocol and PIEVC Protocol in Part A.

Within each step there are several activities to be completed. Though these steps (and the activities they contain) are laid out in a linear fashion for clarity, in practice, sometimes earlier steps or activities will need to be revisited as further information is gathered or the context changes. Some activities may also be skipped if not relevant. Climate risk assessment is an iterative process, rather than a linear one.

Note that you may choose to conduct a high-level screening prior to, or instead of, executing a detailed climate risk assessment (see the PIEVC High Level Screening Guide [HLSG] for further guidance). The PIEVC HLSG process may also be the initial screening step before other processes or further detailed assessment.

Step 1 Project Definition

In this step, you will define the project parameters and boundary conditions for the climate risk assessment. This step narrows the focus to allow efficient data acquisition and assessment of climate risk. This step will define:

- Which infrastructure is being assessed
- The infrastructure's location
- Uses of the infrastructure
- Climate and geographic considerations
- Severity of climate impacts and potential risks to be assessed in detail

The key activities of Step 1 are presented in Figure 10, within the context of the PIEVC Green Protocol steps, and described in greater detail below:

Figure 10 Step 1 key activities

1. Identify the infrastructure

a. Choose the infrastructure to be evaluated for climate change risk.

b. Provide a general description of the infrastructure.

c. Reference additional background and detailed information sources, such as engineering drawings, infrastructure component capacity and performance specifications, operator interviews, and management policies and procedures.

2. Identify climate parameters

a. State the climate parameters that will be considered in the evaluation.

   i. Based on professional judgment, identify which climate hazards may contribute to infrastructure vulnerability.

   ii. Based on professional judgment, identify which climate hazards may ***combine*** to create infrastructure vulnerability (Box 1).

b. See Annex E for additional guidance on climate information

3. Identify the Time Horizon

a. For the climate risk assessment, define the period over which the infrastructure must operate, and over which climate hazards will be projected.

> Box 1 – Combined climate hazards may occur sequentially, such as snow events followed by high ambient temperatures, or simultaneously, such as hail events in combination with extreme precipitation. While individual climate hazards may not constitute a risk, the combined events may result in conditions that result in vulnerability.

4. Identify the severity of climate impacts

a. As a basis for the next steps, including the impact chain development, identify severity of climate impacts and risks (e.g., risk of damage to infrastructure due to landslides triggered by extreme rainfall events), without quantifying the degree of severity. See explanation of 'severity of impact' in Part A if needed.

b. The severity of impacts and risks can be to the infrastructure itself, or on the system if the infrastructure's and system's thresholds are exceeded and subsequent impacts occur (e.g., risk for public safety if water levels behind a dam get too high for spillways and overtop the dam).

5. Identify the ecosystem and geography

a. Summarize site-specific, local, ecosystem, ecosystem services and/or geographical features relevant to the infrastructure and hence the assessment.
   i. Decide on the geographic scope of the assessment (e.g., a community, a river delta) and whether there is a specific spatial scale that needs to be considered. Note: geographic scope needs to be selected based on the nature of the infrastructure of focus (e.g., a dam vs. a small road segment), and the system boundaries of the ecosystem that is closely interdependent with the infrastructure.
   ii. This activity is an opportunity to begin identifying how the surrounding ecological system may increase or potentially decrease the infrastructure's climate risk, or how the ecological system may be at risk in different ways if the infrastructure is impacted by climate change.

b. Provide references.

6. Identify jurisdictional and socio-economic considerations

a. List the jurisdictions, laws, regulations, guidelines and administrative processes that are applicable to the infrastructure.

b. List relevant stakeholders, both internal and external to the organization that may be directly affected by the organization's risks and adaptation measures.

c. Begin identifying how the surrounding socio-economic system may increase or decrease the infrastructure's climate risk, or how the socio-economic system (e.g., local communities) may be at risk in different ways if the infrastructure is impacted by climate change.

d. Provide references.

7. Site visit

a. Conduct a site visit.

b. Based on information gathered to date, conduct interviews with facility owners and operating personnel to field-test and validate initial project definition findings.

c. If possible, interview members of the community to better understand interactions with the infrastructure, ecosystem and climate risks.

d. Examine infrastructure and local geographical and ecosystem features as they may apply to the climate risk assessment.

e. Note key observations and areas for follow-up in subsequent assessment steps.

Step 2 Data Gathering and Sufficiency

In this step, you will provide further definition regarding the infrastructure, climate trends, climate projections and the social-ecological system that are being considered in the evaluation, based on the development of an impact chain. You will undertake a data acquisition exercise and identify where, based on professional judgment, the data is insufficient. Data insufficiency may arise from:

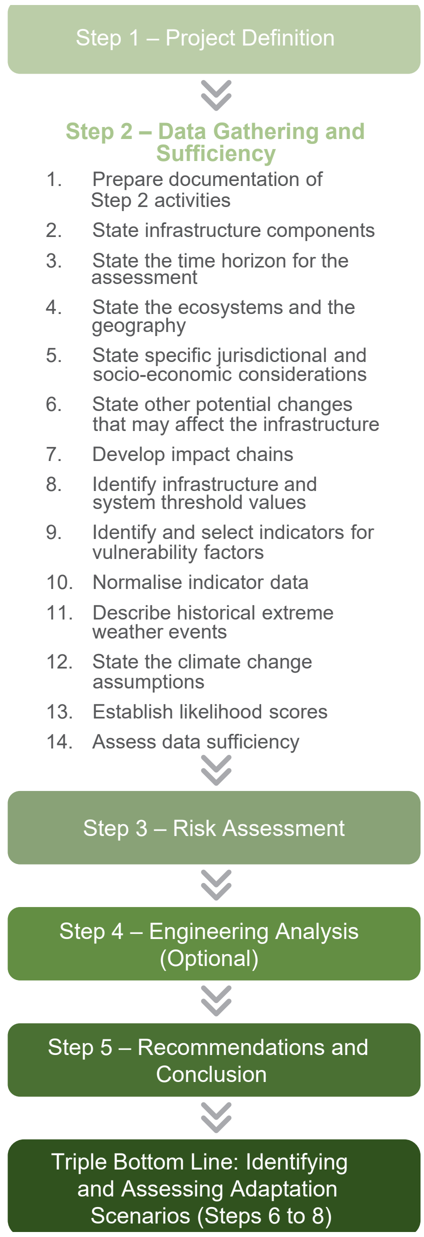
- Poor quality
- High levels of uncertainty
- Lack of data altogether

This step further focuses the evaluation and starts to establish activities to infill poor quality or missing data.

Given the diversity of information needed to understand interactions with the infrastructure's surrounding social-ecological system, Indigenous, traditional or local knowledge is highly valuable throughout the PIEVC Green Protocol process.

The entire PIEVC Green Protocol and especially Step 2 are iterative processes. While the activities are given in a specific order, new factors may come up that require returning to earlier activities. The key activities of Step 2 are presented in Figure 11, within the context of the PIEVC Green Protocol steps, and described in greater detail below:

Figure 11 Step 2 key activities



1. Prepare documentation of Step 2 activities

a. Practitioner documentation MUST detail each task outlined in this step of the Protocol.

2. State infrastructure components

a. List the major components of the infrastructure that are influenced by climate.
   i. Only select those infrastructure components that, in your professional judgment, are relevant to this assessment.
   ii. Where available, review operations incident reports, daily logs and reports to assist in the identification of infrastructure components with a history that could result in vulnerability and are relevant to this process.

iii. Interview infrastructure owners, operators and maintenance staff to identify historical events that may not be documented or retrievable from databases and evaluate if these events are relevant to this assessment.

b. Provide references.

All infrastructure comprise organized systems of equipment, processes or structures. For this assessment, you will need to assess the infrastructure system and subdivide the overall system into logical components. This is infrastructure specific. In some systems, you may evaluate individual pieces of equipment or structures as infrastructure components. Examples may include individual culvert structures in a roadway or drainage system. In other cases, you may group equipment or structure categories. For example, all culverts in the infrastructure system may be grouped and assessed as one sub-component. In some cases, the entire infrastructure may be classed as a single entity and evaluated. This could be done if in the professional judgment of the team, there would be no differences in climate risk by defining the infrastructure to the component level.

Component, sub-component selections must be based on professional judgment and are dictated by the scope of the climate risk assessment. These choices can drive the level of analysis of the assessment. If there are too many sub-components, the assessment may become expensive and difficult to manage. On the other hand, if the selection of sub-components is insufficiently detailed, the assessment may miss potentially vulnerable infrastructure sub-components.

3. State the time horizon for the assessment

a. State the period over which the infrastructure must operate.
b. State the design life of the infrastructure components.
c. Document the maintenance and/refurbishment schedule for the infrastructure as it may apply to the useful service life of the infrastructure.
d. State the useful service life remaining in the infrastructure components.

Local geographical features may result in subsequent impacts following a climate impact on infrastructure. For example, a minor culvert failure resulting from a rainfall event could result in loss of slope stability leading to a mudslide. You may judge the culvert failure to be a low risk but the contribution to the subsequent impact on the broader social-ecological system may be quite significant. You are encouraged to consider the sequence of events arising from projected failures as one element of the risk assessment, as part of the impact chain development. Knowledge about local geographical conditions is one key element of this analysis.

4. State the ecosystems and the geography

a. List the major features of the local ecosystems and geography that may impose or reduce subsequent impacts on the different components of the infrastructure listed, building on those identified in Step 1 Activity 5.
   i. Try to find out which ecosystems play a key role contributing to the risk and potentially reducing the risks and how they are managed. What key ecosystem services (e.g., water regulation, flood prevention, erosion control) do they provide to the infrastructure that could reduce risks? For example, identify forests, wetlands, hills, valleys, river systems, lakes, ocean frontage that may moderate the risk of the infrastructure and the climate parameters considered in the evaluation.
   ii. Only select those geographical and ecosystem features that are within the geographical scope selected and, in your professional judgment, are relevant to this assessment.
   iii. State the sources of environmental and geographic information.

b. Provide references.

5. State specific jurisdictional and socio-economic considerations

a. Building on those identified in Step 1, as applicable, itemize:
   i. Jurisdictions that have direct control/influence on the infrastructure
   ii. Sections of laws and bylaws that are relevant to the infrastructure
   iii. Sections of regulations that are relevant to the infrastructure
   iv. Standards that are relevant to the design, operation and maintenance of the infrastructure
   v. Guidelines that are relevant to the design, operation and maintenance of the infrastructure
   vi. Infrastructure owner/operator administrative processes and policies as they apply to the infrastructure

b. Provide details on relevant stakeholders and socio-economic conditions within the geographic scope of the assessment, and how these may interact with the infrastructure's climate risk.

c. Provide references.

This information is necessary to evaluate other activities that could potentially influence infrastructure management, operation and maintenance. These factors could potentially influence infrastructure vulnerability or resiliency and must be considered when evaluating the impact of climate change on the infrastructure.

6. State other potential changes that may affect the infrastructure

a. Identify and document other factors that can affect the design, operation, and maintenance of the infrastructure:
   i. Document changes in use pattern that increase/decrease the capacity of the infrastructure (e.g., population change).
   ii. Document operation and maintenance practices that increase/decrease the capacity or useful life of the infrastructure.
   iii. Document changes in management policy that affect the load pattern on the infrastructure.
   iv. Document changes in laws, regulations and standards that affect the load pattern on the infrastructure.

7. Develop impact chains

See explanation of impact chains concept in Part A and a fictional example in Figure 12. The development of impact chains is highly recommended to be done in a participative workshop with multidisciplinary stakeholders.

a. Based on the information collected in Step 1 and in Step 2 Activities 1-6, identify the severity of impact(s), determine climate hazards, identify intermediate impacts, identify the vulnerability and determine if the infrastructure is exposed (see suggested order in Figure 13):
   i. Identify severity of impact(s).
      1. Recall that the severity of impacts can be to the infrastructure itself, a single infrastructure component, or to the social-ecological system.
      2. Consider what would be the severity of impact if the selected infrastructure or its component(s) interact with climate hazards, and how the infrastructure would respond.
      3. If the assessment covers more than one risk (e.g., of increase in erosion and risk of damage to critical infrastructure due to tropical storms), different impact chains could optionally be developed for each risk. For example, a different impact chain could be developed for each of the infrastructure components selected in Step 2 Activity 2. These could then be combined in a later stage of the risk assessment (see Step 3).
   ii. Determine climate hazards.
      1. Consider which climate parameters could pose a risk to the infrastructure and broader system of concern, and which intermediate impacts link the climate parameter and the severity of impact(s).

2. Identify the relevant climate parameter(s) (e.g., too much precipitation) that lead(s) to the severity of impacts identified earlier in the impact chain development. The climate parameter leads to a sequence of intermediate impacts (which can be partly influenced by the vulnerability of the social-ecological system), such as too high-water levels or increased flow velocity and flooding.
   a. For all climate parameters and intermediate impact factors, try to use wording that implies a critical state, e.g., 'too much precipitation' rather than 'precipitation'.

iii. Identify Intermediate Impacts (Potential Cumulative or Synergistic Effects) that link the climate parameters to the severity of impact.
   1. Review the selected climate parameters and evaluate the potential cumulative impact of combining or sequencing weather events and/or climate trends to assess the possibility of these combined events yielding a higher impact compound event.
   2. Consider the potential for compounded risk if the broader system is not considered beyond the infrastructure project. For example, there may be compounded risk from simultaneous erosion upstream from a dam along with a flooding event.

iv. Identify the vulnerability of the infrastructure or the selected infrastructure components.
   1. Factors allocated to the vulnerability component should represent two aspects, sensitivity and adaptive deficit[3] (see definitions of sensitivity and adaptive deficit/capacity in Part A).
   2. Consider the state of relevant ecosystems, their services (particularly regulating services) and how they might contribute to increased climate risk(s) and/or help to mitigate risk(s) of the infrastructure or selected component.
   3. Consider also adding to your impact chain what the drivers of sensitivity could be.

Consider also, if possible, how climate change may impact the ability of ecosystems and their services over time to mitigate the risk of climate change on infrastructure.

v. Determine if the infrastructure or selected infrastructure components are exposed (yes/no) to the climate hazard(s) identified.
   1. If yes, continue to the next activities and steps.

b. Remember that impact chain development is an iterative process which means that you might go back to earlier steps or activities at any time.

c. See the GIZ Climate Risk Assessment for Ecosystem-based Adaptation guidebook for additional examples of impact chains (GIZ, EURAC & UNU-EHS, 2018).

[3] Recall that here the term adaptive deficit is used rather than adaptive capacity. That is because sensitivity is a negative trait, and for the analysis to align it is simpler for both vulnerability components to be negative.

Figure 12 Example impact chain, loosely based on British Columbia example in Part A, with some aspects added for educational purposes

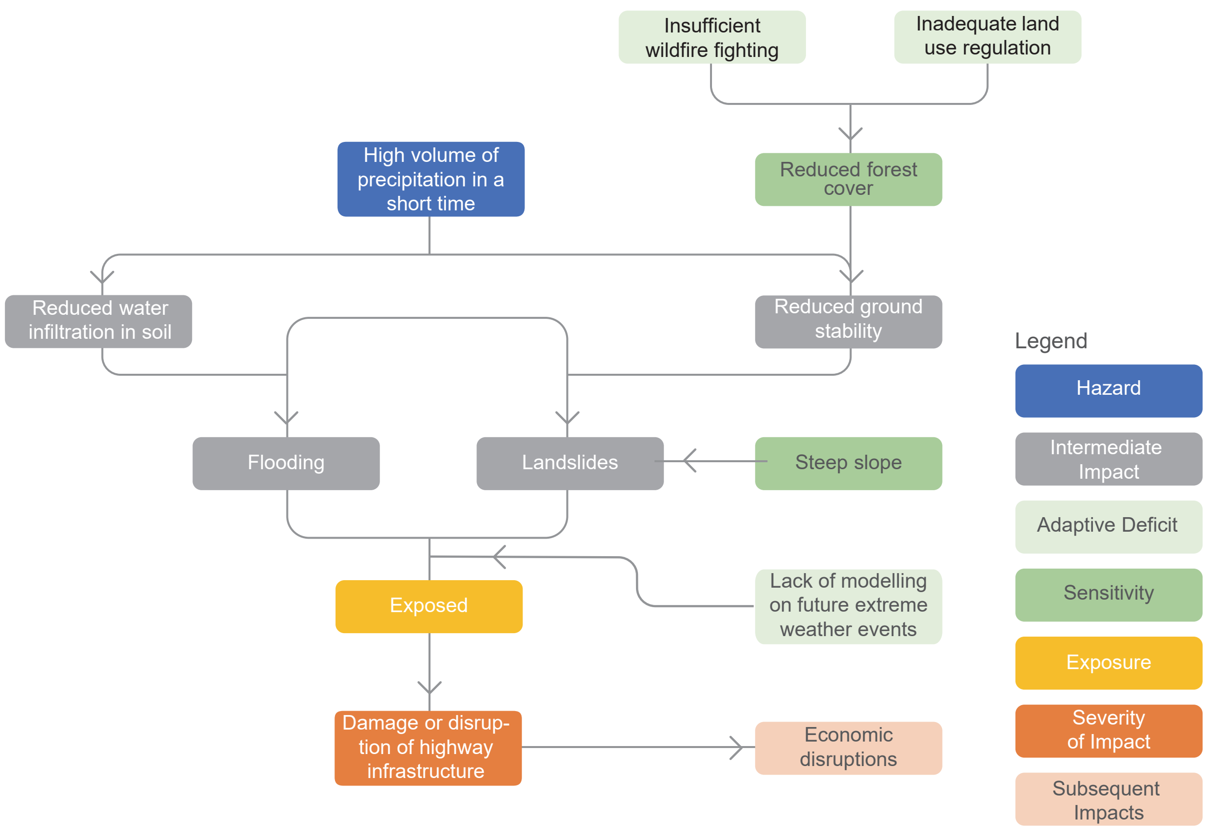
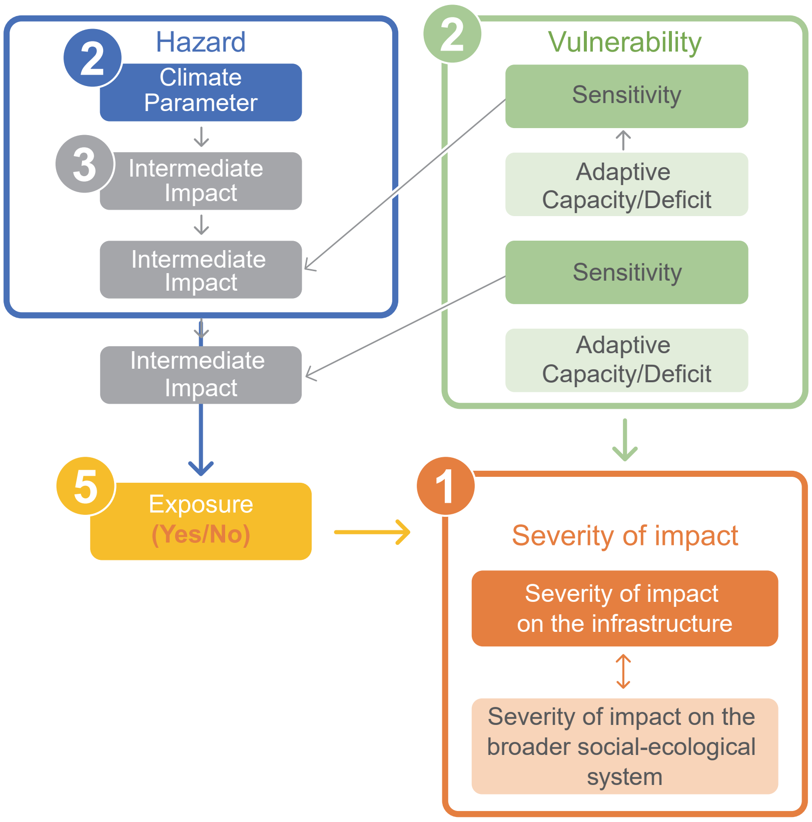


Figure 13 Suggested order of activities for impact chain development



The following two activities relate to vulnerability indicators. Figure 14 lists all three activities related to vulnerability indicators, spread across Steps 2 and 3.

8. Identify infrastructure and system threshold values

a. For each climate parameter selected, identify a threshold value above which, or below which, the infrastructure performance will be affected.
   i. Threshold values may be based on:
      1. Codes
      2. Standards
      3. Engineering Guidelines
      4. Operating or Maintenance Procedures
      5. Professional Judgment
      6. Other factors, as appropriate
   ii. As appropriate, several different thresholds may be identified for a specific climate parameter based on varying degrees of infrastructure response arising from parameter values changing over a broader range.
      1. In such cases, each parameter-threshold pair would be treated as a separate event within the context of the assessment.

b. Identify thresholds or tipping points for the performance of ecosystem services, if possible. For example, there can be thresholds for soil stability with a given soil characteristic and slope, thresholds of water absorption capacity of soils depending on land use, or a threshold for trees to collapse due to wind speed.

c. Clearly document the source of the threshold value.

d. Provide justification for the threshold value selected.

e. Revise the impact chain if needed based on this threshold information.

> For example, the individual impact of hail and rain events may be considered very low risks while the cumulative impact of a hail event followed by rain may be considered a significantly higher risk overall. Or, a single 100-year storm event is considered to be minor while two such events over a 48-hour period are viewed to be very significant.

9. Identify and select indicators for vulnerability factors

a. Select indicators for the level of sensitivity and of adaptive deficit to determine describing vulnerability (see examples in Table 1).
   i. Integrate the identified infrastructure threshold values (Step 2 Activity 8) into the infrastructure indicators.
   ii. Recall that indicators from the broader social-ecological system can be included, such as the system thresholds identified in Step 2 Activity 8 as they contribute to increasing or decreasing the infrastructure's (or its components') sensitivity or adaptive deficit (e.g., missing buffer strips – percentage of river line aligned by buffer strips).

b. Check if indicators are specific enough
   i. Check again that each indicator is a suitable description of the factor, that it is explicitly phrased, and that it has a clear direction regarding the risk considered.

c. Create a list of provisional indicators for each risk factor
   i. At this point, at least one indicator per factor in the impact chain will have been identified.
   ii. Compile all indicators in a table with relevant information about each indicator: the reason for selecting it, the spatial as well as temporal coverage, unit of measurement, intervals for updates, and potential data sources required.

Figure 14 Activities related to vulnerability indicators in Steps 2 and 3

Table 1 Examples of sensitivity and adaptive deficit indicators

Component	Factor	Indicator
Sensitivity	Lack of vegetation on slope next to infrastructure	Percentage of slope not covered by vegetation
Sensitivity	Pavement surface material of highway	Index of surface condition
Adaptive deficit	Restoration of ecosystems	Absence of programme for ecosystem restoration
Adaptive deficit	Maintenance of infrastructure	Lack of financial investment in maintenance

10. Normalise indicator data

The different indicator datasets need to be transferred (normalized) into unitless values with a common scale from 0 (optimal, no improvement necessary or possible) to 1 (critical, system no longer functions) (see Box 2).

a. Determine the scale of measurement for each indicator (e.g., metric, ordinal for descriptive classes).

b. Normalise the indicator values using one of the following two approaches, depending on the scale of measurement:

   i. For metric values:

      1. Check the 'direction' of the value range and define thresholds.

      2. The values of indicators measured using a metric scale are allocated to numbers between 0 and 1, with '0' representing an optimal and '1' representing a critical state. Identified thresholds define the range of indicator values that represent this range of criticality levels.

   ii. Indicators specified by categorical values and an ordinal scale (e.g., land cover, soil type, government efficiency):

      1. Apply a five-class evaluation scheme following a rating scale by defining classes with a meaning applicable to the risk assessment from class value 1 = optimal to class value 5 = critical (Table 2).

Box 2 Normalisation of indicator data

Normalisation converts numbers into a meaning by evaluating the criticality of an indicator value with respect to the risk. Assigning indicator values to numbers ranging from 0 to 1 requires setting thresholds. For some indicators these thresholds are obvious. For example, in the case of 'percentage of area covered by natural forest,' the value '0 %' is critical and represents the upper threshold of the normalization range: during the process of normalization, it will be transformed to the value '1.' The value '100 %' is optimal and represents the lower threshold of the normalisation range: it will be transformed to the value '0.'

In other cases, the allocation of thresholds is less evident. For instance, in a drought-prone area a region with an annual precipitation of 600 mm/year may be '0' (optimal), while a region with precipitation of 200 mm may be '1' (critical). Precipitation values between 200 mm and 600 mm will be allocated to respective values between 0 and 1. Values exceeding this range will be either allocated to 0 (in this example all values > 600 mm will receive the number 0) or to 1 (all values < 200 mm) (see also Step 2). For this normative step, it is highly recommended to involve experts to agree on a suitable evaluation scheme.

Table 2 Class scheme for variables with ordinal scale

Categorical class values within the range of 1 to 5	Class value within range of 0 to 1	Description
1	0.1	Optimal (no improvement necessary or possible)
2	0.3	Rather positive
3	0.5	Neutral
4	0.7	Rather negative
5	0.9	Critical (could lead to high severity impact(s))

The following activities 11-13 involve establishing the likelihood score and gathering the relevant information needed. See Annex F for additional guidance on establishing likelihood scores.

11. Describe historical extreme weather events

a. List historical extreme weather events:
   i. Identify the frequency of the events
   ii. Identify the duration of the events
   iii. Identify the date(s) of the events
   iv. Identify the magnitude/intensity of the events
b. If data is not available:
   i. Based on professional judgment, infill missing data using reasonable assumptions.
   ii. Provide written justification/substantiation for the assumptions.
a. List the values that are chosen.
b. Provide references.

> Often the owner of the infrastructure will already have an ongoing database of climate information as it pertains to infrastructure design, operation and maintenance. They may have already accessed the sources identified above to create this database. You are encouraged to review the climate data needs with the owner and operator of the infrastructure prior to engaging in other data gathering activities.

12. State the climate change assumptions

a. Assess the relevancy and applicability of observed global, regional or site-specific climate trends with respect to the infrastructure.
   i. Document how these trends influence the infrastructure.
b. Where appropriate, identify incremental changes to the climate normals conditions based on the trends identified in (a) above.
c. Where appropriate, use surrogate information from other geographic areas to respond to identified data gaps and uncertainties.
   i. Document the source of the infill data.
   ii. Provide written justification/substantiation for using the infill data.
a. Where appropriate, use a multi-model ensemble of global or regional climate change models to identify how the region's climate is projected to change.
   i. Review the basis and basic assumptions of the models.
   ii. Provide written justification/substantiation for using the models in the evaluation and for the selection of emission scenarios.

> You are encouraged to base initial assessment on observed trends, surrogate information and professional judgment prior to engaging in a regional climate modelling exercise. Climate modelling can be time-consuming and expensive. By sequencing the work in this fashion, you will be able to make an educated decision regarding the need for climate modelling in this particular assessment and will also be able to focus the scope of the modelling to ensure a more timely and cost-effective application of resources.

13. Establish likelihood scores

a. Using the information gathered in the impact chain development (Step 2 Activity 7), identify the climate parameters, climate indicators, and climate indices of interest for the infrastructure elements under assessment.
   i. Identify the climate hazards associated with the potential malfunction or failure of each infrastructure element.
   ii. Identify any combination of climate hazards that may result in infrastructure malfunction or failure.
      1. Examples of combination events include rain on snow, high temperature coupled with high humidity.
   iii. Establish for each climate hazard at least one indicator that represents the magnitude and/or duration of the hazard that could result in the malfunction or failure of the infrastructure element(s) under assessment.
      1. For combination events, identify the indicator that is relevant to contributing climate hazards (e.g., for rain on snow events, the indicator could be based on a certain amount of rain and snow, or combined into a synthetic snow-water total equivalent).
      2. Indicators for malfunction or failure may be based upon codes, standards, constructed design values, engineering guidelines, operating or maintenance procedures, professional judgement and experience, or other relevant information. Be sure to provide robust justification or rationale where possible for the chosen climate indicator.

b. For each climate hazard, determine whether an annual occurrence, or occurrence over the study time horizon, is of most concern.
   i. For example, extreme rainfall events may cause recurring flooding issues whose risk would be more usefully evaluated based upon the annual likelihood of occurrence.
   ii. On the other hand, organizations should also consider the risks of extreme, rarer but more devastating events like ice storms or tornadoes. It is important to note that climate models may not be able to defensibly support estimates of future changes in the frequency or intensity of phenomena such as tornadoes and that other techniques may be required to arrive at such estimates.
   iii. For these types of events, the low annual likelihood of occurrence in any given year is less telling but knowing about whether it could occur at least once over the study time would retain it within the organization's understanding of its risks.

c. Using the methods in Table 3, determine Likelihood (L) scores. The process should be repeated for a baseline climate period and any future climate horizons selected. The primary method shown in the table below is referred to as the "middle-baseline" scoring method, which is seen as appropriate for a screening level assessment.

d. The "middle-baseline" scoring method assigns likelihood to hazard indicators by establishing the baseline conditions in the historical period (e.g., 1981–2010), with the mean conditions over this period being represented as a 3 in the scoring system. For example, if the climate hazard chosen is Days with Maximum Temperature over 35°C and historically, these occur 5 times per year, this would be represented in the baseline period by a 3 on the likelihood scale.

e. Using the time horizon(s) chosen for climate change projections, the scoring system allows for the scores to increase or decrease depending on the percent change from baseline frequency. For example, if Days with Maximum Temperature over 35°C increase from 5 times per year to 7 times per year (an increase from baseline of 40%), the score for this future time horizon is 4. If they increase to 12 times per year (140% from baseline), the score for the future time horizon is 5.

f. The "middle-baseline" scoring scenario is flexible and allows for interpretation by the project team.

g. It is also appropriate to use other scoring systems, with appropriate documentation and justification for the choice made by the project team.

h. See additional key considerations in establishing likelihood scores in Box 3 and further guidance in Annex F.

Table 3 Example scoring methodology

Likelihood Score (L)	Middle Baseline Approach – Establish Base	Method	Suggested Rationale
1	↑	Likely to occur less frequently than current climate	50 – 100% reduction in frequency or intensity with reference to Baseline Mean
2			10 – 50% reduction in frequency or intensity with reference to Baseline Mean
3	Establish Current Climate Normal per Parameter	Likely to occur as frequently as current climate	Baseline Mean Conditions or a change in frequency or intensity of ±10% with reference to the Baseline Mean
4			10 – 50% increase in frequency or intensity with reference to Baseline Mean
5	↓	Likely to occur more frequently than current climate	50 – 100%+ increase in frequency or intensity with reference to Baseline Mean

Box 3 Additional key considerations for the likelihood scoring process

Scoring is an iterative process, where hazard definitions and likelihood scores are developed by the climate specialist and reviewed with the project team. Time for revisions and consultation should be considered in the process.

Hazards should not only include historically occurring hazards, but ones that could potentially manifest under future climate change. For example, if a region has never experienced maximum temperatures over 40°C historically but could within the assessment time horizons, this hazard should be included in analysis.

Some hazards may require multiple indicators/thresholds as severity of impact is not always proportional to event likelihood.

Estimates of likelihood are sometimes based on climate parameters that are not perfect matches for the ones of interest by the project team. This is possible as likelihood scores represent a wide range of likelihoods within each "bin."

In some cases, to avoid biasing the scoring process with a conflation between changes in likelihood and severity of impact, it is appropriate to withhold climate likelihood scores until after the severity of impact scoring is complete. Whether the two processes are completed separately before joining the results is a decision to be made by the project team.

14. Assess data sufficiency

Review the dataset developed in **Step 2 Activities 1 to 13**.

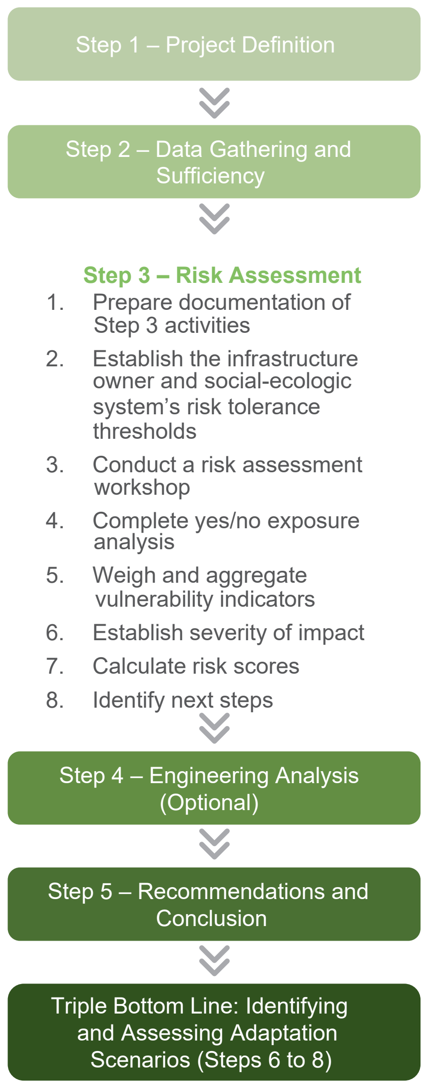
a. For data selected for the evaluation, assess and comment on:
   i. Data gaps
   ii. Data quality
   iii. Data accuracy
   iv. The applicability of trends
   v. Reliability of selected climate model(s)
   vi. Reliability of climate change assumptions or scenarios
   vii. Other factors, as appropriate
b. Clarify and summarize the priority of the documentation referenced in the evaluation.
   i. Present these in a tabulated prioritized form.
   ii. The intent is to reduce confusion in applying documents where dissimilar information, direction, or recommendations may possibly be provided.
c. Document where there is insufficient information currently available to proceed with a particular portion of the assessment.
d. Where there is insufficient information currently available, identify a process to develop or infill that data.
e. Where data cannot be developed, identify the data gap as a finding in Step 5 of the PIEVC Green Protocol – Recommendations.

Step 3 Risk Assessment

In this section, you will combine information on vulnerability, exposure and likelihood to assess climate risk.

The key activities of Step 3 are presented in Figure 15, within the context of the PIEVC Green Protocol steps, and described in greater detail below:

Figure 15 Step 3 key activities



1. Prepare documentation of Step 3 activities

f. Practitioner documentation MUST detail each task outlined in this step of the Protocol.

2. Establish the infrastructure owner and social-ecologic system's risk tolerance thresholds

a. Review the reference set of risk tolerance threshold values with the infrastructure owner.
b. The reference threshold values are presented in Table 4, if a 5x5 risk matrix is used. If a different matrix is used, adjust the risk range values.
c. Ensure that the owner understands the implications of these thresholds.
d. Ensure that the owner agrees to the use of these thresholds in the risk assessment.
e. If, in discussion with the owner, different thresholds are established, document these thresholds and use the infrastructure owner's threshold values in subsequent steps of the Protocol.
f. Obtain consensus with the infrastructure owner regarding the threshold values to be used in the risk assessment.

Table 4 Reference risk tolerance thresholds

Risk Range	Threshold	Response
<10	Low Risk	No action necessary
10 – 19	Medium Risk	Action may be required Engineering Analysis may be required
> 19	High Risk	Action required

3. Conduct a risk assessment workshop

a. Conduct a workshop with the infrastructure operations, management and engineering staff, all risk assessment team members, and other relevant stakeholders.
b. At the workshop, confirm preliminary information you identified in Step 2.
c. Carry out the following Step 3 Activities 4 to 7 in the workshop.
d. See Annex G for key considerations on conducting the workshop.

> Although the Protocol allows you to conduct the risk assessment through a series of one-on-one meetings, where necessary, experience to date demonstrates that a properly executed workshop yields the most robust risk analysis. It is therefore STRONGLY recommended that you use a workshop unless there are significant, compelling and material, reasons to the contrary.

4. Complete yes/no exposure analysis

a. Assess whether it is possible the infrastructure could be exposed to the identified climate hazard or intermediate impact (yes or no).
b. Where the team cannot decide if the exposure is possible, conduct further assessment.
c. Carry forward for further assessment all exposures tagged "Yes, exposure is conceivably possible."

> Yes/No analysis is a screening exercise. In cases where there are many climate parameters and infrastructure components, the number of potential interactions (exposure) can be very large. The Yes/No analysis removes irrelevant interactions from further analysis. This ensures that the actual risk scoring exercise is executed as efficiently as possible and avoids unnecessary allocation of staff and consultant resources on matters that do not contribute to the overall risk profile of the infrastructure. Yes/No analysis identifies exposure that could conceivably occur. The severity of those interactions is addressed in Step 3 Activity 6.

5. Weigh and aggregate vulnerability indicators

This activity allows you to weigh indicators if some of them are considered to have a greater or smaller influence on the severity of impact(s) than others. Recall that vulnerability is comprised of sensitivity and adaptive deficit. Multiple indicators for each sensitivity and adaptive deficit may be considered and each should be developed separately.

a. Weighting indicators:
   i. Assign weights to each of the indicators based on existing literature, stakeholder information or expert opinions.
   ii. Consider different procedures for assigning weights, from sophisticated statistical procedures (such as principal component analysis) to participatory methods.
b. Aggregating indicators:
   i. Aggregation allows you to combine the normalized indicators into a composite indicator representing a single severity of impact component.
   ii. Though there are various approaches, here the recommended approach is 'weighted arithmetic aggregation':

Step 3 – Risk Assessment

1. Individual indicators are multiplied by their weights, summed and subsequently divided by the sum of their weights to calculate the composite indicator of a risk component:

$$VI = \frac{(I_1 * W_1 + I_2 * W_2 + \cdots I_n * W_n)}{\sum_1^n W}$$

where:
VI = vulnerability indicator
I = indicator (of sensitivity or adaptive deficit)
W = weight

2. If there is no difference in weight, indicators are simply summed and divided by the number of indicators.

6. Establish severity of impact

a. Continue for the next activities only for the infrastructure or infrastructure components that are exposed (Step 2 Activity 4), based on the following formula:

Severity of impact = Exposure * Vulnerability

where:
Exposure = 1 (yes) or 0 (no)

b. Multiply the severity of impact result by 5 to convert it to a 5-point scale that can be used on the risk matrix in the risk calculation.

c. For additional guidance on establishing severity of impact scores, see Annex H.

Figure 16 Example risk matrix

Severity of impact					
5	5	10	15	20	25
4	4	8	12	16	20
3	3	6	9	12	15
2	2	4	6	8	10
1	1	2	3	4	5
	Likelihood				
	1	2	3	4	5

low risk; medium risk; high risk

7. Calculate risk scores

a. For each infrastructure or infrastructure component calculate the climate risk by the using the following equation and the matrix in Figure 16:

R = L × SI
where:

R = Risk
L = Likelihood of the

climate event or change
in the climate event
SI = Severity of Impact
(as a function of vulnerability
and exposure)

b. Record the calculated risk scores for each climate-infrastructure interaction.

8. Identify next steps

a. Discard from further evaluation:
   i. Low-risk interactions.
   ii. Medium-risk interactions that do not contribute to an overall pattern of risk.
   iii. Medium-risk interactions where you are confident with the reliability of the score as determined by the data sufficiency review.
b. Provide a written summary of interactions that are not considered for further evaluation and document their risk scores.
c. For high-risk interactions, go immediately to Step 5 and assess appropriate recommendations to address the identified vulnerability.
d. Identify interactions for Step 4 engineering analysis, as appropriate, and carry forward into Step 4. These would normally include:
   i. Medium-risk items that contribute to a pattern of higher risk.
   ii. Medium-risk items that could shift to higher risk based on minor increases in likelihood or severity.
   iii. High-risk items that contribute to a pattern of vulnerability including medium and high-risk interactions.
   iv. Other interactions deemed appropriate as approved by the infrastructure owner.
e. Identify matters that require additional study or evaluation outside of the current assessment and document these as recommendations in Step 5. These would normally include:
   i. Interactions requiring additional data that cannot be acquired within the schedule of the current risk assessment.
   ii. Evaluating climatic events that specifically contribute to heightened infrastructure risk where you and/or the infrastructure owner determine that a better understanding of the factors that contribute to the event can help resolve identified risks.
   iii. Areas where identified patterns of risk could be resolved through the development or amendment of codes, standards, guidelines, procedures, etc.
   iv. Special-case interactions requiring better definition that cannot be resolved within the budget and/or schedule of the current assessment.
   v. Other issues you deem appropriate.

Step 4 Engineering Analysis

In Step 4, you will conduct focused engineering analysis on climate/infrastructure interactions requiring further assessment, identified in Step 3.

This step is optional. Not every interaction requires engineering analysis. Normally, you would designate items for Step 4 analysis when it is deemed that additional, more focused analysis will further resolve the risk profile. This may include, but is not limited to:

- Interactions found to be medium risk during Step 3 that generated significant debate amongst team members.
- Interactions that were found to be part of a pattern of vulnerability, regardless of the risk assessment score.
- Areas where information gaps made Step 3 risk assessment problematic.
- Areas where additional work would help identify mitigation responses that can be immediately implemented.

The decision to conduct Step 4 analysis is fundamentally driven by available budget, depth of study required and project scheduling constraints. The Vulnerability Assessment Module of the PIEVC Protocol sets out equations that direct you to numerically assess:

- The total load on the infrastructure
- The total capacity of the infrastructure

Based on the numerical analysis:

- A vulnerability of the infrastructure exists when total projected load exceeds total projected capacity.
- Adaptive capacity of the infrastructure exists when total projected load is less than total projected capacity.

At this stage, you must make one final assessment about data availability and quality. If, in your professional judgment, the data quality or uncertainty does not support clear conclusions from the engineering analysis, revisit Step 2 to acquire and refine the data to a level sufficient for robust engineering analysis. You may determine that this process requires additional work outside of the scope of the assessment. Such a finding must be identified in the recommendations outlined in Step 5.

Once you have established sufficient confidence in the results of the engineering analysis, make recommendations based on your analysis (Step 5).

For more detailed guidance on how to conduct the Step 4 Engineering Analysis, see the PIEVC Vulnerability Assessment Module.

Step 5 Recommendations and Conclusions

In this section, you will provide conclusions and recommendations, and prepare a statement of risk.

The key activities of Step 1 are presented in Figure 17, within the context of the PIEVC Green Protocol steps, and described in greater detail below:

Figure 17 Step 5 key activities

Step 1 – Project Definition

Step 2 – Data Gathering and Sufficiency

Step 3 – Risk Assessment

Step 4 – Engineering Analysis (Optional)

Step 5 – Recommendations and Conclusion

1. Prepare documentation of Step 5 activities
2. Declare assumptions regarding available information, data sources, uncertainties and relevant limitations
3. State conclusions
4. State recommendations
5. Prepare statement of risk

Triple Bottom Line: Identifying and Assessing Adaptation Scenarios (Steps 6 to 8)

1. Prepare documentation of Step 5 activities

f. Practitioner documentation MUST detail each task outlined in this step of the Protocol.

2. Declare assumptions regarding available information, data sources, uncertainties and relevant limitations

a. Comment on the limitations of the climate risk assessment. These include limitations associated with:
   - i. Major assumptions
   - ii. Available infrastructure information and sources
   - iii. Available climate change information and sources
   - iv. Available other change information and sources
   - v. The use of generic or specific examples to represent populations
   - vi. Uncertainty and related concepts
   - vii. Analysis of the surrounding ecosystem
   - viii. Other relevant limitations, if they exist

b. These are the guiding steps for future practitioners who revisit your assessment of this infrastructure in later years.

3. State conclusions

a. Present specific conclusions arising from Steps 1 through 4.
   i. Report on infrastructure components that have been assessed to be vulnerable.
   ii. Summarize infrastructure components that have been assessed to be resilient.
   iii. Summarize role of broader social-ecological system in positively or negatively influencing the infrastructure components' risk.
   iv. Present impact chain results.

4. State recommendations

a. Present specific recommendations arising from Steps 1 through 4. As appropriate, classify recommendations into the following categories:
   i. Remedial engineering actions
   ii. Monitoring activities
   iii. Management actions
   iv. Actions to protect or strengthen surrounding ecosystems that reduce the infrastructure's risk
b. Report on data gaps and availability requiring additional work or studies.
c. Identify matters that require further action.
d. Identify and share lessons learned.

5. Prepare Statement of Risk

a. Based on the limitations, conclusions and recommendations outlined above, prepare a statement of risk.
b. For infrastructure that is deemed to be generally resilient the statement should include:
   i. A declaration that the infrastructure is generally resilient
   ii. A declaration of the global limitations of the assessment
   iii. A declaration of the time horizon of the assessment
   iv. A declaration of climate trends, climate projections or interactions that may contribute to the risk of the infrastructure
c. For infrastructure that is deemed to be generally at risk the statement should include:
   i. A declaration that the infrastructure is generally vulnerable
   ii. A declaration of the global limitations of the assessment
   iii. A declaration of the time horizon of the assessment
   iv. A declaration of climate trends, climate projections or interactions that significantly contribute to the risk of the infrastructure
   v. A declaration of the potential risks to the social-ecological system should the infrastructure or its component(s) be impacted

Figure *18 - Triple Bottom Line steps and key activities*

The Triple Bottom Line: Identifying and Assessing Adaptation Scenarios

The Triple Bottom Line[4] analysis can be conducted as a next phase upon completing the climate risk assessment. This needs-based module (i.e., Steps 6 to 8) is a decision-support system designed to aid organizations determine a course of action to reduce risk of infrastructure assets and services to climate change impacts. Once risks are identified (through Steps 1 to 5), scenarios for adapting the infrastructure system can be identified. If more than one scenario can be identified, they can be compared based on different criteria using a tool like the one set out in this guide. The process should be transparent and traceable. The identification and assessment of adaptation options is a high-level planning and screening exercise that relies heavily on professional judgment for its execution.

The steps and key activities of the Triple Bottom Line module are presented in Figure 18, within the context of the PIEVC Green Protocol steps, and described in greater detail below.

Figure 18 Triple Bottom Line steps and key activities

Step 1 – Project Definition

Step 2 – Data Gathering and Sufficiency

Step 3 – Risk Assessment

Step 4 – Engineering Analysis (Optional)

Step 5 – Recommendations and Conclusion

Triple Bottom Line: Identifying and Assessing Adaptation Scenarios (Steps 6 to 8)

Step 6 – Identifying Adaptation Scenarios

1. Establish decision-making context
2. Identify components at risk requiring adaptation
3. Identify subsequent impacts
4. Develop adaptation scenarios
5. Provide a basic description and high-level determination for each adaptation scenario
6. Screen adaptation scenarios

Step 7 – Assessment of Adaptation Scenarios

1. Choose evaluation factors
2. Establish evaluation matrix
3. Determine relative importance of evaluation factors
4. Evaluate the performance of adaptation scenarios
5. Aggregate performance scores based on weighting

Step 8 – Recommendations and Follow-up

1. Present MFA results and recommendations
2. Follow-up

[4] As implementing an infrastructure-adaptation strategy requires the allocation of limited resources, the decision-making process should not only integrate engineering criteria, but also consider economic, environmental and social factors, known as triple bottom line factors (TBL), when comparing adaptation and business-as-usual scenarios to make decisions more optimal for society.

Step 6 Identifying Adaptation Scenarios

The objective of Step 6 is to generate different adaptation scenarios for comparison. Recall that Steps 1-5 generally lead to the identification of several components or services within an infrastructure system at risk of climate change impacts. Adaptation scenarios, comprising both immediate and future measures, are designed to address those risks.

The main activities under Step 6 are:

1. Establish decision-making context

a. Revisit the results of Step 1 – Project Definition.
b. List infrastructure organizational goals, policies, mission statements and values as relevant to the infrastructure components and services under consideration.
c. List any operational, service level, technical, or safety requirements that are pertinent to the infrastructure.
d. List the jurisdictions, laws, regulations, guidelines and administrative processes that are applicable to the infrastructure.
e. Describe the social-ecological system surrounding the infrastructure.
f. List any other organizations that have jurisdiction in the infrastructure's location and area of service.
g. List any other potential (non-climate change related) changes and trends that may affect the infrastructure (e.g., changes in use patterns that affect infrastructure capacity, changes in operations and maintenance practices, changes in management policy; changes in laws, regulations, and standards).
h. List any available national or provincial programs and funding opportunities.

2. Identify components at risk requiring adaptation

a. List the main infrastructure components and services at risk requiring adaptation, based on the results of Steps 1-5.
b. For each vulnerable infrastructure component, include any functionally related infrastructure components[5] that the project proponent may wish to act upon. If it is uncertain as to whether actions on the main component will affect functionally related components, include the latter at this time.
c. Identify functional relationships between components.
d. For each infrastructure component or service, list the associated climate parameters and intermediate impacts causing the risk, along with relevant vulnerability factors (i.e., sensitivity and adaptive deficit).
e. Describe how the climate event will impact vulnerable components.

[5] Functionally related infrastructure components are generally those located adjacent to the infrastructure component being considered, and are structurally or operational tied, and where actions on one generally require modifications to the other. For example, where a culvert needs to be replaced, the road and embankment above the culvert could be considered as dependent components. In a water treatment plant, a chemical treatment process may be functionally dependent on the filtration system.

3. Identify subsequent impacts

a. List the plausible subsequent impacts to the social-ecological system if the risks to infrastructure components were to occur, based on the results of Steps 1-5. For example, if a road floods, a community's economic activities may be disrupted, community members may lose access to emergency health services, and vegetation may be uprooted.
b. For each subsequent impact, describe how the social-ecological system interacts with the infrastructure, its component or the system.

4. Develop adaptation scenarios (see key considerations in Box 4)

a. Identify adaptation scenarios, comprised of a range of alternative adaptation actions, that can address the infrastructure risks listed in Step 6 Activity 2.
b. Generate alternative adaptation actions that can address the vulnerabilities of each of the components listed. Where full independent alternative adaptation actions exist, create a new adaptation scenario for them.
    i. Build scenarios that address the risks of the overall system.
    ii. Include actions that address the risks of interdependent infrastructure components.
c. Develop as many alternative scenarios as possible to have the widest breadth of options from which to choose.
d. Impact chains developed in Step 2 can provide entry points and first guidance for the identification of adaptation options.
    i. The impact chains may need further revision as different adaptation scenarios are identified.
e. Identify potential co-benefits.
    i. For each adaptation scenario identified, brainstorm on possible social, economic and ecological co-benefits that could affect the different risk components (intermediate impacts, exposure, vulnerability). The factors identified for these components can serve as a starting point for such a brainstorming exercise.
f. Identify potential unintended consequences or drawbacks.
    i. For each adaptation scenario identified, brainstorm on potential unintended social, economic and ecological consequences or drawbacks.
g. Name adaptation scenarios to reflect the general nature of the actions contained within.

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Box 4 Key considerations in the process of identifying possible adaptation actions

- Adaptation options for infrastructure may generally be defined for the following generic adaptation domains:
  - Reduce the exposure of the infrastructure to climate change (e.g., upstream management).
  - Protect the infrastructure (e.g., dyke systems, mangroves).
  - Increase physical and operational robustness of the infrastructure (e.g., design / material, creating redundancy).
  - Employ adequate warning and response systems (e.g., institutionalized and threshold-based warning decision-making and warning chains, temporary protection of assets, change in operations, evacuation).
  - Institutionalize business continuity management mechanisms and procedures (e.g., recovery mechanisms).
  - Retreat (e.g., of communities, of infrastructure) might become a realistic adaptation path (though is an option of last resort).
  - A decision not to act, or to maintain a business-as-usual approach is also an option.
- Adaptation options always come with a bundle of complementary measures (i.e., adaptation scenarios).
  - For each option, multiple mutually exclusive or / and complementary social, environmental, economic, institutional, and physical-structural adaptation measures can be identified. Therefore, it is important to note the difference between complementary and mutually exclusive measures.
  - Climate risk management does not only refer to implementing structural-physical adjustments to the infrastructure, but also refers to adjustments of operational and institutional procedures that often go hand in hand with introducing new structural-physical features. This is especially true for the adjustment of maintenance schemes that are tailored to specific physical assets.
  - Ecological solutions can go hand in hand with the implementation of structural measures. For example, when aiming to minimize climate change-induced increased sedimentation of water reservoirs, upstream afforestation is a complementary measure for the effective implementation of technical sedimentation extraction mechanics of the reservoir dam system.
- Adaptation options may include conventional hard/'grey' (e.g., engineering-based), soft (e.g., training, insurance), ecosystem-based/'green' and hybrid (combined grey and green) solutions.
- Actions that are robust against a range of climate events and variability are preferred (e.g., burying telephone lines makes them resistant to a range of above ground climate impacts, including those from tornadoes, ice-storms, strong wind, hail).
- Actions that are robust against a range of future climate change scenarios are preferred.
- Actions should favour flexibility in their ability to accommodate, or avoid constraining, future course changes. For example, undertaking several large-scale projects may be less flexible than undertaking many small-scale projects. In this way, adaptive management, or the continual and regular process of decision-making and review, can be adopted. Adaptive management is necessary to allow for course corrections in the face of climate change uncertainty.
- Actions should enhance both adaptation and mitigation efforts. Actions should not hinder greenhouse gas mitigation efforts.
- Consider actions that work at the strategic, policy, program, or project level.
- Identify no-regrets or low regrets actions (i.e., actions that improve the resiliency of the infrastructure system today).
- Including a range of stakeholders in the process of identifying adaptation scenarios can promote innovation and fill gaps team members were unaware of.

5. **Provide a basic description and high-level determination for each adaptation scenario, including information such as (where relevant):**
   a. Basic design, location, dimensions, performance, service life or lifetime before major rehabilitation or reconstruction.
   b. Technical feasibility from engineering, regulatory, jurisdictional, construction, and/or operations perspectives.
   c. Potential to address climate change. Based on service life of proposed action, conduct high level assessments using climate projection data and design information to assess whether the adaptation scenario builds adequate capacity into infrastructure for the expected time period before rehabilitation or reconstruction.
   d. Residual vulnerability and potential risks after the application of a scenario.
   e. Responsible agency.
   f. Other relevant departments or agencies that should be involved with planning and/or implementation.
   g. Timeframe of action – should the action begin immediately, or in the near-, mid-, or long-term? Is the action a one-time event or ongoing? Does the action require a short, medium or long time duration to complete?
   h. Anticipated costs of an action. Consider estimating life-cycle costs, including construction, operations, management and monitoring activities.
   i. Sources of funding the action can draw upon.
   j. If or how the scenarios take advantage of ecosystem-based adaptation or incorporate green-grey measures.
   k. Related actions – which other actions must also be implemented in tandem to reduce vulnerability and ensure infrastructure functionality?
   l. Potential co-benefits and synergies to other national/international goals.

6. **Screen adaptation scenarios**
   a. Review adaptation scenarios and remove any that:
      i. Are not feasible, in terms of engineering, operations, safety, regulatory and jurisdictional considerations.
      ii. Clearly fail to meet mandatory safety requirements, operational requirements or service levels.
      iii. Are not able to address the range of climate change related risks under consideration.
      iv. Are too complex or costly to implement.
      v. Have too many potential negative effects (e.g., would increase greenhouse gas emissions).
   b. Prepare a shortlist of adaptation scenarios, highlighting key differences.

Step 7 Assessment of Adaptation Scenarios

There are various approaches to assess the adaptation scenarios, including cost-benefit analysis (CBA), cost-effectiveness analysis (CEA), and multi-factor analysis (MFA)[6]. They can be combined to consider environmental, social and economic costs and benefits in order to make the best recommendations. MFA is designed for complex multi-dimensional problems and is useful when aspects to be assessed are both qualitative and quantitative, as is usually the case in infrastructure and social-ecological system risk. This guidance thus focusses on MFA, though CBA and CEA can also be considered (see GIZ, 2013 for a comparison of these three approaches).

The main activities under Step 7 are as follows:

1. Choose evaluation factors

a. Identify factors to evaluate the performance of adaptation scenarios.
b. The choice of appropriate evaluation factors and sub-factors will depend on the context of the infrastructure. This includes:
   i. The physical, and natural environmental areas surrounding the infrastructure (e.g., infrastructure located next to water bodies may need to consider aquatic habitat and water quality factors, while other infrastructure located within urban areas would require the consideration of property assets).
   ii. The type of actions included in adaptation scenarios, and their potential impacts (e.g., some measures may directly generate greenhouse gases and air pollution).
   iii. The population served by the infrastructure, and the population living in proximity to the infrastructure (e.g., impacts to public health and safety, emergency services, quality of life, viewscapes, noise).
   iv. The organization's goals and objectives, as well as wider social and environmental objectives and considerations.
   v. Co-benefits of adaptation scenarios, for example, for meeting environmental goals or other national/international goals.
c. Assess the appropriateness of factors and evaluation criteria (see Box 5).

6 This guide employs the term multi-factor analysis (MFA) when describing the technique to be used to compare adaptation scenarios in this TBL analysis. MFA is synonymous with multi-criteria analysis (MCA), the term commonly employed by operational research literature. The term MFA was created to distinguish between factors and criteria, which is necessary for the development of the TBL analysis in Step 7.

Box 5 Criteria selection

To assess the appropriateness of factors and evaluation criteria to the MFA procedure, they should be screened for the following qualities (Dodgson, et al. 2001):

- **Completeness** – have all important considerations been properly accounted for? Note that a "complete" list of factors does not necessarily need to be exhaustive or extensive.
- **Redundancy** – factors should not be redundant to avoid being given additional emphasis in the MFA. However, you may choose to assess some factors from two different perspectives (e.g., using cost measure and a qualitative preference factor).
- **Mutual independence of preferences** – are factors and their criteria mutually independent? Consider eliminating one of the factors or consider merging the two.
- **Temporal aspects** – understand impacts in terms of whether they are one-time or recurring, temporary or permanent, present or future. Evaluation factors and criteria should reflect an explicit consideration for temporal aspects. This can be accomplished through a statement of preference for whether temporary or permanent, or one time or recurring effects are better or worse. The application of a discounting rate for future costs or impacts can also be used.
- **Mandatory versus desirable outcomes** – evaluation factors and sub-factors should aid you in assessing how well adaptation scenarios meet outcomes which are considered desirable (the "wants") by the infrastructure organization. Mandatory objectives and requirements (the "musts") are not used to compare scenarios in a MFA, as they should be assessed when scenarios are screened.

2. Establish evaluation matrix

a. For each of the factors or sub-factors identified in the previous activity, identify the evaluation criteria and performance indicators. Provide reference sources, if any were used. See Annex I for a list of criteria and sub-criteria relevant to the Triple Bottom Line analysis.
b. For each factor or sub-factor, setup a scoring scale. This guide recommends the use of a five-point scoring scale. If a different one is used, document it and provide justification. Define performance thresholds between scores. Provide reference sources for performance thresholds, if applicable.
c. Build an evaluation matrix for each factor or sub-factor (see example Table 5).

Table 5 Example of an evaluation scoring matrix for three factors

Factor	Public Safety	Water Quality	Economic Cost
Criteria	The project should minimize the loss of accessibility by emergency services during severe weather conditions	The project should minimize the impacts by effluent on water quality	The project should minimize capital, operating, and maintenance costs
Indicator of Performance	% of population potentially affected by loss of emergency services	Qualitative assessment of the impact on water quality	Qualitative assessment or financial value
Scoring Scale	Performance Thresholds		
1	> 95%	Severe, Extreme, Critical	Very High >$ 1 M
2	< 75%	High, Serious	High $ 500K < $ 1M
3	< 50%	Moderate	Moderate $100K < $ 500K
4	< 25%	Low	Low $25K < $ 100K
5	< 5%	Negligible	Very low < $ 25K

Source: AECOM Consulting Inc. 2011

3. Determine relative importance of evaluation factors to the overall assessment

a. Select participants (practitioner team members and/or study participants) who will contribute weighting schemes.

b. Obtain weighting schemes from selected participants.

   i. Attribute weights to the three TBL categories: social, environmental and economic.

   ii. Attribute each category's weight across its factors. If sub-factors are used, distribute each factor's weight to its sub-factors.

   iii. Ask participants to provide justification for their weighting schemes, such as how the factors or sub-factors contribute to international goals and treaties, support livelihoods, overall health and well-being, biodiversity and water/soil/air quality. Document justification.

c. Develop a weighting scheme representative of the "group perspective". This guide recommends that the group perspective be based on the median values for each TBL category, factor and sub-factor.

d. Develop the weighting schemes that will be used for testing sensitivity. Minimum and maximum values may be used to define the testing ranges. In some cases, study participants or you may decide that some values are too extreme (outliers) and choose to disregard them. Document weighting schemes to test sensitivity and justify as necessary.

4. Evaluate the performance of adaptation scenarios

a. Evaluate the performance of scenarios using the evaluation matrix developed in previous tasks:
   i. First, evaluate performance using descriptive words or numerical values as set out in the evaluation matrix. Provide comments as necessary to support evaluation.
   ii. Translate performance into a score using evaluation matrix scoring scale.
b. Where there is insufficient information available to evaluate the relative performance of scenarios, either:
   i. Gather more information to sufficiently define the associated aspect(s) of the adaptation scenario, time permitting.
   ii. Apply the lowest performance score for the factor, resulting in a lower overall score for the adaptation scenario. Effectively, this makes uncertainty a reason for poor scenario performance.
c. Document information insufficiencies or other comments related to performance evaluation.
d. Check for mutual independence of preference. If the performance score on one factor cannot be assessed without knowledge of another, mutual dependence exists. Modify evaluation factors and criteria as necessary.

5. Aggregate performance scores based on weighting schemes

e. Calculate aggregated performance scores:

Overall weighted performance score = $\Sigma W_i / S_i$

In other words, the overall weighted performance score is the sum of Wi divided by Si.

where:

i represents each shortlisted factor being considered
Wi represents the weight attributed to factor i
Si represents the performance score attributed to factor i

6. Review ranking results

a. Review calculated rankings from the previous task. If intuitive ranking was done, compare against calculated ranking.
b. Decide whether the MFA should be iterated. The following elements could be revised in an iteration:
   i. Scenario descriptions or actions to account for new information
   ii. Evaluation criteria or indicators to reflect new data or views
   iii. Performance thresholds if scenario performance on certain factors do not allow for adequate distinction
   iv. Certain factor weights if differences in scenario performance for those factors were small
c. Proceed with an iteration of the MFA, if applicable.

Step 8 Recommendations and Follow-up

At this stage, you have developed a set of adaptation scenarios, compared them using a MFA procedure, and are now faced with one of several possible outcomes. In Step 8, you will make a recommendation based on the outcome, prepare final documentation, and present results to participants. Finally, different methods of following up on the results to the TBL analysis are presented. The TBL analysis and your role essentially conclude at this point. The decision as to the future directions for the infrastructure organization will then be left to the decision-maker.

The main activities under Step 8 are:

1. Present MFA results and recommendations

a. Summarize the findings of the performance evaluation and aggregation.
b. Develop recommendations for the TBL analysis, which could include one or more scenarios for further analysis and implementation.
c. Document and present MFA results and recommendations to study proponents and participants. Check that description of the recommended scenario(s) is adequate. Recommendations should reflect all aspects of the adaptation scenario(s), and not solely the elements which were put through the MFA.

2. Follow-up

a. You should attempt to include recommendations on the following:
   i. Update existing monitoring activities and information systems (or creating new ones where necessary), to include proposed physical and operational changes.
   ii. Where further study, analysis or design exercises are necessary, set out the scope and parameters of further work while acquired knowledge is still recent.
   iii. Identify whether and when the TBL analysis should be revisited following further studies and monitoring activities.
   iv. Determine a time interval to assess whether adaptation actions are performing as expected, and that infrastructure assets and services continue to function reliably. To do so, information from monitoring activities should be assessed on a regular basis. A future re-evaluation of infrastructure vulnerability using the PIEVC Green Protocol could also be conducted.

By applying a systems thinking approach to climate risk assessments for infrastructure and thereby including social-ecological aspects, you will have been able to integrate the intrinsic value of surrounding ecosystems to optimize “grey” infrastructure projects’ structural integrity as well as service reliability. In addition, possible climate change impacts on the surrounding natural environment, which may in turn exacerbate some of the vulnerabilities of the built environment, will also have been accounted for at an earlier stage of the PIEVC process toward holistic, risk-informed development.

Further Resources

Ecosystem-based Adaptation

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PIEVC Resources

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Annexes

The following annexes provide additional guidance to the PIEVC Green Protocol methodology presented above:

- Annex A. Glossary
- Annex B. Infrastructure response considerations
- Annex C. Comparison of terminology interpretation in the engineering and climate communities

- Annex D. Team
- Annex E. Climate information for infrastructure climate risk assessments
- Annex F. Establishing likelihood scores
- Annex G. The climate risk assessment workshop
- Annex H. Establishing severity of impact scores
- Annex I. List of criteria and sub-criteria relevant to Triple Bottom Line analysis for infrastructure climate risk assessment

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Annex A Glossary

Adaptation	In human systems, the process of adjustment to actual or expected climate and its effects, in order to moderate harm or exploit beneficial opportunities. In natural systems, the process of adjustment to actual climate and its effects; human intervention may facilitate adjustment to expected climate and its effects. (IPCC, 2022b, p.2898)
Adaptive capacity	The ability of systems, institutions, humans and other organisms to adjust to potential damage, to take advantage of opportunities or to respond to consequences. (IPCC, 2022b, p.2899)
Adaptive deficit	Adaptive deficit is the lack of adaptive capacity. Since the other vulnerability factor, sensitivity, is a negative trait, adaptive deficit is used for simplicity rather than adaptive capacity for analysis in the PIEVC Green Protocol, so that both vulnerability factors are negative.
Climate	In a narrow sense, climate is usually defined as the average weather -or more rigorously, as the statistical description in terms of the mean and variability of relevant quantities- over a period of time ranging from months to thousands or millions of years. The classical period for averaging these variables is 30 years, as defined by the World Meteorological Organization (WMO). The relevant quantities are most often surface variables such as temperature, precipitation and wind. Climate in a wider sense is the state, including a statistical description, of the climate system. (IPCC, 2022b, p.2902)
Climate normals	Climate normals are used for two principal purposes. They serve as a benchmark against which recent or current observations can be compared, including providing a basis for many anomaly-based climate datasets (for example, global mean temperatures). They are also widely used, implicitly or explicitly, as a prediction of the conditions most likely to be experienced in a given location. The general recommendation is to use 30-year periods of reference. The period from 1961 to 1990 has been retained as a standard reference period for long-term climate change assessments. (WMO, 2017, p.1)
Climate change	A change in the state of the climate that can be identified (e.g., by using statistical tests) by changes in the mean and/or the variability of its properties and that persists for an extended period, typically decades or longer. Climate change may be due to natural internal processes or external forcings such as modulations of the solar cycles, volcanic eruptions and persistent anthropogenic changes in the composition of the atmosphere or in land use. Note that the United Nations Framework Convention on Climate Change (UNFCCC), in its Article 1, defines climate change as: 'a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods.' The UNFCCC thus makes a distinction between climate change attributable to human activities altering the atmospheric composition and climate variability attributable to natural causes. (IPCC, 2022b, p.2900)
Climate model	A qualitative or quantitative representation of the climate system based on the physical, chemical and biological properties of its components, their interactions and feedback processes and accounting for some of its known properties. The climate system can be represented by models of varying complexity; that is, for any one component or combination of components, a spectrum or hierarchy of models can be identified, differing in such aspects as the number of spatial dimensions, the extent to which physical, chemical or biological processes are explicitly represented, or the level at which empirical parametrisations are involved. There is an evolution towards more complex models with interactive chemistry and biology. Climate models are applied as a research tool to study and simulate the climate and for operational purposes, including monthly, seasonal and interannual climate predictions. (IPCC, 2022b, p.2903)

Climate parameter	A specific set of weather conditions or climate trends deemed to be relevant to the infrastructure under consideration. The parameter may be a single variable, such as mean monthly temperature, or a combination of variables, such as low temperature combined with rainfall. Within the context of a climate risk assessment, climate parameter selection is tailored to the specific design, operational and maintenance characteristics of the infrastructure being assessed.
Climate projection	Simulated response of the climate system to a scenario of future emissions or concentrations of greenhouse gases (GHGs) and aerosols and changes in land use, generally derived using climate models. Climate projections depend on an emission/concentration/radiative forcing scenario, which is in turn based on assumptions concerning, for example, future socio-economic and technological developments that may or may not be realised (IPCC, 2022b, p.2903)
Climate risk	The potential for adverse consequences for human or ecological systems, recognising the diversity of values and objectives associated with such systems. [...] In the context of climate change impacts, risks result from dynamic interactions between climate-related hazards with the exposure and vulnerability of the affected human or ecological system to the hazards. (IPCC 2022b, p.2921).
Design life	The period of time during which the infrastructure is expected to operate within design parameters. Notionally, the length of time between commissioning and the onset of wear-out. Typically, design life is a shorter duration than the period between commissioning and the anticipated time of actual failure. In some cases, design life is stated in terms of the economic return period of an engineering project. The design life of the infrastructure as a whole may be different than the individual components that comprise the infrastructure based on routine refurbishment or replacement of components over the useful life of the infrastructure.
Ecosystem-based Adaptation (EbA)	The use of biodiversity and ecosystem services as part of an overall adaptation strategy to help people to adapt to the adverse effects of climate change. (CBD, 2009, p.9)
Ecosystem services	Ecosystem services are the benefits of nature for human well-being, including: Provisioning services (e.g., food, raw materials) Regulating services (e.g., preventing soil erosion, wetland water treatment) Habitat or supporting services (e.g., maintaining genetic diversity) Cultural services (e.g., tourism, recreation)
Exposure	The presence of people; livelihoods; species or ecosystems; environmental functions, services, and resources; infrastructure; or economic, social, or cultural assets in places and settings that could be adversely affected. (IPCC, 2022b, p.2908)
Functionally related infrastructure	Functionally related infrastructure components are generally those located adjacent to the infrastructure component being considered, and are structurally or operational tied, and where actions on one generally require modifications to the other. For example, where a culvert needs to be replaced, the road and embankment above the culvert could be considered as dependent components. In a water treatment plant, a chemical treatment process may be functionally dependent on the filtration system.
Hazard	The potential occurrence of a natural or human-induced physical event or trend that may cause loss of life, injury or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, ecosystems and environmental resources. (IPCC, 2022b, p.2911)

Impact	The consequences of realised risks on natural and human systems, where risks result from the interactions of climate-related hazards (including extreme weather/ climate events), exposure, and vulnerability. (IPCC, 2022b, p.2912) See also severity of impact.
Infrastructure capacity	The load that an infrastructure or infrastructure component is designed to accommodate.
Infrastructure component	One of several physical features, processes, procedures and/or human resources that comprise the infrastructure. For example, an expansion joint is an infrastructure component of a bridge.
Infrastructure owner	The corporate or government agency that has jurisdictional control over the infrastructure. In a risk assessment, a project manager normally acts as an agent of the infrastructure owner. However, the project manager may defer strategic or policy matters to key managers within the owner organization. Depending on the owner organization, these decisions may be referred to senior management staff or the political level of some municipal organizations.
Infrastructure response	The generally anticipated impacts arising from the climate and other change parameters interacting with the infrastructure components.
Infrastructure threshold value	A value representing an infrastructure specific climate hazard that triggers an undesirable infrastructure response. In a climate risk assessment, the climate parameter establishes the general weather or climatic conditions while the infrastructure threshold denotes a specific value of those conditions that must not be triggered. Thresholds may be maxima or minima depending on the climate parameter. In some cases, an assessment may contemplate several threshold values for a specific climate parameter. This would be done to identify the impact of a range of climate hazards that may elicit different, notionally more severe, infrastructure responses.
Likelihood	The chance of a specific outcome occurring, where this might be estimated probabilistically. (IPCC, 2022b, p.2914)
Multi-factor analysis (MFA)	The term MFA is used when describing the technique to be used to compare adaptation scenarios in the Triple-Bottom Line (TBL) analysis, Step 7. The term is synonymous with multi-criteria analysis (MCA), the term more commonly employed by operational research literature. MFA was created to distinguish between factors and criteria, which is necessary for the development of the TBL analysis in Step 7.
Severity of impact	Severity of impact refers to the combination of exposure and vulnerability in the PIEVC Green Protocol. See also impact.
Professional judgment	The application of training, knowledge, experience, and skills gained over a prolonged period of professional practice. Within a climate risk assessment, professional judgment refers to the combined judgment of the practitioner team and infrastructure owner and staff. Individuals can contribute a unique perspective regarding climate-infrastructure interactions based on their history of dealing with similar or analogous situations.

Public infrastructure	For the purposes of this project, public infrastructure is defined as those facilities, networks and assets operated for the collective public benefit including the health, safety, cultural or economic well-being of communities, whether operated by government and/or non-government agencies.
Resilience	The capacity of interconnected social, economic and ecological systems to cope with a hazardous event, trend or disturbance, responding or reorganising in ways that maintain their essential function, identity and structure. Resilience is a positive attribute when it maintains capacity for adaptation, learning and/or transformation. (IPCC, 2022b, p.2920-2921)
Risk profile	The pattern of high, medium and low risks established through a risk assessment. The risk profile is based on the risk scores calculated by the assessment placed within the context of the risk tolerance thresholds established by the infrastructure owner. Through the profile you can identify the infrastructure-climate interactions that generally lead to higher levels of risk. Each infrastructure will have a unique risk profile within a specified time horizon.
Risk tolerance threshold	The risk score values established by the infrastructure owner that define high, medium, low and special-case risk scores.
Sensitivity	The degree to which a system or species is affected, either adversely or beneficially, by climate variability or change. The effect may be direct (e.g., a change in crop yield in response to a change in the mean, range, or variability of temperature) or indirect (e.g., damages caused by an increase in the frequency of coastal flooding due to sea level rise). (IPCC AR6 WGII p.2922)
Social-ecological system(s)	Systems of people and nature, emphasising that humans must be seen as a part of, not apart from, nature. (Berkes and Folke 1998)
Subsequent impact	A subsequent impact may occur when local geographical features result in follow-on events following a climate hazard. For example, a minor culvert failure resulting from a rainfall event could result in loss of slope stability leading to a mudslide. You may judge the culvert failure to be a low risk but the contribution to the subsequent impact may be quite significant.
Surrogate information	Information from other models, regions or assessments used to compensate for information gaps in the current assessment. The Protocol allows you to use information from regions with similar climatic and geographic conditions as a surrogate for information not currently available for the region of the assessment.
Time horizon	The period in time that the assessment considers. Time horizon will usually look forward several years you have determined. Often this horizon will be the remaining useful life of the infrastructure that is being assessed.
Triple Bottom Line (TBL)	A term developed in response to a growing recognition that organizations needed to address the three dimensions (social, environmental and economic) of sustainable development in an integrated manner.

Useful service life	The time between commissioning an infrastructure, or infrastructure component, and mandatory refurbishment or replacement. Useful service life is normally defined by the mean time between failures and is longer than the design life of the infrastructure or infrastructure component.
Vulnerability	The propensity or predisposition to be adversely affected. Vulnerability encompasses a variety of concepts and elements, including sensitivity or susceptibility to harm and lack of capacity to cope and adapt. (IPCC, 2022b, p.2926) In the PIEVC Green Protocol, vulnerability is a composite of sensitivity and adaptive capacity/deficit.
Weather	The state of the atmosphere at a given time and place, with respect to variables such as temperature, moisture, wind velocity, and barometric pressure. Weather refers, generally, to day-to-day temperature and precipitation activity. Climate refers to average atmospheric conditions over longer periods of time.
Weather event	Specific atmospheric conditions related to temperature, moisture, wind velocity, and barometric pressure. Within the context of the risk assessment, a weather event is defined by a value for specific atmospheric conditions that could potentially exceed infrastructure threshold values.
Weighting scheme	A distribution of weights across TBL categories, evaluation factors and sub-factors.

Annex B Infrastructure Response Considerations

In establishing conceivable infrastructure responses, consider the most likely effect of a climate hazard on the infrastructure or infrastructure component. This is based on your professional judgment and experience. The following list is provided for guidance. During a climate risk assessment, you are encouraged to identify all conceivable and reasonable infrastructure responses.

Infrastructure response criteria establish a range of climate-infrastructure outcomes tailored to the specific assessment and provide a basis for the severity of impact scoring exercise outlined in the PIEVC Green Protocol and assist you to define plausible outcomes from an identified interaction.

Possible infrastructure responses include, but are not limited to:

Consideration for infrastructure	With respect to the infrastructure or infrastructure component being assessed, climate loading may affect:

Structural Design	• Safety
	  • Load carrying capacity
	  • Overturning
	  • Sliding
	  • Fracture
	  • Fatigue
	  • Serviceability
	• Deflection
	  • Permanent deformation
	  • Cracking and deterioration
	  • Vibration
	• Foundation Design
	  • Permafrost

Functionality	• Effective Capacity of the infrastructure (short-, medium- and long-term) • Equipment - Component Selection (design, process and capacity considerations)

Serviceability	• Ability to conduct routine and/or planned maintenance and refurbishment activities
	  • Short-, medium- and long-term
	• Equipment - component replacement frequencies
	  • Design, process and capacity considerations

Consideration for infrastructure	With respect to the infrastructure or infrastructure component being assessed, climate loading may affect:
Watershed, Surface Water, and Groundwater	• Erosion along streams, rivers, and ditches • Erosion scour of associated or supporting earthworks • Slope stability of embankments • Sediment transport and sedimentation • Channel realignment / meandering • Water quality and quantity • Water resource demands • Public, hydro, industrial, agricultural use of water resources • Groundwater recharge characteristics • Run-off • Recharge • Thermal characteristics of the water resource

Operations, Maintenance, and Materials Performance	• Occupational safety
	• Access to worksite
	• Structural integrity
	• Equipment performance
	  ◦ Maintenance and replacement cycles
	  ◦ Electricity demand
	  ◦ Fuel use
	• Functionality and effective capacity
	• Materials performance
	  ◦ Changes from design expectation
	• Pavement performance
	  ◦ Hail, softening, cracking from freeze-thaw and other causes

Emergency Response	• Procedures and systems to address, for example, severe storm events, flooding, ice dams, ice accretion and water damage
Insurance Considerations	• Insurance rates • The ability to acquire insurance • Insurance policy limitations and exclusions

Consideration for infrastructure	With respect to the infrastructure or infrastructure component being assessed, climate loading may affect:
Policy Considerations	• Codes • Guidelines • Standards • Internal operations and maintenance policies and procedures • Public-sector policy • Land-use planning
Social Effects	• Accessibility to critical facilities such as hospitals, fire and police services • Transportation of goods to a community • Energy supply to a community • Dislocation of affected populations • Provision of basic services such as potable water distribution and wastewater collection • Closure of schools and other public services • Community business viability • Destruction or damage to heritage buildings, monuments, etc. • Destruction or damage to archeological resources • Destruction or damage to historically important resources
Environmental Effects	• Release of toxic or controlled substances • Degradation of air quality • Damage to sensitive ecosystems • Physical harm to birds and animals • Contamination of potable water supplies • Public perception and interaction

Annex C Comparison of terminology interpretation in the engineering and climate communities

Below is an over-simplified comparison of how the engineering and climate communities interpret different terminology, based on observations of these different understandings.

Terminology	"Engineering Community" Interpretation	"Climate Community" Interpretation
Climate and Weather	Within professional practice, some engineering professionals may not make clear distinctions between climate and weather. They may use these terms interchangeably, particularly when referring to extreme events. Systems tend to be planned and designed based on climate but operated and managed for day-to-day weather.	According to the World Meteorological Organization, climate in the narrow sense can be defined as the average weather conditions for a particular location and period of time. In a wider sense, it is the state of the climate system. Climate can be described in terms of statistical descriptions of the central tendencies and variability of relevant elements such as temperature, precipitation, atmospheric pressure, humidity and winds or through combinations of elements, such as weather types and phenomena that are typical to a location, region or the world for any period. The classical time period used in past is 30 years. The term weather is used to describe atmospheric events that are discrete in time. Weather mostly considers the shorter-lived phenomena within the part of the Earth's climate system that has the least heat capacity, the most statistical variability, and the messiest precipitation phase transitions.
Climate Variability and Change	The differences between ongoing climate variability, climate change and future potential changes in climate variability may not be appreciated in the assessment. The challenges in attributing specific extreme events to either ongoing climate variability or to climate change also may not be appreciated. Occasionally, an event or sequence of events that has never been witnessed before (or recorded before) occurs which could be part of natural climate variability.	Climate variability is defined as variations in the mean state and other statistics of the climate on all temporal and spatial scales, beyond individual weather events. Climate change refers to a statistically significant variation in either the mean state of the climate or in its variability, persisting for an extended period (typically decades or longer). Climate variability looks at changes that occur within smaller timeframes, such as a month, a season or a year, and climate change considers changes that occur over a longer period of time, typically over decades or longer. Care must be taken not to confuse variability with change. A key difference between climate variability and change is in persistence of "anomalous" conditions - only a persistent series of unusual events taken in the context of regional climate parameters can suggest a potential change in climate has occurred.

Terminology	"Engineering Community" Interpretation	"Climate Community" Interpretation
Climate Data and Analyses	Most engineers will define almost any set of numbers and facts as data.	Values based on actual measurement or interpolated values (e.g., gridded data). The scientist may call outputs from model runs "information" rather than "data" since these values are based on computational outputs and assumptions and not upon actual physical measurements.
Normals, Indices and Scores	For most engineers, "Normals" and "Indices" are not common terminology (context specific). Within the context of the Protocol, "scores" are defined on a scale from 0 to 7.	Values defined for specific climate contexts. For example, "Normals" are defined by the World Meteorological Organization as typical 30-year averages of historical climate variables. The global research Expert Team on Climate Change Detection and Indices has defined a core set of 27 extremes Indices that describe characteristics of selected temperature and precipitation extremes, including frequency, amplitude and persistence.
Dealing with Uncertainties	Many engineers may use the term "uncertainty" in a general or non-numerical sense. Engineers design under conditions of uncertainty on a routine basis. Examples include seismic and other engineering designs reliant upon modelled physical phenomena. References to the uncertainty of information may indicate the accuracy and precision of the data set and all the factors considered in generating the information. The precautionary principle is based on the principle that less-than-complete knowledge is no reason for inaction. Hence, engineering applications often use scientifically- based safety factors to account for uncertainties.	As with other branches of science, climate science involves scientific uncertainty, which doesn't mean that something is unknown. For reasons of transparency, climate scientists like to point out their levels of uncertainty to highlight how well a projection or phenomenon is known (or unknown). Although scientists have gained significant insight into how the climate system functions, they do not have 100% confidence in their climate change projections—and they never will. Climate change science accounts for the uncertainties in its projections by referring to a range of plausible future climate values that are dependent on future GHG emission assumptions, among other influences.
Ensembles	Ensemble is not a word typically used in engineering practice. In terms of grouping results, engineers are quite familiar with sets of data, but they would treat the set as a unified whole and would feel absolutely free to compute averages, interpolate and extrapolate within the data set.	The climate scientist will refer to an ensemble as a group of results from various climate models and emissions scenarios. Ensemble averages may be used to report general changes. However, the scientist may advise practitioners to consider each model outcome individually and to be mindful of the influence of using ensembles that include different emissions scenarios.

Terminology	"Engineering Community" Interpretation	"Climate Community" Interpretation
Validation and Uncertainties	The engineer may use the term validation generically. They may refer to validating or endorsing a document. They would not typically use the term with respect to "ground truthing" information or calibrating measured data. Also, within engineering, the term "validate" may be used to establish that proper engineering analysis is being used in a calculation process. This is a common use of the term in greenhouse gas reduction activities, where greenhouse gas offset calculations are validated to ensure that proper analytical processes have been applied.	Climate scientist will use the term "validation" to refer to the process of "ground truthing" climate model data and its downscaling for a historical period against actual historical meteorological data (often gridded).
Emissions and Mitigation	An engineer, especially one experienced with environmental impact and risk assessment processes, will use the term "mitigation" to refer to the process of taking action to reduce identified risks.	The climate scientist may use the term "mitigation" as it appears in climate change literature, referring to mitigation as activities related to reducing greenhouse gas emissions.
Confidence	The overall comfort with a set of data. This goes beyond the statistical variance and encompasses the entire process of generating the data, including the veracity of the stated and unstated assumptions. The less confidence engineers have in a data set, the more safety margins and contingencies they will add to a project.	Climate scientists will often rely on statistics to articulate the level of confidence in climate information. They are focused on their ability to reproduce results and will tend to view confidence as a measure of whether or not multiple lines of evidence point to a consistent result.
Precision versus Accuracy	Most engineers will use the words "accuracy" and "precision" interchangeably in their day-to-day work.	Climate and weather professionals have varying needs for accuracy and precision. Accuracy generally refers to the closeness of the estimate to the actual value, while precision would refer to consistency or scatter of estimates. Climate change scientists aim for best accuracy when parameterizing detailed climate processes in models for projections of future changes from the baseline climate conditions. Precision is critical for monitoring and detecting changes in the climate. Ideally, understanding of climate change impacts and risks requires best efforts in both accuracy and precision, although neither may be possible. A cautious approach to decision-making generally emphasizes that it is better to be generally right than precisely wrong.

Terminology	"Engineering Community" Interpretation	"Climate Community" Interpretation
Professional Judgment	The use of technical standards, procedures, methodologies, science, and other tools obtained through many years of training and professional practice. It is a process of forming an opinion or evaluation for the situation at hand by discerning and comparing while conforming to the technical or ethical standards of a profession while requiring the application of specialized knowledge and often long and intensive academic preparation.	The scientist often sees professional judgment as a subjective process. Where data is unavailable, it would entail the application of quantitative assumptions, interpolations and extrapolations necessary to move forward. The scientist may be uneasy about applying judgment in this way and may wish to pursue additional work to test and/or replace judgment-based information with measured or computed results.
Conservative	For most engineers, the term "conservative" usually refers to a design value or other estimate containing an explicit or implied factor to ensure that a system will perform according to specification under all reasonable conditions. For example, the application of a safety factor to a baseline climatic design value (explicit) or use of the most extreme value within a given data set (implied) would ensure that the design is conservative.	For climate scientists, a conservative value is often one that is somewhat less than the highest point in a data range. A conservative estimate will ensure that the value is covered within the entire range of data quoted and therefore, is much more defensible than perhaps a more extreme value. Where a scientific basis does not exist for an estimate, the scientist will tend to exclude that information.
Data Sufficiency	A result that is based on data or information sufficient for the purposes of the project.	A result based on accurate and precise data or information that is as close as possible to the "true" value.

Annex D Team

Of paramount importance in addressing the types of questions raised by the PIEVC Green Protocol is a well-balanced team of professionals dedicated to the execution of the risk assessment. The correct blend of professional and local expertise can support and validate assumptions that allow you to compensate for missing or poor-quality data and account for the lack of other technical resources. Team composition and depth of experience has a very significant bearing on the veracity of the final assessment report.

Examples of team resources may include (* required):

- **Risk Assessment:** The risk assessment specialist(s)* have in-depth knowledge of the fundamentals of risk and the risk assessment process. They have strong skills in facilitation and communication that strengthen the knowledge and expertise of other team resources and guide the process.

- **Climate:** The climate specialist(s)* have a strong understanding of climate that is relevant to the local context. They can interpret climate data and communicate uncertainty effectively with other team resources.

- **Planning:** Individuals or groups with knowledge of community planning, land-use planning, infrastructure planning and other related expertise relevant to the scope of the assessment (like transportation) can provide a broader understanding of multi-stakeholder goals and relevant policy.

- **Technical / Engineering:** Professional engineer(s)* and technical or engineering subject matter specialist(s) have relevant experience working with the infrastructure or systems being assessed.

- **Natural Environment:** Natural environment subject matter specialists have relevant experience working with and managing natural systems. Expertise needed will vary depending on the assessment scope but can include knowledge about sustainability, hydrology, landscape architecture, ecology, aquatic biology, or forest management.

- **Operation & Maintenance:** Individuals or groups involved in operations and maintenance can provide valuable insight into the system being assessed or similar systems they have worked with previously.

- **Management, Finance:** Individuals or groups involved with financing or managing the assets can assist with encouraging buy-in across the organization and aligning project objectives with the organization's goals and strategy.

- **Legal, Insurance:** Individuals or groups with legal and insurance expertise can provide insight on topics like liability, risk tolerance, the ability to acquire insurance, and relevant policy.

- **Social Science:** Individuals or groups with expertise in sociology, political science or public policy can strengthen social and governance aspects of the assessment.

- **Indigenous and/or local peoples:** Meaningful engagement with communities and knowledge holders can improve understanding of climate conditions and its impacts in the areas and communities being assessed.

- **Other stakeholders:** Non-organizational stakeholders who rely on the services of the systems or assets being assessed have critical perspectives to contribute related to service disruptions and levels.

The importance of local knowledge in conducting a climate risk assessment cannot be overstated. Local knowledge, filtered through the overall expertise of the assessment team, more often than not, will compensate for data gaps and provide a solid basis for professional judgment of the vulnerability of the infrastructure.

Having a gender-balanced team can also enhance assessment results and promote innovation by including a diversity of perspectives and solutions, particularly when it comes to affected communities.

Annex E Climate information for infrastructure climate risk assessments

In past engineering applications, it has been typically assumed that the climate conditions for a given geographical region from the previous decades could be extrapolated forward into the future decades, especially when referring to extremes. While this assumption has worked well, it is increasingly less valid. Climate change modelling tools are needed that include the influences of GHG emissions and land-use change to account for potential changes in design conditions. Changes in the seasonality of atmospherically driven events, such as peak stream flow, or in the frequency and intensity of extreme events, such as extreme precipitation, need to be considered in the within the context of future climate change due to their direct impact on infrastructure.

Below are some guiding principles for the use of climate information to support infrastructure climate risk assessments:

- Climate information relates to all climate parameters that can be reasonably expected to interact with infrastructure under study. This is not solely limited to temperature and precipitation but can also include a myriad of parameters ranging from highly localized extreme events (e.g., tornadoes) to long-term parameters acting over years or decades (e.g., weathering).
- The focus is typically on extreme values and not averages, although complex day-to-day weathering processes may be important.
- The desired climate information may not be available, or the scope of climate analysis may be restricted by budget and other resources.
- A key consideration for climate is the likelihood of exceeding climate values or thresholds one or more times over the future time period of interest (rather than the total number of exceedances).
- Short return-period climate events (e.g., 2-3 year, 1 year or less) may also be important, particularly for operations and maintenance considerations.
- Historical climate data typically is not available for the exact study location; however, the nearest or most climate representative airport station, or representative and calibrated gridded climate data may provide the best available data for the assessment.
- The baseline climate and future climate projections will be scored according to the PIEVC likelihood scale with each increment of the scale capturing a range of climate values. In many cases, this will reduce requirements for climate precision.
- Expert climate judgment and documentation may be needed for the climate and climate change variables, particularly events that are relatively complex in nature (e.g., localized severe weather events).
- Collaboration between the engineering, environmental, social and climate professionals, including ongoing data sufficiency review to determine the most relevant climate information, will be critical in defining climate variables and thresholds for the assessment.

- The team will need to clarify interpretations of climate and engineering terminology, preferably at the beginning of the study, to ensure that decision-relevant climate information is provided to the climate risk assessment (see Part A Section 3 and Annex D).

For more in-depth guidance on climate information and its applications for infrastructure climate risk assessments, see the PIEVC Protocol.

Some example sources of climate data and information products are provided in the table below. National meteorological services or climate services organizations can be a useful starting point for data and information. Sub-national governments or municipalities may also have collected additional local or regional data. Useful climatic design information may also be available from flood-plain mapping and monitoring, and from regionally specific climate modelling studies, among others.

Example sources of climate data and information products.

Source	Organization	Link
IPCC WGI Interactive Atlas	IPCC Working Group I (WGI): Sixth Assessment Report	https://interactive-atlas.ipcc.ch
Climate Change Knowledge Portal for Development Practitioners and Policymakers	World Bank	https://climateknowledgeportal.worldbank.org
WMO Catalogue for Climate Data	World Meteorological Organization (WMO)	https://climatedata-catalogue.wmo.int
Climate Scenario Data	Nile Basin Initiative	http://ikp.nilebasin.org/en/content/climate-scenario-data
Historical, current and future hydrometeorological and climate data	Mekong River Commission (MRC) Data and Information Services	https://portal.mrcmekong.org/home
Copernicus	Copernicus / European Union	https://www.copernicus.eu/en/access-data
Historical and future climate datasets for Canada, support desk, climate data portal, library of resources	Canadian Centre for Climate Services	https://www.canada.ca/climate-services
Climate projections for Brazil	Brazilian National Institute of Space Research	http://pclima.inpe.br
Climate Data Service Portal	India Meteorological Department	https://cdsp.imdpune.gov.in

Annex F Additional guidance on establishing likelihood scores

Basis

You must first clearly define the set of circumstances for which the likelihood score is being assigned. Results from earlier studies clearly indicate that this analysis requires much more than simply identifying whether a particular climate parameter will change over the time horizon of the assessment.

The idea of identifying hazards assumes that there is a preliminary screening of the potential events to determine those that could result in the infrastructure (infrastructure component) failing to meet its operational objectives. This preliminary screening is accomplished through the Yes/No Analysis outlined in the Protocol. Otherwise, the entire process may become cumbersome and resource intensive.

Definition

Likelihood is defined as as: "The chance of a specific outcome occurring, where this might be estimated probabilistically" (IPCC, AR6, WGII, p.2914).

Since there can be different understandings of the term likelihood (and the associated term probability) across disciplines, it is recommended that you clearly define to the team that the likelihood-scoring exercise is not a quantitative process. Rather, it is a process based on informed professional judgment and decision-making. The team assigns a score for the likelihood of the events under consideration.

Clarification

Be careful not to focus on the severity of impact of the event when establishing the likelihood score. To better define the likelihood scoring process, you should specifically evaluate the likelihood of a climate parameter triggering a defined threshold during the time horizon of the assessment.

Professional Judgment

Professional judgment is a critical element of assigning likelihood scores. Within the context of a climate risk assessment, professional judgment refers to the combined professional expertise, knowledge and wisdom of the entire team. It is critical that as much information and insight from different professional backgrounds be applied in forming the ultimate professional judgment.

Decisions based on any one element of the team's expertise alone (e.g., climate science, engineering) may miss critical information from the other areas of expertise and result in a potentially erroneous assessment of likelihood.

Defining Thresholds

Each climate parameter is assigned an associated threshold value that is specific to the infrastructure being considered, for example, the number of days with temperature greater than 30oC. Thus, the assessment does not simply evaluate the impact of higher temperatures on infrastructure. Rather, the assessment considers the frequency and magnitude of climate parameters triggering defined threshold values. These thresholds may be defined from a variety of sources including, but not limited to:

- Design standards
- Operational standards
- Rules of thumb
- Maintenance guidelines
- Codes of practice
- Engineering/design practice literature
- Experience (past events)
- Professional judgment

Note that some threshold values define maximum conditions while others define minimum conditions relative to a particular infrastructure service level. For example, the threshold may define a maximum temperature above which the infrastructure may start to exhibit loss of function. Conversely, the threshold could be a minimum temperature below which the infrastructure may start to exhibit loss of function. For this reason, we advise to avoid using the word "trigger" when discussing these interactions. This avoids the confusion of language that, for example, could suggest that a minimum temperature exceeds a minimum threshold value. Although this language is technically correct, it may lead to confusion among members of the team.

For each climate parameter, define a corresponding threshold value. These threshold values should be shared with the climate specialists who can then tailor their efforts to provide climate projections relevant to the specified threshold.

Examples of thresholds are presented in **the table below**. Note that the thresholds applied in any given assessment are specific to the infrastructure under consideration and the area where the infrastructure is located (thresholds for rain or high temperatures will vary according to region) and that the examples provided in **the table below** may not apply to all infrastructure assessments. These examples are provided for reference only.

Examples of Infrastructure Threshold Values

Climate Parameter	Infrastructure Indicator
High Temperature	Number of days with maximum temperature exceeding 30° C
Low Temperature	Number of days with minimum temperature below -24° C
Temperature Variability	Number of days with daily temperature variation of more than 24° C
Freeze / Thaw	17 or more days where maximum temperature > 0° C and minimum temperature <0° C

Climate parameters that do not interact with the infrastructure, do not present the opportunity to trigger a threshold, or that are irrelevant to the normal functioning of the infrastructure, are not assigned risk scores. Normally, these interactions are screened out of the evaluation process in Step 3.

Frame of Reference

If a climate projection results in more frequent triggering of a threshold value, assign a higher likelihood score. However, if the change were projected to result in a significant decrease in trigger signals / events, assign a lower likelihood score.

It is important to maintain this frame of reference throughout the execution of the assessment. Should positive and negative likelihood outcomes be mixed together, assessing the overall risk to the infrastructure may become very misleading and confusing.

Considerations Affecting Likelihood Scores

Assignment of likelihood scores is an informed decision based on your professional judgment validated through the expertise of participants at the risk assessment workshop. Where appropriate, input from climate specialists can significantly improve overall confidence in the scoring.

Note that these processes are not precise numerical computations. Rather, this is a consultation process designed to generate dialogue between the various professionals engaged in the assessment. The intent is to draw on the combined professional judgment of the team to score (or rate) the likelihood of projected climatic events. This draws upon standard engineering practices that evaluate statistical, technological and resource limitations to assign functional parameter values that allow the advancement of an issue. Most commonly, this is associated with the application of safety factors that accommodate the uncertainties associated with a parameter to ensure estimates that err on the side of the overall integrity of the engineered system and, most importantly, public safety.

Generally, professional judgment on likelihood scoring may be guided by five considerations:

1. Will climate conditions, relevant to the infrastructure, change over the time horizon of the assessment?
2. Will thresholds be triggered more often, the same as, or less than in current conditions?
3. What is the impact of the projected change in magnitude of the climate event on the frequency of trigger events?
4. What is the projected impact of the change in frequency of climate events on the frequency of trigger events?
5. How robust are the results of the climate projections?

Consider input data from several sources (e.g., grey or published literature, experience) to assess likelihood, including, but not limited to:

- Weather and climate science
  - Scenarios based on climate-model output
  - Analysis of weather patterns
  - Statistical analysis
  - Local knowledge
- Professional judgment of the members of the team

Regarding the fifth consideration on robustness of the results of the climate projections, your confidence in the climate projection can have a mitigating effect on the overall likelihood score. For example, regional climate projections may indicate a change in climatic parameters that would exceed design or operational thresholds. Notionally, this would support a higher likelihood score. However, the climate specialists may state that the model results are highly variable or that there is a high level of uncertainty associated with the projection. In considering this information, you may lower the likelihood score to account for the uncertainty of the projection. Conversely, the climate specialists may anticipate an improvement in climate conditions but with high level of uncertainty. This may result in increasing the overall likelihood score.

Example Likelihood Scoring

The table below demonstrates an example of a likelihood scoring exercise using climate projections.

Example Likelihood Scoring Exercise

		Will the Interaction Change Over Time Horizon of Assessment?	More-Same-Less?	Projected Change in Magnitude?	Projected Change in Frequency	Robustness of Forecast?	Professional Judgment	Likelihood Score
		Y/N	+ 0 –	H M L	H M L	H M L	Comments	0–5
		↓	↓	↓	↓	↓	L = *f* (A,B,C,D, & E)	
Climate Parameter	Infrastructure Indicator	A	B	C	D	E	→	L
High Temperature	Number of Days with maximum temperature exceeding 30°C	Y	+	H	H	H	Regional climate modelling forecast suggests that both frequency and magnitude will increase from an average of 0.6 to ~ 3 days per year. The climate specialists have a high level of confidence in the projection. This is a significant change. The projection is consistent with other predictions. This suggests that the likelihood of change is relatively high.	*4*

Legend: Y: Yes; N: No; H: High; M: Medium; L: Low

Annex G The climate risk assessment workshop

Step 3 of the PIEVC Green Protocol requires that you execute a workshop with representatives from the infrastructure ownership and operations teams. Development of the impact chain in Step 2 would also benefit from a workshop. This is a way to draw on the combined experience of the people who have direct contact and history with the infrastructure, along with yourself. This method allows the team to apply professional judgment in a transparent and consistent manner. This can be done in a technically rigorous way and yield results that can withstand professional scrutiny.

Where data exists, use it. However, if the data is missing or suspect in any manner, rely on the professional judgment of the practitioner team and workshop participants. Thus, the workshop represents the most important phase of the evaluation.

Given the importance of the workshop, it is critical that the right mix of knowledge, experience and professional skills be present. If the practitioner team has been structured properly, the professional skills and experience should be available to the workshop. However, the practitioner team may be missing hands-on experience with this particular infrastructure. Local knowledge regarding weather events and how the infrastructure and operations team responded to those events is critical information of interest to the practitioner team. Participants at the workshop can fill these gaps. It must be stressed that it is not sufficient to include only management and engineering staff from the infrastructure owner. Operations and maintenance staff must also participate. It is not uncommon for operations staff and management/engineering staff to have a distinctly different perspective of climate-infrastructure interactions. Events that the management team view to be very significant may already have been encountered and addressed by the operations team. This is critical input to your climate risk assessment.

Generally, participants at the workshop should include:

- The practitioner team
- Representatives from the infrastructure management team
- Representatives from the infrastructure engineering team
- Representatives from the infrastructure operations team
- Local expertise/knowledge regarding severe weather events in the region and climatic trends that may have affected the infrastructure
- Representatives from the organization providing climate information
- Representatives from any advisory groups or technical experts who may be supporting the climate risk assessment, for example on ecology, biodiversity, economic or social aspects
- Others deemed necessary by the infrastructure owner or practitioner team

This Protocol has been used to assess the climate risk of many different types of infrastructure. The workshop approach outlined above has consistently unearthed issues that would otherwise have escaped the notice of practitioners. For this reason, it is STRONGLY recommended that a workshop be used within the climate risk assessment process. Only in cases where there are compelling and material reasons to use alternative approaches should these alternatives be considered. Even then, it is recommended that findings derived from the alternative still be reviewed with the infrastructure owner in a workshop environment.

Annex H Additional guidance on establishing severity of impact scores

Basis

Severity of impact scoring is fundamentally an exercise in the application of professional assessment and judgment. This is informed by the expertise and experience of the assessment team and though consultation with infrastructure-owner staff who may have experience in dealing with similar situations to those under consideration.

Never underestimate the value of site-specific experience in finalizing the severity of impact scoring. As well, avoid the assumption that the majority opinion regarding the severity of impact of an event is correct. Sometimes, only one individual may have hands-on experience relevant to their particular severity of impact score. It is very important for to test the basis for the severity of impact score values proposed both within the practitioner team and from other sources. This process can unearth circumstances overlooked by the rest of the team that could dramatically change the final severity of impact score result.

The hands-on experience of operations, maintenance and facility management staff is very important. These individuals ultimately will have to translate the risk-profile scores into real-world actions. Without their perspectives, the entire process may be viewed as an academic exercise.

Definition

The PIEVC Green Protocol defines considers severity of impact as the combination of exposure and vulnerability. Severity of impact may be to the infrastructure itself, a single infrastructure component, or to the social-ecological system.

Professional Judgement and the Practitioner Team

Professional judgment is a critical element of assigning severity of impact scores. Within the context of a climate risk assessment, professional judgment refers to the combined professional expertise, knowledge and wisdom of the entire team. It is critical that as much information and insight from different professional backgrounds be applied in forming the ultimate professional judgment.

Operations and management personnel as well as ecologists can provide insight regarding the “real-world” behaviour of the infrastructure and its surrounding system under weather conditions similar to those projected by the climate specialists. The engineering team can provide insight into how the infrastructure is supposed to operate under design conditions and the limits of the infrastructure’s functional capacity. Ecologists or geographers may estimate how much risk factors of the surrounding system contribute to the severity of impact. Decisions based on any one element of the team's expertise alone may miss critical information from the other areas of expertise resulting in a potentially erroneous assessment of severity of impact.

Thresholds

Each climate parameter is assigned an associated threshold value that is specific to the infrastructure being considered. These thresholds may be defined from a variety of sources including, but not limited to:

- Design standards
- Operational standards
- Rules of thumb
- Maintenance guidelines
- Codes of practice
- Engineering/design practice literature
- Experience (past events)
- Professional judgment

Note that some threshold values define maximum conditions while others define minimum conditions relative to a particular infrastructure service level. For example, the threshold may define a maximum temperature above which the infrastructure may start to exhibit loss of function. Conversely, the threshold could be a minimum temperature below which the infrastructure may start to exhibit loss of function. For this reason, we advise to avoid the word "trigger" when discussing these interactions. This avoids the confusion of language that, for example, could suggest that a minimum temperature exceeds a minimum threshold value. Although this language is technically correct, it may lead to confusion among members of the team.

Climate events that do not interact with the infrastructure do not present the opportunity to trigger a threshold or that are irrelevant to the normal functioning of the infrastructure are not assigned risk scores. Normally, these interactions are screened out of the evaluation process through the Yes/No Analysis.

Considerations Affecting Severity of Impact Scores

The Protocol provides two suggested scoring methods that are intended to help focus the discussion of severity of impact scores. These methods outline two different ways of looking at the scoring exercise. You are not limited to these methods. However, if they choose an alternative method, the Protocol requires that they clearly document the method that they do use.

> You are directed to express a professional opinion regarding the severity of the impact. This should not be confused with the likelihood of that event. You are asked to assess the likelihood of the event separately.

These methods are presented in the table below:

Severity of Impact Score Definitions

Score	Severity of Impacts	
	Method A	Method B
1	No Effect	Negligible Not Applicable
2	Minor	Low Slight Loss of Serviceability
3	Moderate	Moderate Loss of Serviceability Some Loss of Capacity
4	Serious	Loss of Capacity Loss of Function
5	Catastrophic	Extreme Loss of Asset

Assignment of severity of impact scores is an informed decision based on your professional judgment validated through the expertise of participants at the risk assessment workshop.

Note that these processes are not precise numerical computations. Rather, this is a consultation process designed to generate dialogue between the various professionals engaged in the assessment. The intent is to draw on the combined professional judgment of the team to score (or rate) the severity of impact of projected climate events. This draws upon standard engineering practices that evaluate statistical, technological and resource limitations to assign functional parameter values that allow the advancement of an issue. Most commonly, this is associated with the application of safety factors that accommodate the uncertainties associated with a parameter to ensure estimates that err on the side of the overall integrity of the engineered system and, most importantly, public safety.

Identify a set of infrastructure responses for each infrastructure component. These responses define ways that the infrastructure could conceivably react to external stimuli. For example, more maintenance may be required. Normally you would consider the identified infrastructure responses to inform their deliberations and guide their insight into how severe an interaction may be. It is important to understand that often you will identify several outcomes from an identified interaction. These may include reactions in several of the identified infrastructure responses. For example, the event may require more frequent maintenance and also reduce the service life of the infrastructure. All these factors enter into the professional judgment used to assign severity scores.

Generally, professional judgment on scoring may be guided by five considerations:

- Have you or infrastructure owner experienced similar events in the past?
- Does the infrastructure owner have initiatives or programs in place that address the issue?
- Have other organizations experienced the event?
- Does design information accurately reflect the installed infrastructure?
- Will local jurisdictional considerations impact the outcome of an interaction?

Annex I List of Criteria and Sub-Criteria Relevant to Triple Bottom Line Analysis Infrastructure Climate Risk Assessment

The following table presents a non-exhaustive list of factors and sub-factors that can be used in a TBL analysis (list adapted from National Research Council and National Round Table on Sustainable Infrastructure, 2009). Some factors and sub-factors may be repeated in more than one category to reflect possible nuances. You are not obliged to use all factors or sub-factors listed below.

Social

Impact on community
- Number of users affected
- User activities affected

Level of service
- Loss of use – duration
- Loss of use – frequency
- Planned service interruptions
- Power outage performance
- Disaster performance
- Critical service provision area

Social acceptability
- Site location
- Site access route
- Public perception
- Education and awareness

Social equity
- Accessibility to facility
- Availability of service
- Fee structure
- Problem / load transfer

Public health
- Emissions of harmful pollutants – NOx, SOx, VOC, ozone
- Potential for exposure
- Exposure to harmful substances
- Noise levels: actual vs. acceptable
- Vibration levels
- Storage/Reserve capacity
- Illness and disease
- Occupant/user comfort

Public safety
- Emergency services access
- Emergency services response time
- User / operator safety
- Injuries / fatalities per km, per year
- Comprehensibility of markings, signs and messages
- Protection against vandalism

Collective heritage
- Impact on visual landscapes
- Impact on archaeological heritage

Impact on mobility
- Impact on traffic operations
- Impact on transit operations
- Road / load restrictions
- Construction time
- Detour length
- Compatibility with plans and policies
- National, provincial and municipal

Environmental

Impacts on the physical or built environment
- Air pollution
- Noise pollution
- Potential for exposure to harmful substances
- Effluent / outtake quality

Impact on the natural environment
- Soil quality
- Sub-soil quality
- Water quality
- Air quality
- Wetlands
- Floodplains
- Greenhouse gases emissions

Fauna
- Habitat fragmentation
- Fish habitat / spawning grounds / nursery areas
- Species at risk
- Wildlife corridors
- Biodiversity
- Migratory nesting areas

Flora
- Vegetation, forestry, woodlands
- Aquatic vegetation
- Biodiversity
- Species at risk

Environmental protection
- Significant designated areas

Compatibility with regulatory frameworks / policies

Standards certification
- LEED certification

Resource consumption
- Energy use
- Energy generation potential
- Water use
- Chemical use
- Material sourcing

Resource conservation
- Material reuse
- Material recycling

Economic

Economic costs
- Capital costs
- Maintenance costs
- Operating costs
- Replacement value of asset
- Cost of service per capita
- Fee structure
- Education and awareness
- Communication

Revenue potential

Funding source
- Funding availability
- Funding stability

Time
- Project timeline
- Construction time
- Loss of time
- Service life
- Remaining service life
- Time savings

Level of service
- Principal infrastructure
- Dependent infrastructure

Flexibility of the solution

Scope of the solution

Land use
- Impact on business, commerce
- Impact on residential property
- Impact on agricultural property
- Impact on industrial property
- Future development potential

Property value
- Impact on property value
- Property acquisition value

Property requirements

Resource consumption
- Energy use
- Water use
- Chemical use

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