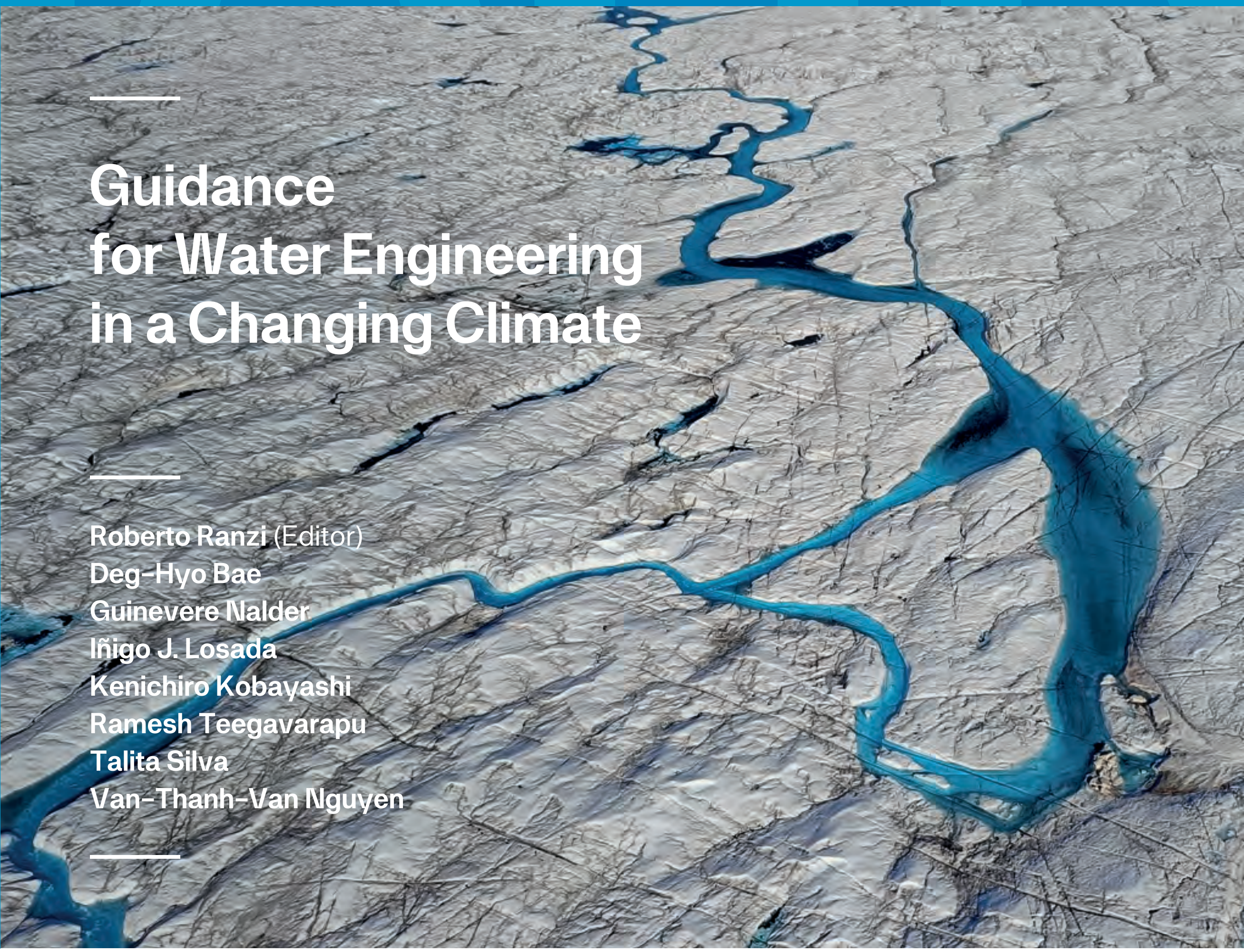
WATER MONOGRAPHS

#WaterMonographs



Guidance for Water Engineering in a Changing Climate

Roberto Ranzi (Editor)
Deg-Hyo Bae
Guinevere Nalder
Iñigo J. Losada
Kenichiro Kobayashi
Ramesh Teegavarapu
Talita Silva
Van-Thanh-Van Nguyen

Supported by
UNIVERSITÀ DEGLI STUDI DI BRESCIA

OPEN ACCESS

IAHR AIRH International Association for Hydro-Environment Engineering and Research
Hosted by Spain Water and IWHR, China
1935 — 2025 90 ANNIVERSARY

IAHR.org

Guidance for Water Engineering in a Changing Climate

Roberto Ranzi, Deg-Hyo Bae, Guinevere Nalder, Iñigo J. Losada, Kenichiro Kobayashi
Ramesh Teegavarapu, Talita Silva and Van-Thanh-Van Nguyen

Guidance for Water Engineering in a Changing Climate

Roberto Ranzi (Editor)
Deg-Hyo Bae
Guinevere Nalder
Iñigo J. Losada
Kenichiro Kobayashi
Ramesh Teegavarapu
Talita Silva
Van-Thanh-Van Nguyen

IAHR WATER MONOGRAPH SERIES

Series Editor
Damien Violeau
LNHE, EDF R&D, France.
Saint-Venant Hydraulics Laboratory, Ecole des Ponts ParisTech, France.
E-mail: damien.violeau@edf.fr

Cover: Photograph of the Greenland Ice Sheet, taken in July 2024.
Used with permission from Paolo Colosio, University of Brescia, Italy.

ISBN (online version): 978-90-835589-4-3

ISBN (printed version): 978-90-835589-3-6

ISSN 2959-7978

doi: 10.3850/IAHR_Watermonograph_005

Typeset by Research Publishing, Singapore
Cover designed by Tres Estudio Creativo, Spain
Technical Editing by Mistaya Langridge, McCloy Consulting Ltd, Ireland

Published by:
IAHR — International Association for Hydro-Environment Engineering and Research

Madrid Office

Paseo Bajo Virgen del Puerto 3, 28005, Madrid, SPAIN
Tel: +34 913357908; Fax: +34 913357935

Beijing Office

A-1 Fuxing Road, Haidian District, 100038, Beijing, CHINA
Tel: +86 1068781128; Fax: +86 1068781890

The International Association for Hydro-Environment Engineering and Research (IAHR), founded in 1935, is a worldwide independent organisation of engineers and water specialists working in fields related to the hydro-environmental sciences and their practical application. Activities range from river and maritime hydraulics to water resources development and eco-hydraulics, through to ice engineering, hydro-informatics and continuing education and training. IAHR stimulates and promotes both research and it's application, and by so doing strives to contribute to sustainable development, the optimisation of the world's water resources management and industrial flow processes. IAHR accomplishes its goals by a wide variety of member activities including: working groups, research agenda, congresses, specialty conferences, workshops and short courses; Journals, Monographs and Proceedings; by involvement in international programmes such as UNESCO, WMO, IDNDR, GWP, ICSU, and by co-operation with other water-related (inter)national organisations.

The monitoring of publishing ethics is a major aspect of editorial and peer-review publications. IAHR is a well-established and long-standing organization whose primary mission is to foster knowledge exchange amongst its community and stakeholder base. Accordingly, IAHR takes its policies on ethics seriously.

The IAHR Water Monograph *Practical Flooding Risk Assessment for Development Projects* has been published under the IAHR Publications Ethics and Malpractice Statement. Additionally, IAHR publications follow the Ethical Guidelines and Codes of Conduct provided by the Committee of Publication Ethics (COPE).

REVIEWERS

The editor and authors acknowledge the work of the reviewers in improving the content of this IAHR Water Monograph:

Prof. Em. Anastasios I. Stamou, National Technical University of Athens (NTUA), Greece
Prof. Jaak Monbaliu, KE Leuven, Belgium
Prof. Marco Marani, Marco Marani, University of Padova, Italy

About the IAHR Water Monograph Series

The IAHR Water Monograph Series is a recent addition to IAHR's long-standing portfolio of publications, which includes peer-reviewed journals, magazines, conference proceedings, white papers, and books. Since its founding in 1935, IAHR has been dedicated to advancing and sharing knowledge that supports progress in hydro-environment engineering and research.

IAHR Water Monographs are medium-length publications-typically between 50 and 150 pages-that bridge the gap between journal articles and full-length books. They are designed to consolidate and communicate authoritative knowledge on specific hydro-environment topics. Each monograph may summarise existing research, address knowledge gaps, or present recent advances in theory, methods, and practice. Topics commonly include physical processes, measurement techniques, theoretical developments, numerical modelling, engineering applications, and relevant historical or cultural contexts. Written in a concise, accessible, and well-illustrated format, Water Monographs serve as valuable resources for both specialists and those newly entering the field.

To ensure academic rigour and credibility, each monograph undergoes a structured peer-review process overseen by the IAHR Task Force on Water Monographs. This Task Force is responsible for issuing calls, evaluating proposals, and appointing editors. Itscurrentmembers are:

- Damien Violeau, EDF, France (Chair)
- Claudia Adduce, Roma Tre University, Italy
- Donatella Termini, University of Palermo, Italy
- Ioan Nistor, University of Ottawa, Canada
- Massimo Guerrero, Università di Bologna-DICAM, Italy
- Pengzhi Lin, Sichuan University, China
- Robert Ettema, Colorado State University, USA
- Vladimir Nikora, University of Aberdeen, UK

Once a proposal is approved by the Task Force, an Editor is appointed to work closely with the author(s) throughout the preparation of the manuscript. When the draft is ready for review, three independent experts, and recognised in the relevant field, are invited to assess the work. Their reviews are shared with the authors for revision. Upon satisfactory revision, the Editor makes the final decision on acceptance. Reviewers are acknowledged in the published monograph, and their names are disclosed to the authors at the end of the process.

All IAHR Water Monographs are published as Open Access, ensuring free and unrestricted access to readers worldwide. This is made possible thanks to the support of IAHR and institutional sponsors committed to advancing hydro-environment knowledge. Sponsors are recognised through the inclusion of their logo on the monograph cover; however, they have no involvement in the editorial or peer-review process.

Through this series, IAHR reaffirms its mission to support the global hydro-environment community by making high-quality, targeted knowledge openly and equitably available.

Damien Violeau
Chair of IAHR Water Monograph Series

Preface

The University of Brescia is pleased to sponsor the publication of this IAHR Water Monograph, as the theme addressed, focused on the climate action of the United Nations Sustainable Development Goals, is well aligned with its strategic plan for education, research and social engagement. In particular, our Professor Carmine Trecroci is President of the Network of Universities for Sustainable Development (RUS) promoted by the Conference of Rectors of Italian Universities for the 2025–2027 mandate. Together with the Polytechnic University of Turin, we also host the Italian section of the United Nations SDSN-Sustainable Development Solutions Network and have promoted the initiative "Climbing For Climate", a demonstration initiative that we started in 2019 in which students, staff and professors every year climb a glacier to raise awareness at local, national and international level on the ongoing effects of climate change in light of the goals of the UN Agenda 2030.

In my role as Vice Rector for International Affairs and Professor of Hydraulic Engineering, I believe that not only mitigation measures but also adaptation measures to climate change in the water sector, such as those addressed in this IAHR Water Monograph, can contribute to the peaceful and sustainable development of our world.

This sponsorship was made possible thanks to the "Artificial Intelligence for water management in the Red River Delta to meet the water demand and control saline intrusion in a changing climate" Grant IG-2023-174 by Climate Change AI Innovation Grants program by Climate Change, Pittsburg, PA.

Prof. Roberto Ranzi, PhD
Vice Rector for International Affairs
University of Brescia, Italy
www.unibs.it

Table of Contents

CHAPTER 1

Introduction
Water Engineering Design Guidance in a Changing Climate: An Overview

Roberto Ranzi

Department of Civil, Environmental, Architectural Engineering and Mathematics, University of Brescia, Italy. E-mail: roberto.ranzi@unibs.it

Bregje van Wesenbeeck

Deltares, P.O. Box 177, 2600 MH Delft, The Netherlands. E-mail: Bregje.vanWesenbeeck@deltares.nl

Van-Thanh-Van Nguyen

Department of Civil Engineering, McGill University, Canada. E-mail: van.tv.nguyen@mcgill.ca

1.1 | Introduction

This IAHR Monograph aims at providing a guidance to professionals, researchers and policy makers for assessing observed and projected impact of climate variability and change on the hydro-systems and to adapt the practice of engineering design of hydraulic infrastructures and water resources management to such changes. It will present an overview of methods for the analysis of non-stationary time series and of the estimate of the hydrological and hydraulic design variables as precipitation, floods, droughts, sea level and storm surges by relaxing the hypothesis of stationarity of the climate. Starting from examples taken from case studies of adaptation measures worldwide, it will provide some guidance for designing a balanced 'blend' of grey and green hydraulic works as urban stormwater drainage systems, dam spillways, river embankments, reservoirs, coastal defence systems and for managing water resources in changing climate conditions. Following similar efforts deployed in scientific communities as IAHS (Montanari et al., 2013) or organization as UNESCO (Stakhiv and Hiroki, 2021) to make predictions of water resources dynamics and water resources planning in a changing environment, it aims at collecting contributions of experts and professionals in IAHR for adapting water infrastructures to changes in the hydrological cycle induced by a variability of climate that often appears to have the characteristics a real change (Stamou et al., 2024).

The bibliography can provide also a useful reference for researchers in the water sector in areas that may not be fully covered by their specialized expertise so that the target of this IAHR Monograph is the typical community of our Association, i.e. a balanced blend of scientists, professionals and practitioners. This was our attempt and we hope that our efforts, with the contribution of the reviewers we thank, will provide some benefit to the community of water engineering and research in addressing the challenges posed by climate change in our disciplines.

1.2 | The IPCC AR6 and water

In August 2021 the IPCC, during its 54th Session, has finalized the first part of the Sixth Assessment Report (AR6), Climate Change 2021: The Physical Science Basis, prepared by the Working Group I (IPCC, 2021). Later, in spring 2022 also the reports of WGII (IPCC, 2022a) and WGIII on Impact, Adaptation and Vulnerability and on Mitigation (IPCC, 2022b) were published on-line and the printed version was issued in 2023. The concern of scientists, media and decision makers on the trends of warming, melting of ice sheets, rate of sea level rise and other impacts on the hydrosphere and the biosphere is very high. The thousands of pages of the seven volumes reports and their Summaries for Policymakers provide a sound basis for an up-to-date approach for the assessment of the impact, design adaptation and mitigation measures also in water engineering, a topic of high interest for IAHR. Some of the headline statements and the summary conclusions from the reports which have a high or at least a medium consensus by IPCC and are of special interest to the water sector, are summarized in the following sections (see also Ranzi, 2021 and the special number 3 of the IAHR Magazine Hydrolink issued in 2022).

1.2.1 | The science basis and impact on the water sector

It is indisputable that human activities are causing climate change, making extreme climate events, including heat waves, heavy rainfall, and droughts, more frequent and severe.

1.2.1.1 | *The current state of the climate*

- The likely range of total human-caused global surface temperature increase from 1850–1900 to 2010–2019 is 0.8°C to 1.3°C, with a best estimate of 1.07°C.
- Human influence is very likely the main driver of the global retreat of glaciers since the 1990s and the decrease in Arctic sea ice area between 1979–1988 and 2010–2019. However there has been no significant trend in Antarctic sea ice area from 1979 to 2020 due to regionally opposing trends and large internal variability.

- It can be stated with high confidence that global mean sea level increased by 0.20 [0.15 to 0.25] m between 1901 and 2018. The average rate of sea level rise was 1.3 [0.6 to 2.1] mm yr^{-1} between 1901 and 1971, increasing to 1.9 [0.8 to 2.9] mm yr^{-1} between 1971 and 2006, and further increasing to 3.7 [3.2 to 4.2] mm yr^{-1} between 2006 and 2018. Thermal expansion explained 50% of sea level rise during 1971–2018, while ice loss from glaciers contributed 22%, ice sheets 20% and changes in land water storage 8%.
- In 19 out of 45 macro regions of the world an increase of heavy precipitation (drawn from one to five days precipitation) is observed, in 8 a low agreement is reached on the type of change and in none of them a decrease is assessed.
- Increased adverse impacts of inland flooding and flood or storm induced damages in coastal areas are observed worldwide, especially in Asia, Australasia, North America and mountain regions.
- In 12 out of 45 macro regions of the world an increase of agricultural and ecological drought, due to increased land evapotranspiration, is observed, in 28 a low agreement is reached on the type of change and just in one of them a decrease is assessed.

1.2.1.2 | *The future state of the climate*

A set of five new illustrative emissions scenarios (named SSPx-y ‘Shared Socio-economic Pathway’ differently from the RCPs in the 5th Assessment Report) labelled with $x=1,..5$ with radiative forcing, y, set to $y=1.9$, 2.6, 4.5, 7.0 and 8.5 Wm^{-2}, is considered in AR6.

- In the mid term (2041–2060) and long term (2081–2100) the very likely range of mean global surface temperature increase compared to 1850-1900 ranges from 2.0°C to 2.4°C and 2.7°C to 4.4°C, respectively, according to the SSP3–4.5 and SSP5–8.5 scenarios.
- It is virtually certain that the Arctic will continue to warm more than global surface temperature, with high confidence above two times the rate of global warming. Additional warming is projected to further amplify permafrost thawing, and loss of seasonal snow cover, of land ice and of Arctic sea ice (high confidence). There is low confidence in the projected decrease of Antarctic sea ice.
- It is virtually certain that global mean sea level will continue to rise over the 21st century. Relative to 1995-2014, the likely (with medium confidence) global mean sea level rise by 2100 is 0.28–0.55 m under the very low GHG emissions scenario (SSP1–1.9), 0.44–0.76 m under the intermediate GHG emissions scenario (SSP2–4.5), and 0.63–1.01 m under the very high GHG emissions scenario (SSP5–8.5).

- Precipitation is projected to increase over high latitudes, the equatorial Pacific and parts of the monsoon regions, but decrease over parts of the subtropics and in limited areas of the tropics.
- Increases in frequency and intensity of hydrological droughts become larger with increasing global warming in some regions (medium confidence). There will be an increasing occurrence of some extreme events unprecedented in the observational record with additional global warming, even at 1.5°C of global warming.
- It is very likely that heavy precipitation events will intensify and become more frequent in most regions with additional global warming. At the global scale, extreme daily precipitation events, with return period of 10 years, are projected to intensify by about 7% for each 1°C of global warming (high confidence).
- There is strengthened evidence since AR5 that the global water cycle will continue to intensify as global temperatures rise (high confidence), with precipitation and surface water flows projected to become more variable over most land regions within seasons (high confidence) and from year to year (medium confidence).
- Global warming of 1.5°C and 2°C will be exceeded during the 21st century unless deep reductions in carbon dioxide (CO_2) and other greenhouse gas emissions occur in the coming decades.

The IPCC AR6 report depicts scenarios consistent with, but, to some extent, even more severe than the AR5 and poses responsibilities to the decision makers on the active measures to be taken to mitigate the effect of the projected global warming.

The water engineering community including IAHR is also challenged in order to properly address the assessment at the regional and local scale the impact of combined climatic and anthropogenic changes in the water cycle and revision of the design and management criteria in the water sector.

1.2.2 | Adaptation measures

The WGII report (IPCC, 2022a) has a particular focus on transformation and system transitions in energy; land, ocean, coastal and freshwater ecosystems; urban, rural and infrastructure; and industry and society. Chapter 4 of the WGII Report if fully dedicated to impact and adaptation in the water sector.

1.2.2.1 | *Land ocean and ecosystem transition*

IPCC recognizes with high confidence that adaptation to water-related risks and impacts are well documented. For inland flooding, combinations of non-structural measures like early warning systems and structural measures like levees have reduced loss of lives. Enhancing natural water retention such as by restoring wetlands and rivers, land use planning such as no build zones or upstream forest management, can further reduce flood risk. On-farm water management, water storage, soil moisture conservation and irrigation are some of the most common adaptation responses and provide economic, institutional or ecological benefits and reduce vulnerability. Irrigation needs appropriate management to avoid potential adverse outcomes, which can include accelerated depletion of groundwater and other water sources and increased soil salinization. However, the effectiveness of most water-related adaptation options to reduce projected risks declines with increasing warming.

1.2.2.2 | *Small islands*

Observed adaptation measures in small islands during drought events includes community water sharing, as well as using alternative water resources such as water purchased from private companies, desalination units or accessing deeper or new groundwater resources and rainwater harvesting.

1.2.2.3 | *Urban, Rural and Infrastructure Transition*

With medium confidence it is perceived that combined ecosystem-based and structural adaptation responses are being developed, and there is growing evidence of their potential to reduce adaptation costs and contribute to flood control, sanitation, water resources management, landslide prevention and coastal protection.

Responses to ongoing sea level rise and land subsidence in low-lying coastal cities and settlements and small islands include protection, accommodation, advance and planned relocation. These responses are more effective if combined and/ore sequenced, planned well ahead, aligned with sociocultural values and development priorities, and underpinned by inclusive community engagement processes. Coastal cities and settlements play a key role in moving toward higher climate resilient development, as almost 900 million people lived within the Low Elevation Coastal Zone, below 10 m of elevation above sea level in 2020. Then these areas make key contributions to climate resilient development through their vital role in national economies.

1.2.2.4 | *Adaptation in the agricultural sector*

Water-related adaptation in the agricultural sector makes up the majority of documented local, regional and global evidence of implemented adaptation. Water and soil conservation measures (e.g., reduced tillage, contour ridges or mulching) are frequently documented as adaptation responses to reduce water-related climate impacts in the agricultural sector. The use of non-conventional water sources, that is, desalinated and treated waste water, is emerging as an important component of increasing water availability for agriculture. While desalination has a high potential in alleviating agricultural water stress in arid coastal regions, proper management and water quality standards for desalinated irrigation water are essential to ensure continued or increased crop productivity. In addition to the energy intensity, risks of desalinated water include lower mineral content, higher salinity, crop toxicity and soil sodicity. Similarly, waste-water reuse can be an important contribution to buffer against the increasing variability of water resources. However, waste-water guidelines that ensure the adequate treatment to reduce adverse health and environmental outcomes due to pathogens or other chemical and organic contaminants will be essential.

1.2.2.5 | *Energy System Transition*

Within energy system transitions, the most feasible adaptation options support infrastructure resilience, reliable power systems and efficient water use for existing and new energy generation systems. Energy generation diversification, including with renewable energy resources and generation that can be decentralised depending on context (including wind and small scale hydroelectric) and demand side management (e.g., storage, and energy efficiency improvements) can reduce vulnerabilities to climate change, especially in rural populations. Adaptations for hydropower are effective in most regions up to 1.5°C to 2°C, with decreasing effectiveness at higher levels of warming. Hydropower can also play a role in compensating for the intermittency of other renewable energies. For example, integrating hydro, solar and wind power in energy generation strategies in the Grand Ethiopian Renaissance Dam can potentially deliver multiple benefits, including decarbonisation, compliance with environmental flow norms and reduce potential conflicts among Nile riparian countries (Sterl et al., 2021).

1.2.2.6 | *Cross-cutting Options*

Effective adaptation options for water-borne diseases include improving access to potable water, reducing exposure of water and sanitation systems to flooding and extreme weather events, and improved early warning systems.

1.2.2.7 | *Enabling Climate Resilient Development*

Structural vulnerabilities to climate change can be reduced through carefully designed and implemented legal, policy, and process interventions. This includes rights-based approaches that focus on capacity- building, meaningful participation of the most vulnerable groups, and their access to key resources, including financing, to reduce risk and adapt. Evidence shows that climate resilient development processes link *scientific, Indigenous, local, practitioner and other forms of knowledge*, and are more effective and sustainable because they are locally appropriate and lead to more legitimate, relevant and effective actions. Pathways towards climate resilient development are founded on societal choices that accelerate and deepen key system transition. Governance for climate resilient development is enabled by adequate and appropriate human and technological resources, information, capacities and finance.

1.2.3 | Mitigation

The WGIII report about mitigation (IPCC, 2022b), focused primarily on GHG emissions and the energy sector was published also in printed version in 2023. As a summary of its two-volumes short hints, relevant for the IAHR community are reported here.

- Sustainable urban planning and infrastructure design including green roofs and facades, networks of parks and open spaces, management of urban forests and wetlands, urban agriculture, and water-sensitive design can deliver both mitigation and adaptation benefits in settlements. These options can also reduce flood risks, pressure on urban sewer systems, urban heat island effects, and can deliver health benefits from reduced air pollution. There could also be trade-offs. For example, increasing urban density to reduce travel demand, could imply high vulnerability to heat waves and flooding.
- Electricity systems powered predominantly by renewables are becoming increasingly viable. Electricity systems in some countries and regions are already predominantly powered by renewables. It will be more challenging to supply the entire energy system with renewable energy. Even though operational, technological, economic, regulatory, and social challenges remain, a variety of systemic solutions to accommodate large shares of renewables in the energy system have emerged. A broad portfolio of options such as, integrating systems, coupling sectors, energy storage, smart grids, demand- side management, sustainable biofuels, electrolytic hydrogen and derivatives, and others will ultimately be needed to accommodate large shares of renewables in energy systems. It has to be noted that IPCC considers the potential contribution of hydropower to net emission reduction relatively low, about

0.4 $GtCO_2$-eq yr^{-1}, i.e. one tenth of that of solar or wind energy. But it is still the predominant source of renewable energy and accounts about 16% of the share in global total electricity generation. Its potential of further development remains high but depends on environmental an social impacts in the planning stages. Fundamental is the role of Pumped Hydroelectric Storage (PHS) which represents the largest fraction of electricity storage capacity globally.

- Marine energy also has a high potential of development, some tens of PWh yr^{-1}, similar to that of hydropower, as energy can be extracted from tides, waves, ocean thermal energy conversion, currents, and salinity gradients.
- It is stated with high confidence that restoration of mangroves and coastal wetlands is becoming a mitigation measure for carbon sequestration, while also reducing coastal erosion and protecting against storm surges, thus, reduce the risks from sea level rise and extreme weather. This is a typical example of Nature Based Solution for adapting to and mitigating climate change, a topic that is addressed more in detail in the next section.

Limiting warming to 2°C or 1.5°C will require substantial energy system changes over the next 30 years. This includes reduced fossil fuel consumption, increased production from low- and zero-carbon energy sources, and increased use of electricity and alternate energy carriers. Electricity systems powered predominantly by renewables are becoming increasingly viable. Electricity systems in some countries and regions are already predominantly powered by renewables. Many accelerated mitigation pathways include high shares of renewable energy, with national variations. High-renewable scenarios also exist for individual Member States in Europe, relying primarily on wind, solar PV and oceans, while hydropower, although being an already established technology, is one of the lowest-cost electricity technology, has still development potential in some countries and is fundamental in providing flexibility and storage.

1.2.3.1 | *Hydropower*

Hydroelectric power grew from 3890 TWh yr-1 (14.0 EJ yr^{-1}) in 2015 to 4290 TWh yr^{-1} (15.5 EJ yr^{-1}) in 2019, or 10.3%,with a share in global total electricity generation remaining around 16% and 43% of global electricity from renewables, and an important share of pumped-storage hydropower systems among technologies for energy storage. Estimates of global gross theoretical available hydropower potential varies from 31-128 PWh yr^{-1}, exceeding total electricity production in 2018, and its estimated technical potential is 8-30 PWh yr^{-1}. The future mitigation potential of hydropower depends on minimizing environmental and social impacts during the planning stages. People generally perceive hydroelectric energy as clean and a non-contributor to climate change and environmental pollution.

However, in areas where the construction of new large-scale hydroelectric energy is met with resistance, people believe that electricity generation from hydro can cause environmental, social, and personal risks.

1.2.3.2 | *Marine Energy*

The ocean is a vast source of energy that can be extracted from tides, waves, ocean thermal energy conversion, currents, and salinity gradients. Tidal energy, which uses elevation differences between high and low tides, and appears in the forms of potential energy (rise and fall of the tide) and current energy (from tidal currents) has a harvestable tidal power estimated as ~1.2 PWh yr^{-1}. Ocean wave energy is abundant and predictable and can be extracted directly from surface waves or pressure fluctuations below the surface. Its global theoretical potential is estimated as 29.5 PWh yr^{-1},which means that wave energy alone could meet all global energy demand. The temperature gradients in the ocean can be exploited to produce energy, and its total estimated available resource could be up to 44.0 PWh yr^{-1}. Salinity gradient energy, also known as osmotic power, has a global theoretical potential of over 1.6 PWh yr^{-1}. The greatest barrier to most marine technology advances is the relatively high upfront costs, uncertainty on environmental regulation and impact, need for investments and insufficient infrastructure.

1.2.3.3 | *Energy storage*

In 2017 an estimated 4.67 TWh of electricity storage was in operation globally. If the integration of renewables is doubled from 2014 levels by 2030, the total capacity of global electricity storage could triple, reaching 11.89–15.27 TWh. In Pumped Hydroelectric Storage (PHS), making use of gravitational potential energy, water is pumped into an elevated reservoir using off-peak and low-cost electricity and stored for later release when electricity is needed. These closed-loop hydropower plants have been in use for decades and account for 97% of worldwide electricity storage capacity. PHS is best suited to balancing daily energy needs at a large scale, and advances in the technology now allow both rapid response and power regulation in both generating and pumping mode. The construction itself can cause social and environmental impact, the initial investment is costly, and extended construction periods delay return on investment. In addition, locations for large-scale PHS plants are limited. Advanced pump-turbines are being developed, allowing both reversible and variable-speed operation, supporting frequency control and grid stability with improved round-trip efficiencies. New possibilities are being explored for small-scale PHS installations and expanding the potential for siting. Pumped technology is a mature technology and can be important in supporting the transition to future low carbon electricity grids.

1.2.3.4 | *Impact of climate change on hydropower potential*

Analyses consistently demonstrate that the global impact of climate change on hydropower will be small, but the regional impacts will be larger, and will be both positive and negative. Gross global hydropower potential in the 2050s has been estimated to slightly decrease between 0.4% (for the low emission scenario) and 6.1% (for the highest emission scenario) for 2080s compared to 1971–2000. Regional changes in hydropower are estimated from 5–20% increases for most areas in high latitudes to decreases of 5–20% in areas with increased drought conditions.

1.3 | Nature-based Solutions

Nature-based Solutions (NbS) make use of ecosystem services and natural processes to adapt to climate or reduce disaster risk, through restoration and protection of natural ecosystems (Veerkamp et al. 2021). They can contribute to mitigation of different types of climate related hazards, from damping waves to retaining soils, in a range of different environments. NbS can be functional from rivers to coasts and from mountains to cities but deviate between environments and geographies by making use of different ecosystems. Natural and healthy ecosystems are at the basis of good functioning of NbS and for this, abiotic processes are key. Fluxes of water, nutrients, sediment and species are essential boundary conditions for ecosystem functioning and, thus, should be integrated in NbS concepts and designs. NbS can not only play a role in adapting to climate change, they directly mitigate climate change by trapping carbon dioxide from the atmosphere and emitting oxygen through photosynthesis. In addition, NbS offer multiple benefits for society, economy and environment, beyond the primary design function, such as tourism, recreation, natural value, fisheries and food provisioning.

The concept of nature-based solutions is increasingly embraced and supported by international and national policies and programs. Although their portfolio constitutes only a marginal part of the entire climate change adaptation portfolio, financial resources are rapidly increasing (UNEP GAP report 2020). They are also seen as an important element in Covid recovery and green growth packages. Basic principles that help implementation can be found in several guidelines on implementation, mainly with a focus on flood risk reduction (World Bank 2018, Cohen-Stacham et al., 2016; USACE Climate Action Plan, 2021). Development of international cross-disciplinary standards can aid in accelerating NbS project implementation. Monitoring of implemented projects based on common criteria of NbS performance and success can help in evaluation of NbS projects. Both these elements are essential for mainstreaming NbS. Main uncertainties for NbS regard the long-term sustainability under a changing climate. Next to direct anthropogenic pressures, such as reclamation and pollution, climate change is heavily impacting ecosystems and thereby reducing the overall potential of NbS efficiency (Pörtner et al. 2021). On the other hand, the strong linkage between the climate crisis and biodiversity crisis constitutes an even more compelling case for increasing the use and implementation of NbS.

1.4 | Climate Change and Engineering in Search of Consensus

According to the recent national climate change assessment report by Environment and Climate Change Canada (ECCC), a representative example of adaptation in engineering design, Canada's climate is changing and is projected to warm substantially faster than the global average (Zhang et al., 2019). For instance, observational datasets show that temperature in Canada has increased at roughly double the global mean rate, with Canada's mean annual temperature having risen about 1.7°C over the 1948–2016 period. In addition, based on the assessment of historical trends and future projections of precipitation, there is high confidence that annual precipitation and rainfall will increase in Canada with global warming. Hence, historical climatic design data is becoming less representative of the future climate, and future climate risks may be significantly underestimated. Consequently, engineers cannot assume that the future will be similar to the past and historical climate trends cannot be simply projected into the future as a basis for engineering work. These changes in weather patterns and deviations from historical climate ranges may adversely affect the integrity of the design, operation, and management of engineered systems. Engineers in Canada are thus encouraged to consider the implications of climate change in their professional practice as recommended in the national guideline established by Engineers Canada (2018). This guideline provides guidance on how to address the implications of climate change in professional practice, and how to create a clear record of the outcomes of those considerations. In particular, engineers are bound by their code of ethics to "hold paramount the safety, health and welfare of the public and the protection of the environment and promote health and safety within the workplace". Hence, it is the engineer's duty to take all reasonable measures to ensure that engineered systems appropriately account for the potential impact of changing climate conditions. As an example, engineers who are responsible for the design of public facilities and infrastructure will have to accommodate climate change into their work to ensure public health and safety. Given the important implications of this issue, engineers that do not exercise appropriate due diligence regarding climate change may ultimately be held personally or jointly liable for failures and/or damages arising from foreseeable climate impacts on engineered systems.

In general, the application of the proposed climate change adaptation guideline will always be a matter of professional judgment. Engineers should understand the scientific basis, strengths, and limitations of any given methodology, approach, or tool used to derive future climatic design information. For instance, for the design of urban drainage infrastructures it is recommended that engineers should work with climate specialists/experts to ensure that interpretations of climatic and weather considerations should reasonably reflect the most current scientific consensus regarding the climate and/or weather information (CSA, 2019). Another important recommendation on the integration of climate change adaptation into existing practice isfocused on the resiliency principle in engineering system design. The guideline now identifies the need to add the "climate flexibility" approach to improve resiliency. This approach is similar to the application of a "safety factor" or the use of "demand flexibility" inherent in current engineering practice. For instance, a bridge could be designed so that a span could be added in the future as traffic flow increases. Therefore, reasonable consideration should be given to the resiliency of an engineered system from the impacts of changing climate conditions when assessing the required length of service over its operating life. This is done through applying life cycle costing and resiliency principles. In summary, flexible adaptation strategies can be applied in stages as climate change impacts become clearer in the future. Examples include modular sea walls that can be raised as needed; highway bridges that can be elevated as peak flows beneath them increase. An incremental approach has fewer social and environmental impacts than building huge structures in one phase to keep up with climate-induced changes. Flexible adaptation could be a valuable alternative approach for suitable cases. When an engineer starts planning climate adaptation actions, the needs vary by each case according to vulnerability assessment results, analysis of alternatives and timelines foreach project.

In summary, climatic factors such as temperature, precipitation, and wind play a key role in the design, operation, and management of various water infrastructures. The current design and management procedures, however, have been mostly based on historical data that do not take into account the potential impacts of climate change. Lack of appropriate information and decision support for the design and management of these critical infrastructures under a changing climate puts many urban communities at risk. Major extreme weather events, such as flooding, ice storms, wildfires and high winds, can cause billions of dollars of damage and loss of life. The accelerated need for rehabilitation and replacement due to increased aging and deterioration from climate change will also increase the existing infrastructure deficits and additional financial pressures. Substantial efforts are hence needed to provide the codes, guidelines and decision support tools needed to protect the public from climate-change-related hazards and to improve the management of infrastructures to minimize the risk of failure and reduce the life cycle costs. It is therefore recommended that significant research and development efforts be focused on the areas of climate-resilient as well as supporting technologies such as design codes and guides, and asset management tools for these existing critical infrastructures.

References

1 CSA (Canadian Standard Association). (2019). Technical guide: Development, interpretation, and use of rainfall intensity-duration-frequency (IDF) information: Guideline for Canadian water resources practitioners, CSA PLUS 4013:19, Canadian Standard Association, Toronto, Ontario, Canada, 126 pages.

2 Cohen-Shacham, E.Janzen, C.Maginnis, StewartWalters, Gretchen (2016). Nature-based solutions to address global societal challenges. IUCN.

3 Engineers Canada (2018), Canadian Engineering Qualifications Board, Principles of Climate Change Adaptation for Engineers, 38 pages.

4 IPCC (2021). Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson- Delmotte, V., P. Zhai, A. Pirani, S. L. Connors, C. PeÃÅan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. YelekcÃßi, R. Yu and B. Zhou (eds.)]. Cambridge University Press

5 IPCC, (2022a): Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)]. Cambridge University Press. Cambridge University Press, Cambridge, UK and New York, NY, USA, 3056 pp., doi:10.1017/9781009325844.

6 IPCC, (2022b): Summary for Policymakers [P.R. Shukla, J. Skea, A. Reisinger, R. Slade, R. Fradera, M. Pathak, A. Al Khourdajie, M. Belkacemi, R. van Diemen, A. Hasija, G. Lisboa, S. Luz, J. Malley, D. McCollum, S. Some, P. Vyas, (eds.)]. In: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [P.R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, J. Malley, (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA. doi: 10.1017/9781009157926.001.

7 Montanari, A., Young, G., Savenije, H.H.G., Hughes, D., Wagener, T., Ren, L.L., Koutsoyiannis, D., Cudennec, C., Toth, E., Grimaldi, S., Blöschl, G., Sivapalan, M., Beven, K., Gupta, H., Hipsey, M., Schaefli, B., Arheimer, B., Boegh, E., Schymanski, S.J., Di Baldassarre, G., Yu, B., Hubert, P., Huang, Y., Schumann, A., Post, D., Srinivasan, V., Harman, C., Thompson, S., Rogger, M., Viglione, A., McMillan, H., Characklis, G., Pang, Z., and Belyaev, V., (2013): "Panta Rhei—Everything Flows": Change in hydrology and society—The IAHS Scientific Decade 2013–2022. Hydrological Sciences Journal. 58 (6) 1256–1275.

8 Pörtner, H.O., Scholes, R.J., Agard, J., Archer, E., Arneth, A., Bai, X., Barnes, D., Burrows, M., Chan, L., Cheung, W.L., Diamond, S., Donatti, C., Duarte, C., Eisenhauer, N., Foden, W., Gasalla, M. A., Handa, C., Hickler, T., Hoegh-Guldberg, O., Ichii, K., Jacob, U., Insarov, G., Kiessling, W., Leadley, P., Leemans, R., Levin, L., Lim, M., Maharaj, S., Managi, S., Marquet, P. A., McElwee, P., Midgley, G., Oberdorff, T., Obura, D., Osman, E., Pandit, R., Pascual, U., Pires, A. P. F., Popp, A., ReyesGarcía, V., Sankaran, M., Settele, J., Shin, Y. J., Sintayehu, D. W., Smith, P., Steiner, N., Strassburg, B., Sukumar, R., Trisos, C., Val, A.L., Wu, J., Aldrian, E., Parmesan, C., Pichs-Madruga, R., Roberts, D.C., Rogers, A.D., Díaz, S., Fischer, M., Hashimoto, S., Lavorel, S., Wu, N., Ngo, H.T. 2021. IPBES-IPCC co-sponsored workshop report on biodiversity and climate change; IPBES and IPCC. DOI:10.5281/zenodo.4782538.

9 Ranzi, R. (2021). Notes on the August 2021 IPCC Summary for Policymakers, Hydrolink, IAHR, Madrid, 3, pp. 68-69.

10 Stakhiv, E. Z., & Hiroki, K. (2021). Special issue for un help:'water infrastructure planning, management and design under climate uncertainty'. Water Policy, 23(S1), 1-9.doi: 10.2166/wp.2021.268

11 Stamou, A., Mitsopoulos, G. & Koutroulis, A. (2024). Proposed Methodology for Climate Change Adaptation of Water Infrastructures in the Mediterranean Region. Environ. Process. 11, 12. https://doi.org/10.1007/s40710-024-00691-w

12 Veerkamp, C. Castellari, S., Zandersen, M. Davis, M. Förster, J., Marttunen, M., Mysiak, J., Vandewalle, M. Medri, S. & Picatoste, J.R. Copyright notice ©European Environment Agency, 2021 Reproduction is authorised provided the source is acknowledged. More information on the European Union is available on the Internet (http://europa.eu). Luxembourg: Publications Office of the European Union, 2021, ISBN 978-92-9480-362-7, ISSN 1977-8449, doi: 10.2800/919315. Nature-based solutions in Europe (2021).

13 World Bank (2018). Adaptation & Resilience Action Plan, Key Messages. Washington, DC.

14 Zhang, X., Flato, G., Kirchmeier-Young, M., Vincent, L., Wan, H., Wang, X., Rong, R., Fyfe, J., Li, G., Kharin,V.V. (2019): Changes in Temperature and Precipitation Across Canada; Chapter 4 in Bush, E. and Lemmen, D.S. (Eds.) Canada's Changing Climate Report. Government of Canada, Ottawa, Ontario, 444 p.,https://changingclimate.ca/CCCR2019/

CHAPTER 2

Climate Change and Stationarity

Ramesh Teegavarapu

Department of Civil, Environmental and Geomatics Engineering, Florida Atlantic University, Boca Raton, USA. E-mail: rteegava@fau.edu

Roberto Ranzi

Department of Civil, Environmental, Architectural Engineering and Mathematics, University of Brescia, Italy. E-mail: roberto.ranzi@unibs.it

2.1 | Introduction

Long-term hydroclimatic series are generally evaluated using extremes and variable-specific indices in research studies focused on climate change and variability assessments. Water resources management and hydrologic design now need to be looked at from a perspective of nonstationary and evolving climate, a crucial aspect of the research (Kolokytha et al., 2016; Teegavarapu, 2020; Cosgrove and Loucks, 2015).Climate change adaptation measures are typically implemented after clear evidence emerges of their potential impacts on hydrologic and hydraulic infrastructure or hydrosystem operations.Non-stationarity assessments based on available time series of hydroclimatic variable observations and projections of future variations are crucial to confirm such change. Hydrologic cycle is not just driven by physical forces but also by anthropogenic activities impacting water quality and quantity (Matalas, 1982). Hirsch (2010) points out three main reasons for consideration of nonstationarity in design and they are (1) human modifications to hydrologic system upstream of a project, (2) quasi-periodic natural climate phenomena that may lead to different degrees of persistence and (3) climate change induced by human-driven changes. In general, the hydrologic design relies on the assumption of stationarity of the hydroclimatic extremes, and its assessment becomes an essential initial task.

2.1.1 | Need for Non-stationarity Assessment

Engineering adaptation to future climate change requires changes to hydraulic and hydrologic infrastructure design and operations of hydrosystems in the short and long-term. However, before any changes can be made to design and operations to develop an infrastructure that can easily adapt to future climatic conditions, nonstationarity or stationarity of hydroclimatic variables in a region needs to be confirmed. According to Matalas (1982) the utility of the assumption of hydrologic stationarity should not be discarded, at least not until the nonstationarity implied by any evidence has been translated into operational terms of water management. Available historical observations along with bias-corrected future projections of hydroclimatic variables from simulations of climate change models need to be assessed for nonstationary conditions. Non-stationarity assessment as the first step will help (1) identification of long-term shifts and variations in climate to rehabilitate existing infrastructure to accommodate evolving conditions. (2) develop robust methods for design that can address nonstationarity and (3) distinguish long-term climate change and natural variability to improve resilience of hydrosystems operations. Integrating nonstationarity assessment into engineering design, climate adaptation strategies can be made more robust, cost-effective, and resilient to future climate uncertainties.

2.1.2 | Assessment of Climate Change

Climate change assessment will require statistical methods to evaluate historical observations and projected values of hydroclimatic variables. Causal information that is linked to specific changes is also collected to confirm changes in the climate. Often, natural climate variability influences the inferences drawn about climate change (Teegavarapu et al., 2014; Goly and Teegavarapu, 2014). Future climate change projections can be evaluated using statistically or dynamically downscaled projections of essential climatic variables (ECVs) (WMO, 2025). ECVs refer mainly to chemical, physical, and biological observations that can help characterize Earth's climate. The spatially and temporally downscaled ECVs are generally bias-corrected (Goly and Teegavarapu, 2020) before they are used in hydrological simulation models used for climate change studies aimed at evaluating future changes in variables that impact the design and operation of hydrosystems. Readers are referred to a report by Brekke et al. (2009) that provided a concise review of climate change, downscaling methods, and their use with general circulation model (GCM) results associated with future climate change scenarios. Uncertainties associated with future climates, considering the limitations of downscaling approaches (Goly et al., 2014; Teegavarapu and Goly, 2018), also need to be accounted for in the case of hydrologic design and water resources management (Teegavarapu, 2010; 2013).

2.1.2.1 | *Homogeneity of Observed Essential Climatic Variables*

Climate change assessments based on observed essential climatic variables (ECVs) require that the measurements available are free of non-homogeneities and errors. Chronologically continuous (i.e., gap-free) data is also needed for such assessments. In the case of a physical system that is nonstationarity, with observations providing some evidence of changes in the processes influencing the system over time, the continuity of observations is critical (Milly et al., 2008; Milly et al., 2015). Observational gaps or infilled data will lead to changes in the characteristics of the time series and biases in trends associated with extremes (Teegavarapu and Nayak, 2017). Missing data must be filled in using appropriate spatial and temporal interpolation methods (Teegavarapu, 2024). Any anomalies and outliers in the time series with no physical reasons for their occurrences need to be handled carefully. Removal of extreme observations deemed outliers without proper analysis may lead to inaccurate inferences when statistical tests are used. Homogeneity issues arise mainly due to how the instruments are sited in the field or moved over time, changes in the type of instruments, measurement accuracies, regional changes in land use, and any other factors that influence the observed variations in the ECVs.The homogeneity of observations can be evaluated using conceptually simple double mass curves to computationally intensive statistical tests such as the Busihand test.

2.1.3 | Stationarity Assessment of Hydroclimatic Variables

Stationarity refers to the time-invariance of statistical properties of a time series. According to WMO (2009), stationarity is defined as the property of climate variables in which the data sequence is unaffected by arbitrary changes across time. Characteristics such as changes in mean, trend, and long-term periodicities in hydroclimatic time series indicate some form of nonstationarity (Bayazit, 2015; Ishak et al., 2013). Cohn and Lins (2005) indicate that realizations from stationary processes can exhibit excursions and trends that persist for decades or centuries.Stationarity assessment becomes the first task to assess changes in hydroclimatic variables. One crucial assumption in detecting nonstationarity or stationarity is that the observed sample reflects the characteristics of the physical process under investigation.

The existence and manifestations of stationarity are highly debated topics in the hydrologic community (Teegavarapu and Sharma, 2021). Stationarity was reported to be '*dead*' (Milly et al. 2008), '*alive*' (Lins and Cohn 20011), '*immortal*' (Montanari and Koutsoyiannis 2014), and '*undead*' (Serinaldi and Kilsby 2015). This ongoing debate underscores the complexity and importance of the issue. Many research studies have questioned the existence and identification of nonstationarity in physical processes (Koutsoyiannis 2006; Koutsoyiannis 2011; Koutsoyiannis and Montanari 2015, Slater et al., 2021). In design floods, stationarity may imply their time invariance and the constant probability of failure of a given water resources structure for its entire design life (François et al. 2019). Recent work by Salas and Obeysekera (2014) addresses the issues related to the return period and risk for nonstationary hydrologic extreme events. However, the assumption of stationarity may lead to over-or under-design if the time series is nonstationary (Rosner et al. 2014). According to the Inter governmental Panel on Climate Change (IPCC) (Bates et al., 2008), climate change challenges the traditional assumption that past hydrological experience provides a reasonably good guide to future conditions. The design guidelines and standards developed for hydrologic and hydraulic infrastructure and management of water resources systems are based on the stationarity assumption, which may no longer be applicable in a warming climate (Sharif et al., 2010).

Teegavarapu and Sharma (2021) have noted that in research works focused on hydrologic design with stationarity assessment: (1) statistical methods used in time series analysis in hydroclimatic studies are based on consistency, trend-free, and distributional assumptions about the random component of a stochastic series. (2) stationarity check is a passing mention in most studies dealing with nonstationarity for hydrologic design. (3) hydrologic designs under a nonstationary environment often rely on a single or couple of tests in detecting nonstationarity, (4) design studies often tend to assume a trend-free and homogenous time series to be stationary, and (5) use of more than one statistical test is advocated for assessment of any time series to obtain reliable and robust information about the presence of changes over time and (6) a single nonparametric or parametric approach is not adequate for a comprehensive assessment of stationarity or nonstationarity conditions of any hydroclimatic time series. Also, most studies resort to one or two tests to check for nonstationarity and neglect any checks that evaluate changes in the characteristics of the time series. Neglecting some of these issues could lead to misconceptions about stationarity detection in hydrologic time series, which warrants devising a comprehensive and robust procedure to address this issue. Results from multiple tests and a prior knowledge of time series will aid in assessing stationarity. However, no unified framework utilizing multiple tests is available except that is recently reported by Teegavarapu and Sharma (2021).

2.1.3.1 | *Strict and Weak Forms of Stationarity*

Various forms of stationarity can be defined based on different characteristics and statistical moments derived from sample data. In simple terms, if the mean and autocorrelation do not change with time, the stationarity is referred to as weak or wide-sense stationarity. Autocorrelation is also referred to as persistence, which suggests that a sequence of values in a time series is not random but is related. Strict stationarity requires time-invariance of statistical moments (e.g., mean, variance, etc.), autocorrelation, and distributional properties. Different orders of stationarity (e.g., Nth-order stationarity) can also be defined based on the number of moments that are constant with time. For example, first-order stationarity requires a constant mean, second-order needs constant variance, the conditions of first-order stationarity, and so on. Other forms of stationarity that can be evident from time series include (1) cyclo-stationarity and (2) trend-stationarity. Periodic changes in mean, variance or autocorrelation characterize a cyclo-stationary time series, while trend-stationarity refers to de-trended time series with random variation with no pronounced seasonality, and cycles produce a series with stationary properties.

2.1.3.2 | *Visual Assessment of Stationarity*

The sample time history of any data observed due to a physical phenomenon provides anyone with limited ability to assess the stationarity of the process or phenomenon. Generally, evidence of non-stationarity time series data is easier to detect from many statistical tests and visual assessments than stationarity. Plots of time series can help identify (1) abrupt change in the mean; (2) gradual change in the mean; (3) shifting levels (more than one change in the mean); (4) continuous trend in the mean and (5) changes in variability and ultimately nonstationarity. Statistical approaches used to assess time series assume that observed sample data of hydroclimatic variables accurately reflect the nonstationary or stationary character of the processes driving the variability in those observed time series. This assumption is reasonable if limited knowledge about the factors affecting the processes is available.

Exploratory and confirmatory data analysis techniques can be used to determine changes in the time series of hydroclimatic variables. McCuen (2002) documents several conceptually simple visual assessment methods for evaluating changes in hydrological time series, and they are (1) histograms and (2) probability density or cumulative distribution plots based on available entire time series data partitioned into two temporal windows. Parametric and nonparametric methods are also discussed by McCuen (2002) and Teegavarapu and Sharma (2021) to assess changes in moments and distributional characteristics. A series of observations can be used for the initial assessment of stationarity or nonstationarity, and different forms of moving averaging or functional transforms with kernel functions as wavelets can be used to highlight discontinuities, change points, or trends at different temporal scales (Ranzi et al. 2021; 2024). A deeper understanding of the generating process resulting in observed time series is essential. EDA can help identify potential nonstationarity signatures when there is prominent seasonality, visible trends that are upward or downward, changing mean and spread, abrupt and time-varying trends, changing seasonality, and irregular cycles. It is essential to have a large sample record (time series data) to provide evidence of changing characteristics of the process. Time series, lag, and autocorrelation plots will provide evidence of randomness and understanding of persistence characteristics.

2.1.4 | Statistical Methods for Assessment of Stationarity

Statistical methods can be used to assess stationarity or nonstationarity. In many studies, as documented by Teegavarapu (2018) and Teegavarapu et al. (2019), parametric and nonparametric tests are used to assess changes in the moments, autocorrelation structure, and distributional properties of the time series (Teegavarapu and Sharma, 2021). Parametric methods can also be used to assess change points in a nonstationary time series if the assumptions on which these tests are based are fulfilled. A change point is a specific moment in time where the characteristics of a time series shift, marking a distinct difference before and after that point.

2.1.4.1 | *Parametric Methods*

A time series conforming to test-specific distributional requirement (e.g., normal distribution) can be assessed for changes in statistical moments using parametric methods. Parametric approaches are not applicable in many situations where transformations or re-expressions of the hydroclimatic time series data may not conform to the distributional assumptions required by these approaches. The available time series sample is split into sub-samples or time slices (Teegavarapu, 2018; Teegavarapu and Sharma, 2021),and two-sample unpaired or multiple-sample parametric hypothesis tests can be conducted. An example of a time series split into two slices is shown in Fig. 2.1.

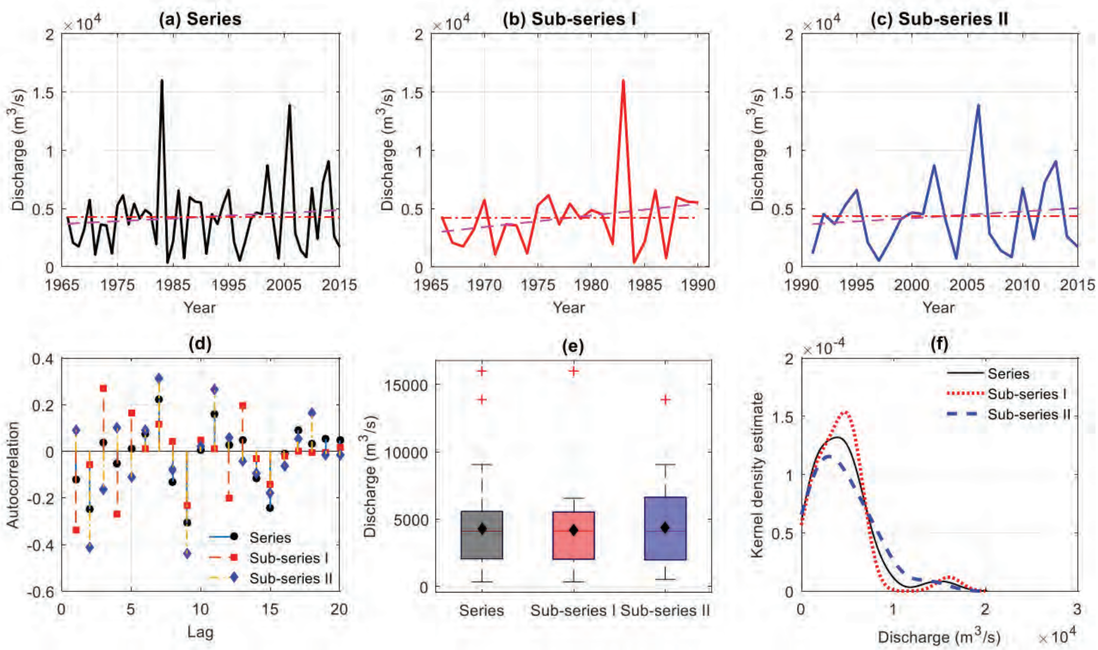


Figure 2.1 | Assessment of autocorrelation and distributional properties of slices of time series (Source: Teegavarapu and Sharma, 2021).

In a two-sample test scenario, two randomly selected temporal slices can be used to assess central tendency (i.e., mean) using a two-sample t-test. Before the t-test, the F-test is conducted to evaluate the variances of two-time slices. Depending on the test results of equality or inequality of the variances, an appropriate t-test is adopted. Multiple time series slices can be evaluated using a one-way analysis of variance (ANOVA) test.

Parametric trend analysis can be conducted using a linear regression model to assess statistically significant changes in the slope of the least-squares fit line. While it is easy to develop a linear regression model with observations against time, a diagnostic analysis of the residuals needs to be conducted to check if the assumptions on which the model is built are satisfied. A check related to residuals is required to confirm independence, normality, and heteroskedasticity. Visual assessments based on residuals using autocorrelation plots for independence and error-estimated value plots can be used to check issues related to heteroskedasticity.

2.1.4.2 | *Nonparametric Methods*

Methods for Assessments of stationarity in the past have relied on evaluation changes in mean values of time series or confirmation of the existence of a monotonic trend in the time series. Nonparametric tests (Corder and Foreman, 2014) can be used to assess stationarity. Many studies have adopted either the Spearman rank (SR) correlation test (Gauthier, 2001) or the Mann-Kendal (MK) test (Mann and Whitney, 1947) for the assessment of trends in the time series (Teegavarapu, 2018;Teegavarapu and Sharma, 2021). Variants of the MK test that address issues related to seasonality and statistically significant autocorrelation can be used when the time series properties influence the tests' power and inferences drawn from the tests. Pre-whitening approaches are also recommended to address the issue of autocorrelation. Limitations of the MK test and its variants in the assessment of climate change have been documented in several studies (Teegavarapu and Sharma, 2021).

In general, stationarity assessments have been primarily based on one or two tests in many works. Using multiple paired and group-based tests can provide robustness to the assessments as reliance on one hypothesis test or low power of the test or Fisher's probability-value (p-value)-based hypothesis inferences attached to the test may lead to inaccurate assessments (Teegavarapu and Sharma, 2022). Each test uses a unique test statistic and draws an inference about the specific statistical tendency (central, spread, or distributional) of the data under consideration. The unit root tests, as parametric tests, can help determine whether a time series is nonstationary and possesses a unit root (Kim and Choi 2017). These tests do not involve dividing the time series into sub-series, and they include Dickey-Fuller or Augmented Dickey-Fuller (ADF) (Dickey and Fuller 1979); Kwiatkowski-Phillips-Schmidt-Shin

(KPSS) (Kwiatkowski et al. 1992) and Phillips-Perron (PP) (Phillips and Perron 1988) tests. The main disadvantage of unit root tests is their inability to distinguish highly persistent stationary processes from nonstationary ones (Zivot and Wang 2007). Gujarati (2015) points out that unit root and non-stationary are not synonymous, and a stochastic process with a deterministic trend is nonstationary but not unit root.Teegavarapu and Sharma (2021) proposed a framework for assessing stationarity in hydroclimatic time series using several two-sample and multiple-sample nonparametric hypothesis tests. Their approach divides the available time series into non-overlapping blocks and evaluates the statistical properties of the two or more blocks taken simultaneously. The approach presented by Teegavarapu and Sharma (2021) is illustrated in Fig. 2.2.

The approach illustrated in Fig. 2.2 uses multiple nonparametric tests in two stages for a robust assessment of the stationarity of a time series. The time series is initially partitioned into non-overlapping slices of time or blocks, and sampling data (without replacement) within each block is obtained in

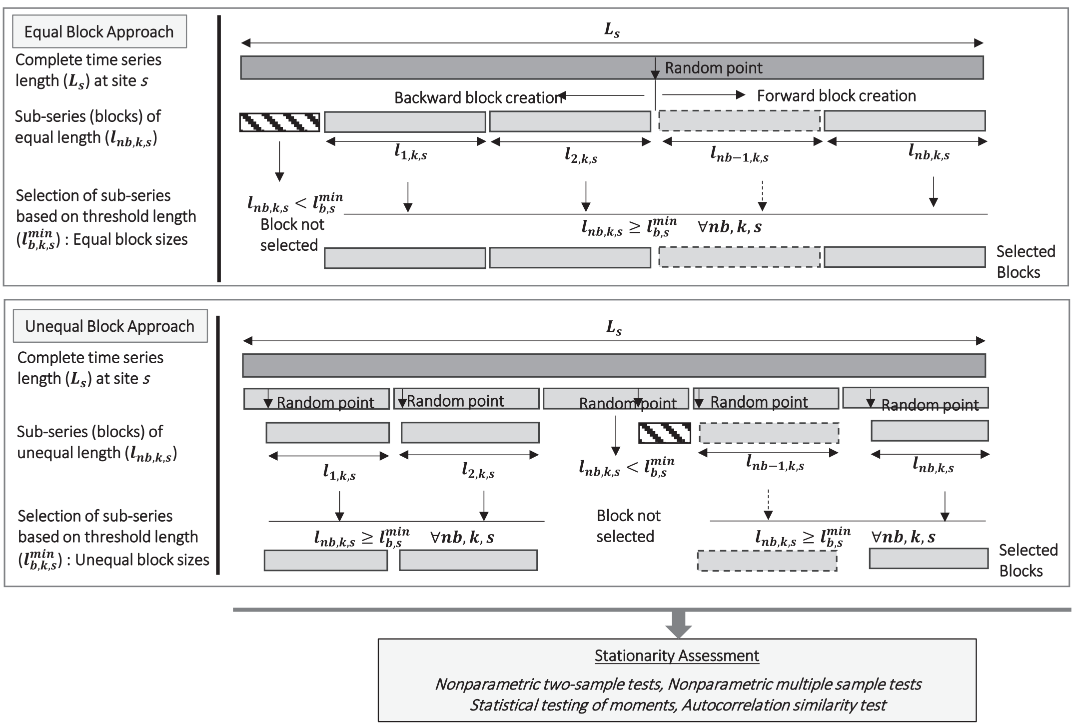


Figure 2.2 | Non-overlapping random sampling framework for assessment of stationarity (Source: Teegavarapu and Sharma, 2021).

stage I (Fig. 2.2). The block partitioning is carried out using two schemes (1) equal and (2) unequal. Several two-sample unpaired and multi-sample nonparametric tests are used to assess statistically significant differences among the data samples from different blocks. This step is called the distribution and median-variance similarity assessment (DMSA) approach. The two-sample unpaired tests used in this approach are Mann-Whitney (MW) (Mann and Whitney, 1947) and Ansari-Bradley (AB) (Ansari and Bradley, 1960). Two-sample Kolmogorov-Smirnov (KS) (Massey, 1951) and Chi-square (Pearson, 1900) and Anderson-Darling (AD) (Anderson and Darling, 1954) tests are used to assess distribution similarity. The multi-sample tests used in the approach include Kruskal-Wallis (KW) (Kruskal and Wallis, 1952), Anderson-Darling (Anderson and Darling, 1954), and Brown-Forsythe (BF) (Brown and Forsythe, 1974).

In stage II (Fig. 2.3.), using the data samples from blocks, an explicit evaluation of changes in four statistical moments and persistence (quantified through autocorrelations at several lags) among different blocks are evaluated. This step is called the statistical moments and autocorrelation assessment (SMAA) approach.Chronologically continuous data from the contiguous blocks are evaluated using two- and multi-sample nonparametric tests to assess distributional, median, and variance similarity,

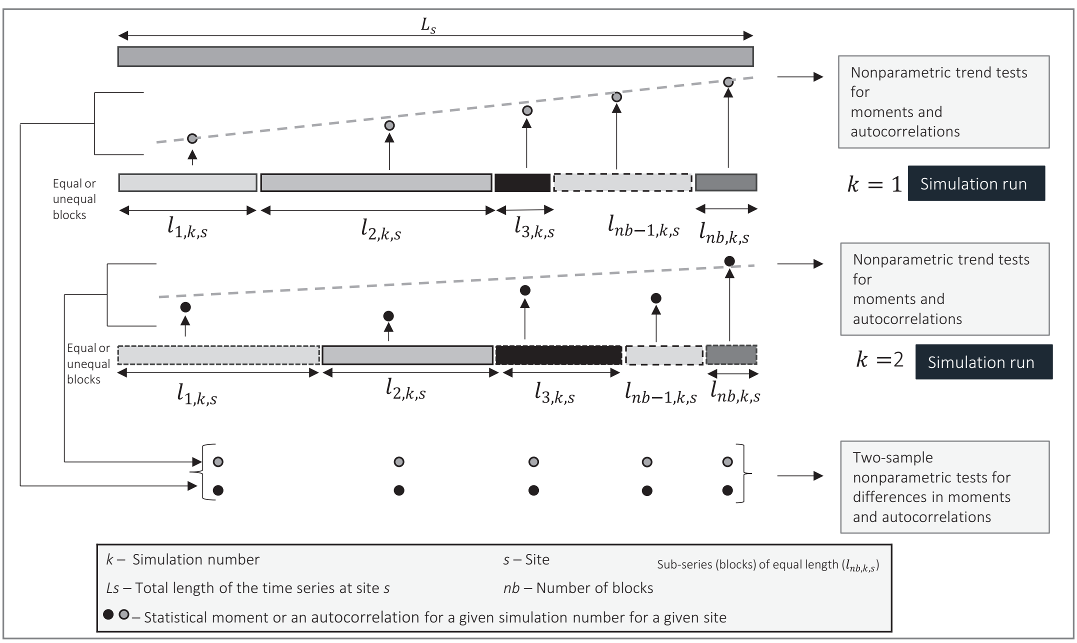


Figure 2.3 | Assessment of changes in statistical moments and persistence.

invariance of statistical moments, and autocorrelation at several lags. The SMAA approach uses modified Mann-Kendall (MK), Spearman's Rho (SR), and reverse arrangement (Bendat and Piersol, 2010) tests.

Explicit methods for evaluating different characteristics of time series are also developed to assess the two forms (weak and strict) of stationarity. The multiple test evaluations are weighted using the analytical hierarchy process (AHP) to draw inferences about stationarity. The approach is a conceptually simple and superior alternative to trend and unit root tests since it provides a comprehensive assessment of stationarity using multiple nonparametric tests. Including several statistical tests in DMSA and SMAA approaches provided a robust mechanism for stationarity assessment, wherein the principle of parsimony is not in contention in this regard.

The approach focuses on detecting nonstationarity and not causal evaluation or attribution of nonstationarity based on hydroclimatic processes, natural climatic cycles, and long-term anthropogenic changes. The length and characteristics of the time series available influence the inference drawn from this approach. Static time series without any trend and having a trend do not necessarily indicate stationary and nonstationary conditions, and it is essential to recognize that stationary stochastic models can represent natural variations observed in hydroclimatic processes (Chy, 2024). Koutsoyiannis (2011) also notes that the size of the temporal window of series used for assessment may change inferences about stationarity or nonstationarity. For this reason, it is recommended to invest efforts in collecting time series as long as possible for rainfall, temperature, and streamflow data at the same time (Crespi et al., 2021).

2.1.5 | Attribution Analysis

The nonoverlapping block stratified random sampling methodology discussed in the previous section provides only an initial assessment of the stationarity or nonstationarity of observed time series. Still, it does not confirm one of these conditions. If the nonstationarity of a time series through initial assessment is confirmed, additional evaluation of the physical mechanisms responsible for such a condition must be carried out. Abrupt anthropogenic changes, gradual climate variability, and change influences must be assessed to support attribution analysis.

2.1.6 | Impacts on Nonstationarity on Hydrologic Design and Water Management

Hydrologic design and operation rules for hydrosystems management (e.g., reservoir operations) are developed using an assumption of stationary climate. In a nonstationary climate, the distribution characteristics and extremes are expected to change, and these must be addressed for sustainable, adaptive and climatechange-sensitive hydrologic design and water resources management.

A few recommendations are provided for climate change-sensitive hydrologic and hydraulic design.

- Hydrologic and hydraulic infrastructure design for adaptation relies on information about long-term historical data to understand the past climate and to compare with future projections of climate. Measured values of essential climate variables are crucial for adjusting biases in spatially and temporally downscaled data. Therefore, there is a need to invest efforts in collecting time series as long as possible for temperature, precipitation, streamflow, and land use, possibly at the same time: a minimum of thirty years of data is needed for any climatological analysis and stationarity assessment.
- Anthropological influences such as land use changes and river training works in river basins that have contributed to an increase in the variability of hydroclimatological variables need to be evaluated. Variability attributed to slow and abrupt changes need to be investigated. In this regard, change point tests can help identify the single or multiple change points in an observed time series.
- The time-invariant changes in probability distributions of hydrological extremes at different temporal scales must be assessed before developing hydrologic and hydraulic infrastructure design procedures.
- Changes in hydroclimatic variables, especially extreme indices, must be evaluated as information about nonstationarity in extremes is critical for design. The nature of changes in distributions and statistical moments of multiple indices over time must be evaluated to understand the spatial variability of nonstationarity of one or more hydroclimatic variables in a region (Singh et al., 2024).
- Non-stationary assessments should also consider human interventions (e.g., land use and cover alterations, reservoir regulations), occurrences of sporadic natural hazards (e.g., forest fires, volcanic eruptions, earthquakes), the low- and high-frequency components of oceanic-atmospheric phenomena manifested as oscillations (e.g., Pacific Decadal Oscillation (PDO), Atlantic Multidecadal Oscillation (AMO) and El Niño-Southern Oscillation (ENSO)) and global warming (Teegavarapu et al. 2013; Salas et al. 2014).
- Metadata about the data is critical for assessing nonstationarity as the sample provides a limited ability to assess the changes in the characteristics of the process or phenomenon.

- The influence of long-term persistence (LTP) on hydroclimatic processes noted in long-observed records needs to be evaluated. Stationarity or nonstationarity conditions based on such records also need further assessment.
- Hydrologic and hydraulic infrastructure design should not rely on single or multiple statistical tests for stationarity or nonstationarity but the existence or nonexistence of factors contributing to changes to the processes responsible for hydroclimatic extremes needs to be confirmed also by *a priori* knowledge.
- Many existing approaches focus only on detecting nonstationarity and not on causal evaluation or attribution of nonstationarity based on hydroclimatic processes, natural climatic cycles, and long-term anthropogenic changes. Studies focussing on attribution are critical for understanding nonstationarity.
- Approaches considering multiple tests for assessing nonstationarity should be adopted to reduce reliance on a single-test-based evaluation.
- While evaluating nonstationarity using any approach that uses multiple statistical hypothesis tests, the limitations of parametric and nonparametric methods that depend on sample size, power, and assumptions to be fulfilled need to be recognized.
- Assessment of nonstationarities associated with processes considering one or more causal variables (e.g., precipitation, temperature, climatic teleconnections, etc.) influencing a variable of interest (i.e., response variable, e.g., streamflow) needs to be carried out if nonstationarity is noted in the latter.

2.1.7 | Conclusions and Summary

Hydrologic design and water resources management under changing climate need to address the issues of nonstationarity. Appropriate statistical methods must be used to assess nonstationarity, considering the sample size and the nature of the hydroclimatic variable time series. Many past studies have focused on assessing stationarity with minimal consideration for causal evaluation or attribution of nonstationarity based on hydroclimatic processes, natural climatic cycles, and long-term anthropogenic changes. Nonstationarity assessments should be complimented with comprehensive attribution analysis rather than solely relying on the evaluation of available limited time series of hydroclimatic variables.

References

1 | Anderson, T.W., Darling, D.A. (1954). A test of goodness-of-fit. Journal of the American Statistical Association. 49 (268): 765–769.

2 Bates, B.C. Kundzewicz, Z. W., Wu. S., Palutikof, J. P. (eds.). (2008). Climate Change and Water, Technical Paper, IPCC Secretariat, Geneva, 201 pages. https://www.ipcc.ch/publication/climate-change-and-water-2/

3 Bayazit, M. (2015). Nonstationarity of hydrological records and recent trends in trend analysis: A state-of-the-art review. *Environmental Processes*, 2 (3), 527-542. https://doi.org/10.1007/s40710-015-0081-7

4 Bendat, J. S., Piersol, A. G. (2010). Random data: Analysis and measurement procedures, 97. Hoboken, NJ: Wiley.

5 Brown, M. B., Forsythe, A. B. (1974). Robust tests for the equality of variances. Journal of American Statistical Association, 69(346). 364–367.

6 Brekke, L.D., Kiang, J.E., Olsen, J.R., Pulwarty, R.S., Raff, D.A., Turnipseed, D.P., Webb, R.S., and White, K.D. (2009). Climate change and water resources management—A federal perspective: U.S. Geological Survey Circular 1331

7 CHy (2024). CHy Statements on the Scientific Basis. https://community.wmo.int/en/chy-statements-scientific-basis.

8 Cohn, T. A., and Lins, H.F. (2005). Nature's Style: Naturally Trendy. https://doi.org/10.1029/2005GL024476

9 Corder, G. W., and Foreman, D. I. (2014). Nonparametric statistics: A step-by-step approach. John Wiley and Sons.

10 Cosgrove, W. J. and Loucks, D. P. (2015). Water management: current and future challenges and research directions. Water Resources Research, 51(6) 4823-4839.

11 Crespi, A., Brunetti, M., Ranzi, R., Tomirotti, M. and M. Maugeri, 2021. Multi-century meteo-hydrological analysis for the Adda river basin (Central Alps). Part I: gridded monthly precipitation (1800–2016) records, International Journal of Climatology, 41(1), 162-180. https://doi.org/10.1002/joc.6614

12 Dickey, D. A. and W. A. Fuller. (1979). Distribution of the estimators for autoregressive time series with a unit root. J. Amer. Stat. Asso., 74 (366a): 427-431. https://doi.org/10.1080/01621459.1979.10482531

13 Francois, B., Schlef, K. E., Wi, S., Brown C. M. (2019). Design considerations for riverine floods in changing climate – A review. Journal of Hydrology, 574, 557-573.

14 Gauthier, T. D. (2001). Detecting trends using Spearman's rank correlation coefficient. Environmental Forensics, 2, 359-362.

15 Gibbons, J. D., and Chakraborti, S. (2014). Nonparametric statistical inference. CRC press, Boca Raton, FL, USA.

16 Goly, A. and Teegavarapu, R. S. V. Optimization, and Variants of Quantile Mapping -based Methods for Bias Corrections of Downscaled Precipitation Data. *Journal of Hydrologic Engineering*, ASCE, 2020. DOI: 10.1061/(ASCE)HE.1943-5584.0001926.

17 Goly, A. and Teegavarapu, R. S. V., Individual and coupled Influences of AMO and ENSO on Regional Precipitation Characteristics and Extremes, Water Resources Research, 2014. 50, doi:10.1002/2013WR014540.

18 Goly, A. and Teegavarapu, R. S. V., Mondal, A. (2014). Evaluation of statistical downscaling models for monthly precipitation in Florida. Earth Interactions. 18, doi: 10.1175/EI-D-14-0024.1

19 Gujarati, D. (2015). Econometrics by example. London: Palgrave MacMillan.

20 Hirsch, R. M. A perspective on nonstationarity in water management, Colorado Water, (2010). 27(2), 5-6. https://www.wucaonline.org/assets/pdf/pubs-denwater-nonstationarity.pdf

21 Ishak, E. H., Rahman, A., Westra, S., Sharma, A., and Kuczera, G. (2013). Evaluating the nonstationarity of Australian annual maximum flood. *Journal of Hydrology*, 494, 134-145. https://doi.org/10.1016/j.jhydrol.2013.04.021

22 Kim, J. H., and I. Choi. (2017). Unit roots in economic and financial time series: a re-evaluation at the decision-based significance levels. Econometrics, 5 (3): 41. https://doi.org/10.3390/econometrics5030041

23 Kolokytha, E. Oishi, S. Teegavarapu, R. S. V. (eds.) (2016). Sustainable Water Resources Planning and Management under Climate Change. Springer,

24 Koutsoyiannis, D. (2006). Nonstationarity versus scaling in hydrology. J. Hydrol., 324 (1-4): 239-254. https://doi.org/10.1016/j.jhydrol.2005.09.022

25 Koutsoyiannis, D. (2011). Hurst-Kolmogorov dynamics and uncertainty. J. Amer. Water Resour. Asso., 47 (3): 481-495. https://doi.org/10.1111/j.1752-1688.2011.00543.x

26 Koutsoyiannis, D., and A. Montanari. (2015). Negligent killing of scientific concepts: the stationarity case. Hydrol. Sci. J., 60 (7-8): 1174-1183. https://doi.org/10.1080/02626667.2014.959959

27 Kruskal, W. H., Wallis, W. A. (1952). Use of ranks in one-criterion variance analysis. Journal of the American Statistical Association, 47, 583–621.

28 Kwiatkowski, D., P. C. Phillips, P. Schmidt, and Y. Shin. 1992. Testing the null hypothesis of stationarity against the alternative of a unit root. J. Econo., 54 (1-3): 159-178. https://doi.org/10.1016/0304-4076(92)90104-Y

29 Lins, H. F., and T. A. Cohn. (2011). Stationarity: wanted dead or alive? J. Amer. Water Resour. Asso., 47 (3): 475-480. https://doi.org/10.1111/j.1752-1688.2011.00542.x.

30 Mann, H. B., and D. R. Whitney. (1947). On a test of whether one of two random variables is stochastically larger than the other. Ann. Math. Stat. 18 (1): 50–60. https://doi.org/10.1214/aoms/1177730491.

31 Massey, F. J. (1951). The Kolmogorov-Smirnov test for goodness-of-fit. J. Am. Stat. Assoc. 46 (253): 68–78. https://doi.org/10.1080/01621459.1951.10500769.

32 Matlas (1982). Note on the assumption of hydrologic stationarity. Journal of Contemporary Water Research and Education, 112(1). https://opensiuc.lib.siu.edu/jcwre/vol112/iss1/11/

33 McCuen (2002). Modeling Hydrologic Change: Statistical Methods. ©CRC Press, Boca Raton, USA.

34 Milly, P.C., J. Betancourt, Falkenmark, M., Hirsch, R. M., Kundzewicz, Z. W., Lettenmaier, D. P., and Stouffer, R. J. Stationarity is dead: Whither water management? 2008. Science., 319, 573-574.

35 Milly, P.C., J. Betancourt, Falkenmark, M., Hirsch, R. M., Kundzewicz, Z. W., Lettenmaier, D. P., Stouffer, R. J., Krysanova, V. On Critiques of "Stationarity is dead: Whither water management?", (2015). Water Resources Research, 51, 7785-7789. https://doi.org/10.1002/2015WR017408

36 Montanari, A., and D. Koutsoyiannis. (2014). Modeling and mitigating natural hazards: Stationarity is immortal! Water Resour. Res., 50 (12): 9748-9756. https://doi.org/10.1002/2014WR016092.

37 Pearson, K. (1900). On the criterion that a given system of deviations from the probable in the case of a correlated system of variables is such that it can be reasonably supposed to have arisen from random sampling. The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science, 50(302), 157–175. https://doi.org/10.1080/14786440009463897

38 Phillips, P. C., and P. Perron. 1988. Testing for a unit root in time series regression. Biometrika, 75 (2): 335-346. https://doi.org/10.1093/biomet/75.2.335

39 Ranzi, R., Colosio, P., and Galeati, G. (2024). Climatology of snow depth and water equivalent measurements in the Italian Alps (1967–2020), Hydrol. Earth Syst. Sci., 28, 2555–2578, https://doi.org/10.5194/hess-28-2555-2024.

40 Ranzi, R., Michailidi, E., Tomirotti, M., Crespi, A., Brunetti, M. and M. Maugeri. (2021). A multi-century meteo-hydrological analysis for the Adda river basin (Central Alps). Part II: Daily runoff (1845–2016) at different scales, International Journal of Climatology, 41(1), 181-199. https://doi.org/10.1002/joc.6678

41 Salas, J. D., and J. Obeysekera. (2014). Revisiting the concepts of return period and risk for nonstationary hydrologic extreme events. J. Hydrol. Eng., 19 (3): 554-568. https://doi.org/10.1061/(ASCE)HE.1943-5584.0000820

42 Serinaldi, F., and C. G. Kilsby. (2015). Stationarity is undead: Uncertainty dominates the distribution of extremes. Adv. Water Resour., 77 (Mar): 17-36. https://doi.org/10.1016/j.advwatres.2014.12.013

43 Sharif, M., Burn, D., and Hussain, A. (2010). Climate change impacts on extreme flow measures in Satluj river Basin in India. In *World Environmental and Water Resources Congress 2010: Challenges of Change*, 46-59. https://doi.org/10.1061/41114(371)7

44 Singh, A., Sharma, P. J., Teegavarapu, R. S. V. (2024). Understanding nonstationarity patterns in basin-scale hydroclimatic extremes. International Journal of Climatology. In Print.

45 Slater, L. J., Anderson, B., Buechel, M., Dadson, S., Han, S., Harrigan, S., Kelder, T., Kowal, K., Lees, T., Matthews, T., Murphy, C., and Wilby, R. L. (2021). Nonstionarity weather and water extremes: a review of methods for detection, attribution and management. Hydrol. Earth Syst. Sci. 25, 3897-3935.

46 Teegavarapu, R. S. V. (2010). Modeling climate change uncertainties in water resources management models, *Environmental Modeling and Software*, 25(10),1261-1265.

47 Teegavarapu, R. S. V. (2012). Floods in a Changing Climate, ©Cambridge University Press, London, U.K.

48 Teegavarapu, R. S. V. (2013). Climate change-sensitive hydrologic design under uncertain future precipitation extremes. Water Resources Research, 49 (1-11). https:doi.or/10.1002/2013WR013490

49 Teegavarapu, R. S. V. (2018) (ed.) Trends and Changes in Hydroclimatic Variables: Links to Climate Variability and Change, Elsevier.

50 Teegavarapu, R. S. V. (2019a). Methods for analysis of trends and changes in hydroclimatological time-series. In: Trends and Changes in Hydroclimatic Variables (Ed. Teegavarapu, R. S. V.), pp. 1-89, Elsevier. https://doi.org/10.1016/B978-0-12-810985-4.00001-3.

51 Teegavarapu, R. S. V. (2019b). Changes and trends in precipitation extremes and characteristics: links to climate variability and change. In: Trends and Changes in Hydroclimatic Variables (Ed. Teegavarapu, R. S. V.), pp. 91-148, Elsevier. https://doi.org/10.1016/B978-0-12-810985-4.00002-5

52 Teegavarapu, R. S. V. (2024). Imputation Methods for Missing Hydrometeorological Data Estimation. Springer.

53 Teegavarapu, R. S. V., Nayak, A. (2017). Evaluation of long-term trends in extreme precipitation: implications of infilled historical data and temporal-window based analysis, Journal of Hydrology. 550: 614–634.

54 Teegavarapu, R. S. V., A. Goly, and J. Obeysekera. (2013). Influences of Atlantic Multi-decadal Oscillation on regional precipitation extremes. Journal of Hydrology, 495 (Jul): 74–93. https://doi.org/10.1016/j.jhydrol.2013.05.003

55 Teegavarapu, R. S. V., A. Goly. (2018). Optimal selection of predictor variables in statistical downscaling models of precipitation. Water Resources Management. 32(6), 1969 -1992.

56 Teegavarapu, R. S. V., and Sharma, P. J. (2021). Non-overlapping block stratified random sampling approach for assessment of stationarity. Journal of Hydrologic Engineering, ASCE. 26(7), 04021020. https://doi.org/10.1061/(ASCE)HE.1943-5584.0002098

57 Teegavarapu, R. S. V., and Sharma, P. J. (2022). Reply to Discussion on Non-overlapping block stratified random sampling approach for assessment of stationarity. Journal of Hydrologic Engineering, ASCE. https://doi.org/10.1061/(ASCE)HE.1943-5584.0002098

58 Teegavarapu, R. S. V., Kolokytha, E., Galvao, C. O. (2020). Climate-Change Sensitive Water Resources Management, Taylor, and Francis.

59 Teegavarapu, R. S. V., Salas, J. D., Stedinger, J. R.(2019). Ed. Statistical Analysis of Hydrologic Variables: Methods and Applications. ASCE.

60 WMO (2025). Essential Climate Variables. https://gcos.wmo.int/site/global-climate-observing-system-gcos/essential-climate-variables

61 WMO. (2009). Guidelines on analysis of extremes in a changing climate in support of informed decisions for adaptation. *World Meteorological Organization*, Geneva, Switzerland.

62 Zivot, E., and J. Wang. (2007). Unit Root Tests. In: Modeling Financial Time Series with S-Plus®(Vol. 191). New York: Springer Science and Business Media. https://doi.org/10.1007/978-0-387-32348-0_4

CHAPTER 3

Hydroclimatic Variability

Roberto Ranzi

Department of Civil, Environmental, Architectural Engineering and Mathematics,
University of Brescia, Italy. E-mail: roberto. ranzi@unibs.it

Ramesh Teegavarapu

Department of Civil, Environmental and Geomatics Engineering, Florida Atlantic University,
Boca Raton, USA. E-mail: rteegava@fau.edu

Yangwen Jia[1]

Department of Water Resources, China Institute of Water Resources and Hydropower Research
(IWHR), China. E-mail: jiayw@iwhr.com

3.1 | Introduction: Climate Variability

In the design of hydraulic structures, understanding the mean, variance and long-term variability of hydro-climatic variables are of central importance. Variability and trends in a changing climate can influence design criteria and challenge the hypothesis of stationarity of hydrometeorological variables typically assumed in engineering practice (Milly et al., 2008). Assessment of indices of persistence, as the time constant of the autocorrelation function or the Hurst coefficient (Hurst, 1951; O'Connell et al., 2016) in the context of a changing climate, is needed for the design of structures as reservoirs and supports decision-making for use of resources, the release of water from reservoirs, groundwater recharge or exploitation.

Teleconnections such as El Niño–Southern Oscillation (ENSO), a well-known oscillation of temperature and wind on the two coasts of the Pacific Ocean (Wallace and Hobbs, 2006), and several other oscillations of pressure, temperature, and wind fields are climatic phenomena that influence precipitation, temperature and runoff regime (Steirou et al., 2017) and can be used for multiyear water resources management in reservoirs and groundwater. Periodic patterns at the annual and seasonal

[1] With a contribution of Guinevere Nalder about ENSO and the Pacific.

scale, detected by spectral methods such as the Fourier and Wavelet transform and other Exploratory Data Analysis (EDA) tools, when adequately known and identified, can improve the predictability of the inter-year water cycle and its fluxes. They pose a *caveat* when collecting and treating data under the operational hypothesis of stationarity (Montanari and Koutsoyiannis, 2014), as the existence of natural decadal and multi-decadal oscillation requires data collection over a period of several cycles, at least. The 30-year period indicated in climatology (WMO, 2017) is the minimum duration requested for statistically sound water engineering design. However, extended observation periods are recommended when data indicates the existence of cycles of a longer time scale.

Trend identification is the first step in analyzing and interpreting hydrometeorological series used in hydraulic design (precipitation, streamflow, snow water equivalent, temperature, soil moisture, etc.). For instance, testing for significance of the null hypothesis through application of least squares or Theil-Sen (Theil, 1950; Sen, 1969) estimators of the slope and intercept and applying the Mann-Kendall test or the Spearman's rank correlation test (Kendall, 1970; Hollander et al., 2014) to assess no existence of trends. Trends are then removed by subtracting from the original series. At this stage spectral analyses such as Fourier transform (further discussed in subsequent sections) or Wavelet transform to search for correlation with hydro-climatological teleconnections can be performed.

3.1.1 | Manifestations of Climate Variability

Inter-year climate variability may be partially attributed to variations of boundary conditions of the atmosphere (such as the sea-surface temperature over tropical oceans, pressure or soil moisture, surface albedo and vegetation status), and, to the internally generated atmospheric dynamics (such as that of convective storms), which are less predictable (Melhauser and Zhang, 2012). In tropical atmospheres, boundary oceanic conditions are the primary driver of annual-scale variability, where ocean temperature is the critical component of climactic memory and is often the primary cause of multi-year climate oscillations. In extra tropical regions, tropical sea-surface temperature is essential to the northern hemisphere winter climate. Soil moisture and ground water storage, the 'memory' of the hydrological cycle, and vegetation status contribute to the persistence of climate anomalies at the intra-year or seasonal scale.

3.1.1.1 | *Coupled Atmospheric and Oceanic Oscillations*

The variability generated by the interactions between the atmosphere and more slowly varying Earth system components, such as the ocean temperature, is called coupled climate variability (Teegavarapu, 2017). Changes in ocean temperature or pressure at large spatial scales with slow dynamics are first filtered, for instance, with appropriate averaging and then highlighting the anomalies, as in Sea Surface Temperature (SST) in Figure 3.1, resulting in wet-dry conditions in the Pacific (Figure 3.2). The correlation between the hydro-meteorological variables exhibiting faster dynamics (i.e. precipitation or runoff), and the anomalies of the large scale signal, can then be estimated. Spectral methods such as a Fourier transform (or the Wavelet transform), as explained later, can be applied to analyse the time series of the variable of interest after applying a normalization to highlight the energy of the signal at different frequencies (or scales) and in the time domain. An example is given in Figure 3.3 where the Wavelet transform is applied to the normalized series of the North Atlantic Oscillation, highlighting the energy of the signal at time scales ranging from four to six years.

3.1.1.2 | *Anthropogenic factors influencing the climate*

Anthropogenic factors may change the local climate, especially at the urban or catchment scale. Road pavement and urbanization have been shown to create the so-called Urban Heat Island (UHI) effect, where urbanized areas may experience higher temperatures than outlying areas (Morris and Simmonds, 2000; Giovannini et al., 2011; Ribeiro et al., 2018). Consideration of this factor is fundamental before analyzing temperature anomalies. To filter the UHI effect on temperatures it is recommended to compare air temperature data collected close to urbanized areas with those measured near by in a natural environment. In this way, temperature anomalies can be assigned more precisely to a natural variability or to the anthropic influence.

Further, land use transformations, such as deforestation or afforestation (FAO, 2022), can dramatically change evapotranspiration losses, sediment transport, surface runoff, and streamflow. Reservoir

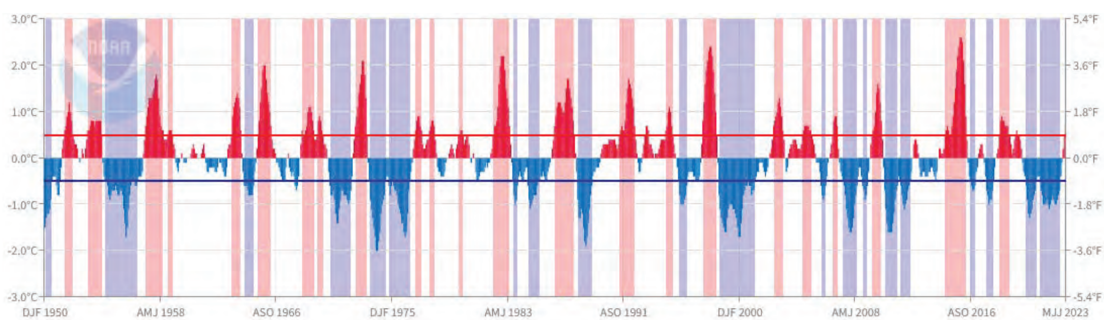


Figure 3.1 | Three-month running mean of Niño 3.4 SST anomalies (Oceanic Niño Index (ONI)).
https://www.ncei.noaa.gov/access/monitoring/enso/sst

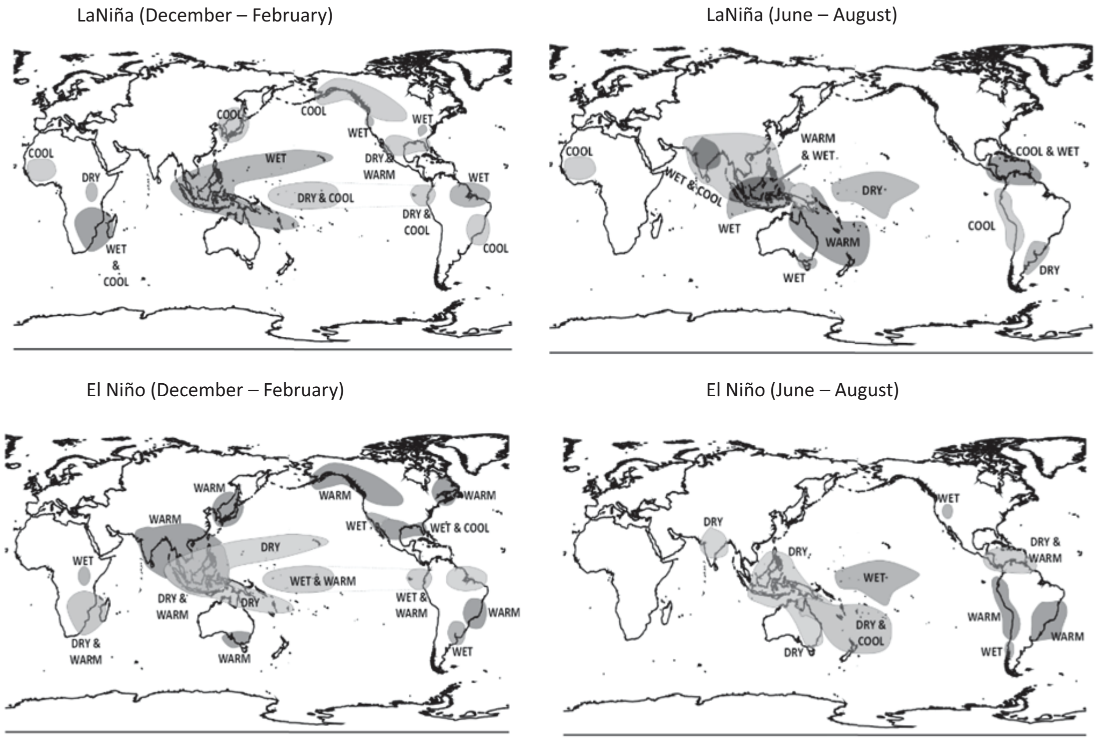


Figure 3.2 | Global conditions for La Niña and El Niño.

regulation and water policies driven by socio-economic factors are highly nonstationary, and tools capable of highlighting artificial variability induced by human-driven triggers are more appropriate.

3.2 | Teleconnections

Teleconnections can be classified based on geographic criteria and the time scale of their period. In the past, the influence of solar activity has been claimed as a possible cause of climate variability. Some authors dating back to the 19th century and still recently (Zanchettin et al., 2008; Zhang et al., 2021) argue that the 11-year solar activity cycle detected, for instance, by changes in the sunspots number (SSN) is influencing stream flow and precipitation regimes, notably when coupled with Oceanic oscillations as El Nino and other multiyear oscillations.

3.2.1 | Multiyear Oscillations

3.2.1.1 | *ENSO-El Nino Southern Oscillation and Expected Climate Change Across the Pacific Ocean*

The most well-documented ocean-atmosphere coupling influencing the climate and the hydrological cycle is El Niño Southern Oscillation (ENSO): a pattern of positive sea-surface temperature anomalies in the equatorial Pacific and associated global pattern of sea-level pressure. During positive, warm El Niño phases, surface temperatures are warmer in the eastern Pacific, and higher pressure is observed in the western Pacific. During El Niño years, the ITCZ and heavy rainfall belt increase rainfall intensity over the eastern Pacific, while Indonesia and other areas in the western Pacific experience droughts. The dominating features of the Pacific Ocean climate are the ENSO and the Walker Circulation.

Easterly trade winds along the Pacific equatorial belt cause the Walker Circulation, where sea water is forced westwards, and as it warms in the process leads to an area of warm water on the Western Pacific. The warm, wet air above this rises, resulting in clouds and precipitation. This airflows back across the Pacific in the upper troposphere, where, once over the colder sea surface, the air falls, completing the circulation. This circulation leads to a pressure gradient across the Pacific. Measurements have shown a negative correlation between pressures at Darwin, Australia, and Tahiti. However, this pressure gradient undergoes variation and in extreme situations, can change direction altogether. This variation is called the Southern Oscillation. When this pressure differential weakens, the easterly trade winds weaken, and the sea surface temperature rises in the eastern Pacific. i. e., the Walker Circulation is reversed with the region of maximum rainfall shifting eastward. This classic El Nino situation leads to the general designation – El Nino Southern Oscillation or ENSO. In contrast, a substantial pressure differential enhances the trade winds and the normal Walker Circulation and this extreme is called *La Nina.* The ENSO results from the interaction of air movement and sea surface temperature. Hence, global warming can be expected to strongly influence the ENSO structure[2]. Recent modeling suggests that extreme El Nino and La Nina events will increase in frequency with global warming. i.e., a general increase in both intensity and frequency of tropical cyclones. Extreme rainfall will shift eastwards during El Nino and westward during La Nina. Measurements to date indicate that there has been a net temperature rise of 0.6°C, leading to a sea level rise of 17cm across the Pacific in the last 100 years. There has been an acceleration in these rises in the last 10–15 years. The ocean has also become more acidic, leading to bleaching and degradation of coral reefs.

[2] An interactive description of Walker Circulation can be found at https://www. climate. gov/news-features/blogs /enso/walker-circulation-ensos-atmospheric-buddy.

3.2.1.2 | *WeMOI-Western Mediterranean Oscillation Index*

In the Mediterranean, the Western Mediterranean Oscillation, defined through the difference of standardized values in surface atmospheric pressure at Padua (45°24'N – 11°52'E) and San Fernando (Cádíz) (36°28' N–6°12' W), was found to be correlated with torrential rains and monthly precipitation and runoff in the Alps (Ranzi et al., 2021).

3.2.2 | Decadal and Quasi-Decadal Oscillations

3.2.2.1 | *NAO-North Atlantic Oscillation*

Hydrometeorological regimes can be determined by prevailing meteorological conditions during a period (months to years), in turn, driven by large-scale atmospheric circulation patterns. Among these, the North Atlantic Oscillation (NAO) is of particular importance in Europe; the NAO is measured as the surface sea-level pressure difference between the Subtropical (Azores) High and the Subpolar Low. Its role has been ascertained as one of the main factors explaining anomalies in winter precipitation and temperature in Europe and the Mediterranean (Hurrel et al., 2003). Strong positive phases of the NAO are associated with above-normal precipitation over northern Europe and Scandinavia and below-normal precipitation over southern and central Europe

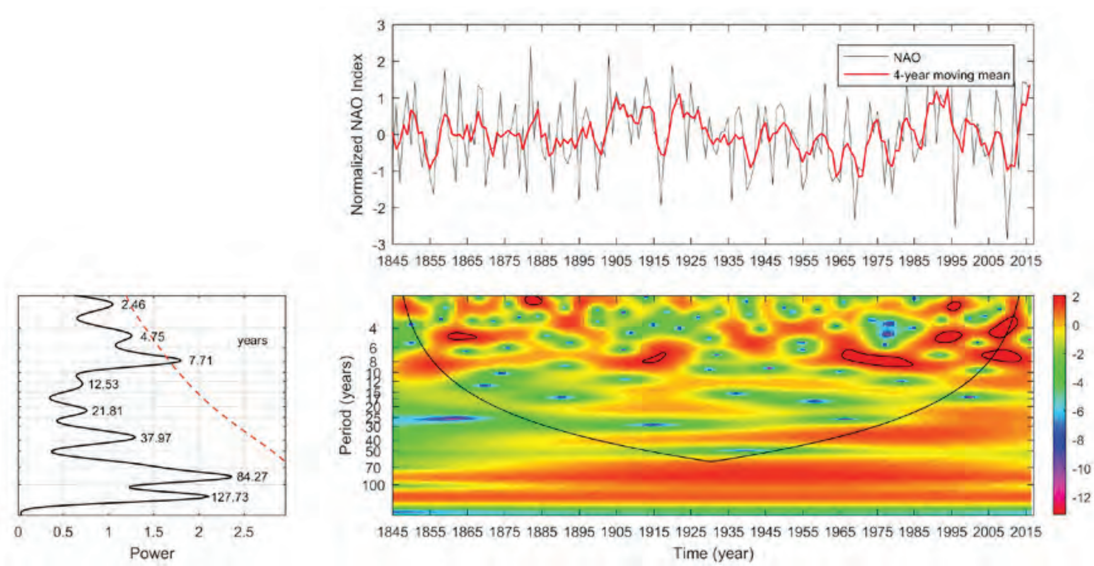


Figure 3.3 | Time series, dimensionless wavelet spectrum (bottom right) and global wavelet spectrum (bottom left) of NAO-North Atlantic Oscillation signal; 5% significance levels are marked with black contour lines in wavelet spectrum and Cone Of Influence; in global wavelet spectrum, 5% significance levels marked with the dashed red line.

(https://www.ncei.noaa.gov/access/monitoring/nao/). A quantitative NAO (NAOI) index has also been considered for runoff prediction purposes (Steirou et al., 2017).

3.2.2.2 | *IOD-Indian Ocean Dipole*

The Indian Ocean Dipole (IOD) is defined by the difference in sea surface temperature between two areas (or poles, hence a dipole): a western pole in the Arabian Sea (western Indian Ocean) and an eastern pole in the eastern Indian Ocean, south of Indonesia. The IOD affects the climate of Australia and other countries surrounding the Indian Ocean Basin and significantly contributes to rainfall variability in this region. In Fig. 3.4 the pattern of IOD in the recent years is represented.

3.2.3 | Multi-Decadal Oscillations

Atlantic multi-decadal and Pacific decadal oscillations are two major coupled atmospheric and oceanic oscillations that influence temperature and precipitation extremes in different regions of the globe.

3.2.3.1 | *Atlantic Multi-decadal Oscillation (AMO)*

Atlantic Multi-decadal Oscillation (AMO), a pattern of Atlantic climate variability, is identified as a fluctuation in sea surface temperatures over the Atlantic Ocean between the Equator and Greenland. The AMO pattern, first recognized in the mid-1990s (Kushnir, 1994; Schlesinger and Rammankutty 1994, 1995) and named by Kerr (2000), is a long-range climatic oscillation that causes periodic changes in

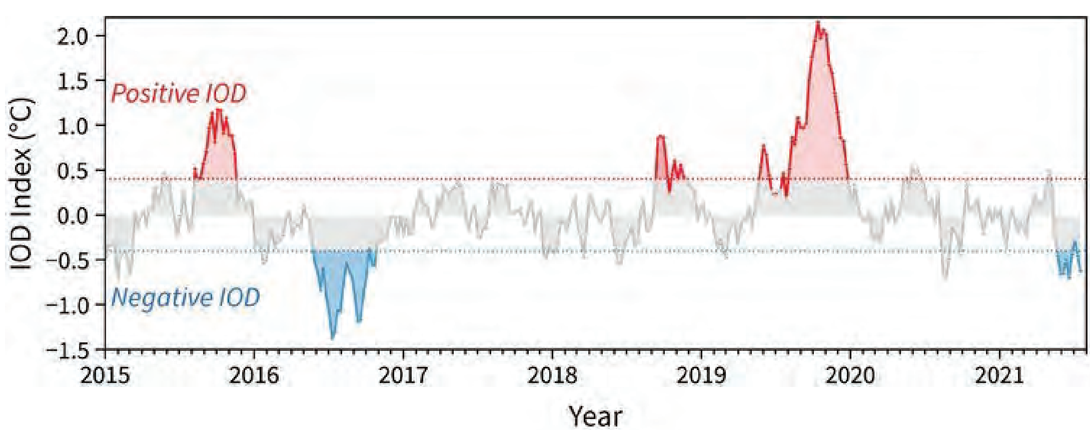


Figure 3.4 | IOD index (source: https://phys. org/news/2021-07-winter-soggy-negative-indian-ocean. html).

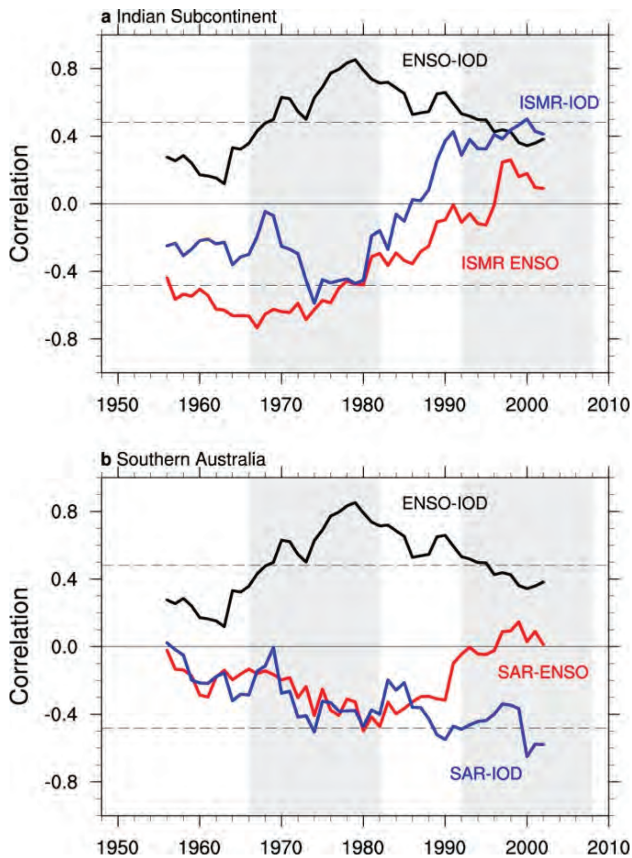


Figure 3.5 | Sliding correlations between JJAS seasonal anomalies of the Indian Summer Monosoon Rainfall and ENSO (red line), the ISMR and the IOD (blue line), and ENSO and IOD (black line) on 17-year windows (Source: Li et al., 2016).

the surface temperature of the Atlantic Ocean, which may persist for several years or decades, usually spanning 20 to 40 years. Several studies have evaluated the impact of AMO on different hydrological variables in the U. S. Studies related to AMO's impacts on rainfall variability are limited. One study by Zhang and Delworth (2006) determined that the anomalies of Sahel summer rainfall are in the same order as the AMO index, and both India and Sahel rainfall anomalies are highly correlated to the AMO index calculated as North Atlantic SST anomaly north of the Equator. Enfield et al. (2001) evaluated the impact of AMO on monthly rainfall and river flows and determined that most of the U. S. experiences less than normal rainfall during the AMO warm phase. AMO cool and warm phases influence precipitation patterns in the southeastern United States, leading to nonuniform temporal and spatial variations. Temporal shifts in occurrences of extremes from the late part of the year for the warm

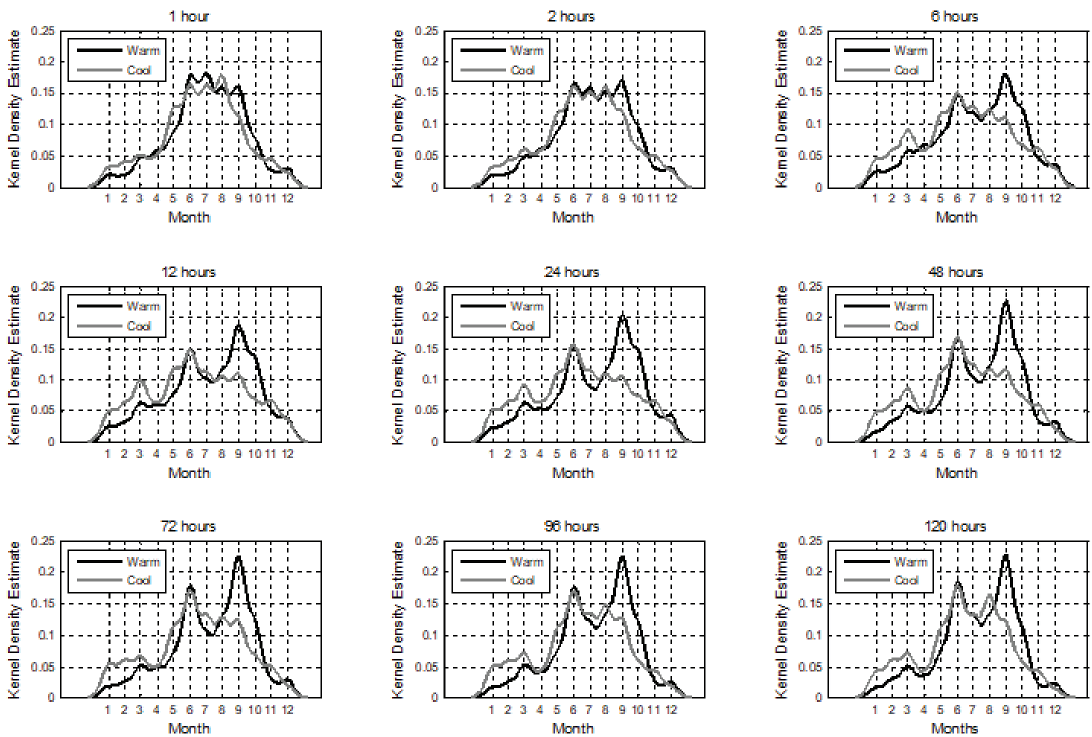


Figure 3.6 | Temporal shifts in precipitation extremes in Florida, USA, during the two phases of AMO are illustrated by kernel density estimates (Source Teegavarapu et al., 2013).

phase to earlier in the year for the cool phase are evident, as shown in Figure 3.6. These shifts will have implications for flooding events in different regions (Teegavarapu et al., 2013). Multiple oscillations (ENSO and AMO) simultaneously occurring at the same time have been known to influence precipitation extremes (Goly and Teegavarapu, 2014).

3.2.3.2 | *PDO-Pacific Decadal Oscillation*

The Pacific Decadal Oscillation (PDO) is an inter-decadal climate variability source, identified as an anomaly in sea surface temperature in the North Pacific. Unlike ENSO, the POD acts across a larger time cycle and has greater influence in North Pacific and North American areas (Trenberth and Hurrell, 1994). PDO cool and warm phases naturally last for around 25 years (Zhang et al, 1997), and its activity is usually denoted as decadal (https://www.ncei.noaa.gov/access/monitoring/pdo/).

3.3 | EDA-Exploratory Data Analysis and Statistical methods to assess climate variability

3.3.1 | Exploratory Data Analysis (EDA)

Exploratory data analysis (EDA) using visual tools helps analyze and investigate variability in hydro-meteorological data sets and summarize their main characteristics. It helps determine and choose which other mathematical and statistical tools to apply to discover patterns, anomalies, transients, systematic changes, test a hypothesis, or check assumptions. One effective EDA technique are the MARTA (Moving Average Running Trend Analysis) triangles, a development (see, e. g., Ranzi et al., 2024) of the visualization method proposed in climatology by Brunetti et al. (2006). As shown in Figure 3.3, the value of the moving average of the snow water equivalent in the Central Alps over a time window of variable years in the y-axis centered in the year on the x-axis is represented with a colour code

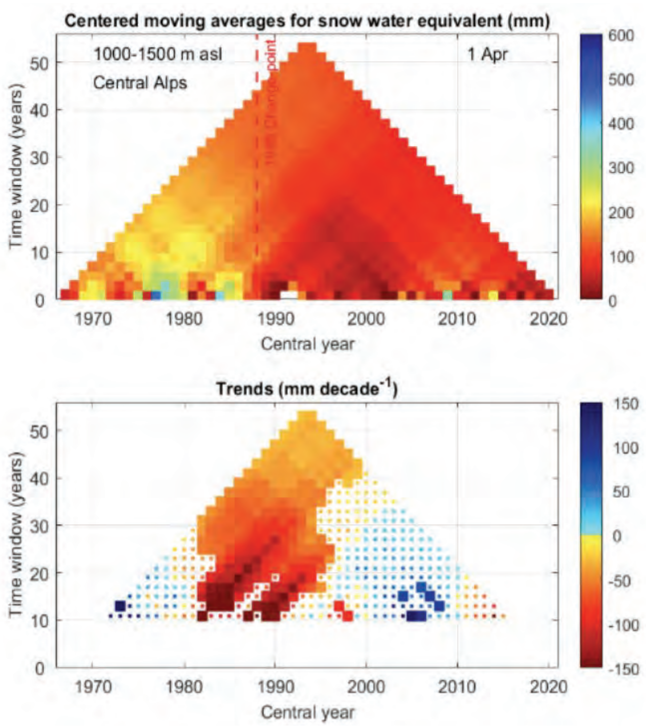


Figure 3.7 | MARTA (Moving Average Running Trend Analysis) triangles, an example of Exploratory Data Analysis applied to the time series of Snow Water Equivalent (SWE) in the Central Alps and showing (top figure) the SWE averaged over a time window with variable duration on the y-axis and centered in the year on the x-axis. In the bottom diagram the trend intensity (mm decade^{-1}) with the size of the symbols indicating Mann-Kendall test significance (p values <. 05, <0. 01).

in the top panel. In the bottom panel, the value of the trend estimated with the Theil-Sen slope is expressed by colors. In contrast, trend significance is represented by the pixel sizes (larger pixels for Mann-Kendall p values <. 05). The figure shows the significantly drier period started in the 1980s and a short-lived restart of snow accumulation in the early 2000s.

3.3.2 | Fourier Transform

To describe how spectral methods can highlight the variability of hydro-meteorological processes we briefly recall here the basics of the Fourier transform and of the Wavelet transform, highlighting their difference. When analyzing natural phenomena with a clear period of, for instance, one day, or one year as those connected to the solar cycle or of 28 days, when linked to Moon's cycle, the application of the Fourier transform is convenient. Considering the trend-free set $x_1, \ldots x_N$ of N variables assumed, for sake of simplicity, to be equispaced at time interval Δt, the sequence can be represented with a combination of L periodic functions.

$$x_t = \mu + \sum_{i=1}^{L} \lambda_i \sin\left(\frac{2\pi i}{T} t + \phi_i\right), \tag{3.1}$$

in which μ is the mean, i/T denote the frequencies, λ_i and ϕ_I are the amplitudes and phases of the i-th harmonics, with i=1,. . L=N/2 (N/2-0.5 if N is odd). The higher is the value of λ_I, the higher is the energy of the signal with a frequency of i/T. However, the position in the time domain of localized changes, for instance induced by a sudden phenomenon or an artificial change, cannot be clearly highlighted by the amplitude and phases of the harmonics.

3.3.3 | Wavelet Transform

The use of the wavelet transform, widely applied in signal processing and fluid mechanics to analyse turbulence, has become more popular over the last decades in the analysis of hydrometeorological time series (Santos et al., 2003; Zolezzi et al.; Ranzi et al., 2021), as it can capture changes in the energy spectrum keeping track of the time (or space) location of the signal changes better than the Fourier Transform. Therefore, it is particularly suitable to analyze series where sources of non-stationarity induced by anthropic influence such as land use changes or river regulations, are present.

The continuous wavelet transform of a discrete sequence x_n (n=1,2,. . ., N; N is the time series length) can be expressed as the convolution of x_n with a scaled and translated function ψ(t), known as "mother" wavelet, as follows (Torrence and Compo, 1998):

$$W_n(s) = \sum_{n=1}^{N-1} x_n \psi^* \left[\frac{(n' - n)\delta t}{s} \right] \quad 3.2$$

where δt is the sampling interval, (n'-n) the dimensionless time, (*) indicates the complex conjugate. To ensure the direct comparison of the energy between different scales, s, the "mother" wavelet is normalised and, therefore

$$\psi \left[\frac{\left(n' - n\right) \delta t}{s} \right] = \left(\frac{\delta t}{s} \right)^{1/2} \psi_0 \left[\frac{\left(n' - n\right) \delta t}{s} \right] \quad 3.3$$

In essence, a basis of orthogonal functions (Haar, Daubechies, Morlet,...) with zero mean and unit square norm with changing scale, s, and shifted in time, varying n, result, applying (3.2), in a set of wavelet coefficients $W_n(s)$, providing a sort of coherence measure between the signal and the wavelet. Consequently, the wavelet spectrum is expressed in a three-dimensional manner in the scale (resolution) and time (position) domain, whose third dimension is the energy. High frequency elements are detected by compressing the wavelet scale and refer to sudden changes, while for low frequency elements, such as long-term processes, stretched wavelets are needed.

The wavelet power spectrum can be defined as $|W_n(s)|^2$, while a measure of the time-averaged energy over various scales, namely the Global Wavelet Spectrum (GWS), representing a section at different scales of the power spectrum is defined as:

$$\bar{W}^2(s) = \frac{1}{N} \sum_{n=0}^{N-1} |W_n(s)|^2 \quad 3.4$$

An example of the wavelet transform applied using the Morlet wavelet to the NAO climatic teleconnection is shown in Figure 3.3, where an energy peak at scales of 7.7 years, about three times that of peaks with a scale of 2.5 years, can be observed. This energy peak is more intense in the 1920s and the 1980s, a piece of information that cannot be highlighted by a harmonic representation with the Fourier transformation.

3.4 | Seasonal Water Availability Forecasting Using Climate Variability Indices

Given the significant impacts of global climate change on regional hydroclimates and operations of hydraulic facilities, it is vital to forecast seasonal water availability in specific river basins or at dam sites using climate variability indices. The effect of sea surface temperatures (SSTs) on ocean-atmosphere heat and water vapor exchange can range across seasonal to annual time scales due to the oceans' vast storage of energy and the large specific heat of oceanic mass and water, and variability in SSTs can help provide predictive information about the hydroclimates in regions across the globe (Switanek et al. 2009).

Over the past several decades, seasonal hydroclimatic predictions in basins and at dam sites have been well explored by using: direct teleconnections between SSTs and particular basins' hydroclimates (Switanek et al. 2009), using the standard climate variability indices deduced from SSTs, e. g., the El Nino-Southern Oscillation (ENSO), the Pacific Decadal Oscillation (PDO) and the Atlantic Multidecadal Oscillation (AMO) (Enfield et al. 2001), or using comprehensive climate variability indices including SSTs, Sea-level Pressure (SLP), global atmospheric circulation factors and snow covers, etc. (Xu et al. 2007; Qiao et al. 2021).

There are two ways to forecast seasonal water availability or river discharge using climate variability indices. The first is to directly forecast river discharge by performing correlation analysis to find the climate variability indices highly correlative to river discharges and establishing regressive model or statistical models like Particle Swarm Optimization algorithm (PSO) (Kennedy and Eberhart, 1995), Support Vector Regression (SVR) (Yu et al., 2006), or Artificial Neural Network (ANN)(Elshorbagy et al., 2000) or their combination. The other method is to first forecast precipitation and temperature by their teleconnections with the climate variability indices and then to force the statistical models or distributed hydrological models like Soil and Water Assessment Tool (SWAT) or Variable Infiltration Capacity (VIC), etc. to obtain river discharges.

Three study cases are introduced below. The first study case is the climate teleconnections to seasonal streamflow at the Three Gorges Dam (TGD) of the Yangtze River, China (Xu et al., 2007). Summer monsoon streamflow at Yichang hydrological station (YHS) was analyzed for 1882–2003. Statistical analysis was used to develop a predictive model for summer streamflow using preceding climate variables. Linear correlation maps were constructed using 3-month climate fields to identify regions that exhibit teleconnections with streamflow at YHS. The analysis revealed that streamflow at YHS is influenced by climate variables in the eastern Indian and western Pacific Oceans. In addition, snow cover in the Yangtze upland region also contributes to stream flow at YHS. A regression model for prediction using these indices provides a prediction result with the determination coefficient greater than 0.5.

The second case study is the monthly runoff forecast model of the Danjiangkou Reservoir in autumn flood season based on PSO-SVR-ANN (Qiao et al., 2021). The Danjiangkou Reservoir in the upper reach of the Hanjiang River is the water source of the Middle Route of the South-to-North Water Transfer

Project. A medium-and long-term (monthly or seasonal and annual time horizon, respectively) runoff-prediction model is developed based PSO-SVR. PSO is used to optimize the parameters of SVR. Hierarchical perceptron ANN is used to analyze the prediction error of SVR, and the coupled PSO-SVR-ANN model is established to realize the self-correction of the runoff forecast. The results show that the average relative error of PSO-SVR-ANN model for the autumn flood season is as small as around 10%, with the qualified rate all higher than 80%. In addition, compared with PSO-SVR, PSO-SVR-ANN model has a higher prediction accuracy, stronger stability and higher credibility with practical importance.

The third case study is the monthly rainfall and runoff prediction in the Danjiangkou Basin (Zhu et al., 2016). To predict monthly rainfall in the Danjiangkou basin of the upper Han River, predictors were selected from 74 atmospheric circulation factors by analyzing correlation of rainfall and factors, and multiple linear regression model for the monthly rainfall prediction was established. The SWAT (Soil and Water Assessment Tool) model, developed by USDA and Texas A&M University, of the study area was built to forecast the monthly runoff by using monthly rainfall forecast values as the model input. The monthly rainfall and runoff of 2012 were forecasted with the passing rate of about 83 percent. It shows the method of monthly rainfall prediction based on the statistical correlation of rainfall and atmospheric circulation factors, and runoff prediction combined with hydrological model, is applicable to the studied area.

3.5 | Conclusions and Summary

Natural climate variability, manifested through coupled oceanic and atmospheric oscillations, impacts hydroclimate extremes and characteristics of essential climatic variables. Therefore, changes to hydrologic design, water resources management, and disaster management are needed to address the stochastic variability inherent in all random processes and the deterministic components of natural climate dynamics. Climate variability manifesting in temporal cycles of some years or decades needs to be addressed in water resources management and in revising hydrologic design considerations. As a guideline for the analyses of climate variability, we recall that:

- It is essential to understand how single or multiple oceanic and atmospheric coupled oscillations spatially and temporally influence the extremes of regional hydroclimatic variables.
- It is necessary to understand the spatial extent of climate variability influences and how it is affected by regional hydroclimatology, topography, and physiography.
- Other factors of anthropic origin (such as the presence of hydraulic works, reservoirs, land use changes and agricultural practices, and the corresponding Urban Heat Island effect) that

influence hydroclimatic characteristics and extremes need to be considered when assessing variability in water engineering.

- The scaling behavior in space and time of hydroclimatic variable extremes in different phases of coupled oceanic and atmospheric oscillations needs to be assessed.
- Hydroclimatic events that occur with low frequency but have devastating effects on hydraulic and hydrologic infrastructure are referred to as rare extremes. In some regions of the world these events are linked to climate variability. Assessment of these events attributed to natural variability need to be evaluated and addressed for planning, and operation of hydrosystems and developing disaster mitigation plans.
- The comparison of the runoff response of pristine (i. e., least anthropogenically disturbed) watersheds and those affected by human activities in different regions of the world can shed light on the differentiation between natural and anthropogenic factors in influencing hydrological extremes and regimes and provide a guidance on the use of Nature Based Solutions in the engineering practice.
- It is essential to establish the physical basis for the influences of climate variability on hydroclimatic variables beyond statistical tests.
- Development of methodologies for hydrosystems operations impacted by short-term cycles of natural climatic variability is required.
- Revisions to hydraulic and hydrologic design reflecting adjustments due to climate variability impacts must be undertaken.

References

1 Brunetti M., Maugeri M., Nanni T., Auer I., Böhm R. and Schönen, W. (2006). Precipitation variability and changes in the greater alpine region over the 1800–2003 period. Journal of Geophysical Research, N°111, doi: 10. 1029/2005JD006674

2 Elshorbagy, A., Simonovic, S. P., Panu, U. S. (2000). Performance evaluation of artificial neural networks for runoff prediction. Journal of Hydrologic Engineering, 5(4), 424-427.

3 Enfield D B, A M Mestas-Nunez and P J Trimble 2001: The Atlantic multidecadal oscillation and its relation to rainfall and river flows in the continental U. S. Geophys. Res. Lett., 28, 2077-2080.

4 Enfield, D. B., Mestas-Nuñez, A. M. and Trimble, P. J., 2001. The Atlantic multidecadal oscillation and its relation to rainfall and river flows in the continental U. S. Geophysical Research Letters, 28, 2077–2080.

5 FAO (2022). The State of the World's Forests 2022. Forest pathways for green recovery and building inclusive, resilient and sustainable economies. Rome, FAO. https://doi.org/10.4060/cb9360en

6 Giovannini, L., Zardi, D., De Franceschi, M. (2011). Analysis of the urban thermal fingerprint of the city of Trento in the Alps. Journal of Applied Meteorology and Climatology, 50(5), 1145-1162.

7 Goly, A. and Teegavarapu, R. S. V., (2014) Individual and coupled Influences of AMO and ENSO on Regional Precipitation Characteristics and Extremes, Water Resources Research. 50, doi:10.1002/2013WR014540

8 Hollander, M, Wolfe, D. A., Chicken, E. (2014). Nonparametric statistical methods, 3rd edn. Wiley & Sons, New York.

9 Hurst, H. E., (1951). Long-term storage capacity of reservoirs. Transactions of the American Social Civil Engineering, 116, 770–808.

10 Kendall MG (1970) Rank correlation methods, 4th edn. Griffin, London.

11 Kennedy, J. Eberhart, R. (1995). Particle swarm optimization, Proceedings of ICNN'95 - International Conference on Neural Networks, Perth, WA, Australia, 1995, pp. 1942–1948 vol. 4, doi: 10.1109/ICNN.1995.488968.

12 Kerr, R. A., 2000. A north Atlantic climate pacemaker for the centuries. Science, 288, 1984–1986.

13 Kottegoda, N. T. (1980). Stochastic Water Resources Technology, ©The Macmillian Press Ltd, London.

14 Kushnir, Y., (1994). Interdecadal variations in North Atlantic sea surface temperature and associated atmospheric conditions. *Journal of Climate*, 7, 141–157.

15 Li, Z., Cai. W., Lin, X. Dynamics of changing impacts of tropical Indo-Pacific variability on Indian and Australian rainfall. *Scientific Reports*. 6, 31767. 2016. https://doi.org/10.1038/srep31767

16 Melhauser, C., Zhang, F. (2012). Practical and intrinsic predictability of severe and convective weather at the mesoscales. Journal of the Atmospheric Sciences, 69(11), 3350-3371.

17 Morris, C. J. G., Simmonds, I. (2000). Associations between varying magnitudes of the urban heat island and the synoptic climatology in Melbourne, Australia. Int. J. Climatol., 20, 1931–1954.

18 O'Connell, P. E., Koutsoyiannis, D., Lins, H. F., Markonis, Y., Montanari, A., & Cohn, T. (2016). The scientific legacy of Harold Edwin Hurst (1880–1978). Hydrological Sciences Journal, 61(9), 1571–1590. https://doi. org/10. 1080/02626667. 2015. 1125998

19 Qiao G, M Yang, Q Liu and Y Zhang 2021: Monthly runoff forecast model of Danjiangkou Reservoir in autumn flood season based on PSO-SVR-ANN. Water Resources and Hydropower Engineering,52(4), 69–78.

20 Ranzi, R., Michailidi, E. M., Tomirotti, M., Crespi, A., Brunetti, M. Maugeri, M. (2021). A multi-century meteo-hydrological analysis for the Adda river basin (Central Alps). Part II: Daily runoff (1845–2016) at different scales. International Journal of Climatology, 41(1), 181–199. https://doi. org/10.1002/joc.6678

21 Ranzi, R., Colosio, P. Galeati, G. (2024). Climatology of Snow Depth and Water Equivalent measurements in the Italian Alps (1967–2020). Hydrology and Earth System Sciences, 28, 2555–2578. https://doi.org/10.5194/hess-2023-223.

22 Ribeiro, F. N., de Oliveira, A. P., Soares, J., de Miranda, R. M., Barlage, M., Chen, F. (2018). Effect of sea breeze propagation on the urban boundary layer of the metropolitan region of Sao Paulo, Brazil. Atmospheric Research, 214, 174–188.

23 Santos, C. A. G., Galvao, C. O., Trigo, R. M. Servat, E. (2003). Rainfall data analysis using wavelet transform. International Association of Hydrological Sciences, Publication, (278), 195–201.

24 Schlesinger, M. E. Rammankutty, N., 1994. An oscillation in the global climate system of period 65–70 years. Nature, 367, 723–726.

25 Schlesinger, M. E. Rammankutty, N., 1995. Is the recently reported 65 to 70-year surface-temperature oscillation the result of climatic noise? Journal of Geophysical Research, 100, 13767–13774.

26 Sen, P. K. (1968). Estimates of the regression coefficient based on Kendall's tau. J Am Stat Assoc 63(324):1379–1389

27 Steirou, E., Gerlitz, L., Apel, H., Merz, B. (2017). Links between large-scale circulation?patterns and streamflow in Central Europe: A review. 'Journal of Hydrology', 549 , 484–500.

28 Switanek M B, P A Troch and C L Castro 2009: Improving seasonal predictions of climate variability and water availability at the catchment scale. Journal of Hydrometeorology, 10, 1521–1533.

29 Teegavarapu, R. S. V., A. Goly J. Obeysekera. (2013). Influences of Atlantic Multi-decadal Oscillation on regional precipitation extremes. J. Hydrol., 495 (Jul): 74–93. https://doi.org/10.1016/j.jhydrol.2013.05.003

30 Teegavarapu, R. S. V. (2017). Climate variability and changes in precipitation extremes and characteristics. In: Kolokytha, E., Oishi, S., Teegavarapu, R. (eds) Sustainable Water Resources Planning and Management Under Climate Change. Springer, Singapore, 3-37. https://doi. org/10. 1007/978-981-10-2051-3_3

31 Theil, H. (1950). A rank-invariant method of linear and polynomial regression analysis, I. Proceedings of the Koninklijke Nederlandse Akademie van Wetenschappen Series A 53:386–392

32 Wallace, J. M. and Hobbs, P. V. . (2006). Atmospheric Science. An Introductory Survey, ©Academic Press, Burlington MA.

33 Xu, K., Brown, C., Kwon, H., Lall, U., Zhang, J., Hayashi, S., Chen, Z. (2007). Climate teleconnections to Yangtze river seasonal streamflow seasonal streamflow at the Three Gorges Dam, China. International Journal of Climatology, 27, 771-780.

34 Yu, P. S., Chen, S. T., Chang, I. F. (2006). Support vector regression for real-time flood stage forecasting. Journal of Hydrology, 328(3–4), 704–716.

35 Zanchettin, D., Traverso, P. Tomasino, M. (2008). Po River discharges: a preliminary analysis of a 200-year time series. Climatic Change, 89(3–4), 411–433. https://doi.org/10.1007/s10584-008-9395-z

36 Zhang, Y., Wallace, J. M. and D. S. Battisti (1997). ENSO-like Interdecadal Variability: 1900-93. J. Climate, 10, 1004–1014. DOI:10.1175/1520-0442(1997)010<1004:ELIV>2.0.CO;2

37 Zhang, L., Liu, Y., Zhan, H., Jin, M. and Liang, X. (2021). Influence of solar activity and EI Niño-Southern Oscillation on precipitation extremes, streamflow variability and flooding events in an arid-semiarid region of China. Journal of Hydrology, 601, 126630. https://doi. org/10. 1016/j. jhydrol. 2021. 126630.

38 Zhu S, Z Liang, C Dai and W Yang 2016: Study on monthly rainfall and runoff predict ion in Danjiangkou Basin. South-to-North Water Transfers and Water Science and Technology, 14(1) : 96–101.

CHAPTER 4

Climate Change Projections

Van-Thanh-Van Nguyen

Department of Civil Engineering, McGill University, Canada. E-mail: van.tv.nguyen@mcgill.ca

Giorgi Filippo

International Centre for Theoretical Physics, Trieste, Italy. E-mail: giorgi@ictp.it

4.1 | Introduction: climate change and water engineering design

In many cases, *streamflow data* of sufficient length and quality for reliable flood estimation is often limited or unavailable at the location of interest; however, extensive precipitation records are typically available. The statistical and physical properties of *precipitation* can thus be used as inputs to various run off models to estimatethe probability and characteristics of flooding across varying temporal and spatial scales. Broadly, there are two main approaches to employ precipitation data to flood estimation: deterministic estimation based upon the "probable maximum precipitation" (PMP), and statistical analysis of precipitation data. While the PMP has been employed worldwide for the design of large hydraulic structures, with the theory and applications of PMP well-documented in hydrologic and engineering literature (see, e.g., World Meteorological Organization, 1982; NRCC, 1989), it does not provide the necessary probability estimates for suitable risk assessment. Therefore, this section focuses on those statistical methods of precipitation estimation which provide both flood magnitudes and their associated probabilities.

Precipitation frequency analyses are commonly used in the design of hydraulic structures, such as dams, culverts, and storm sewers. In particular, for the development of a "design storm": a precipitation temporal patterns used in water resources systems design. The objective of precipitation frequency analysis is to estimate the amount of precipitation falling at a given point or over a given area for a specified duration and return period. Results of precipitation frequency analyses are often summarized as"intensity-duration-frequency" (IDF) relationships for a given site or presented in the form of "precipitation frequency atlas", which provides rainfall accumulation depths for various durations and return periods over the region of interest (see, e.g., Hershfield, 1961; NRCC, 1989).

Climate change will have important impacts on the hydrologic cycle across temporal and spatial scales. In application, relevant temporal scales can vary from short time intervals of 5 minutes (e.g. for urban water cycle) to the yearly time scale (for annual water balance computation). Similarly, relevant spatial resolutions can vary from a few square kilometers (for urban and rural watersheds) to several thousand square kilometers (for large river basins). General Circulation Models, also known as Global Climate Models (GCMs), are recognized for representing the global distribution of basic climate parameters reasonably well. However, due to their coarse spatial and temporal resolution, these models poorly reproduce climate conditions at temporal and spatial scales of relevance to hydrological studies. For example, current GCMs are run at resolutions of the order of 100 km, making the outputs too coarse for application to many climate change impact studies. Consequently, there is a great need for tools to downscale GCM climate change projections to regional and local scales. Over the past decades, various down scaling methods have been developed, ranging from dynamical downscaling (e.g. high resolution Regional Climate Models, or RCMs) to empirical/statistical downscaling (ESD) approaches. The former employs physical based limited-area models to downscale GCM outputs, today achieving resolutions of just a few kilometres. In ESD, statistical models are developed to link large-scale climate predictors to historical observations of surface parameters (e.g., precipitation and temperature). If such a relationship can be established, then the projected change of climate conditions from a GCM can be used to simulate corresponding changes in surface parameters for hydrological impact studies. Today, a wide range of ESD methods are available.

4.2 | Extreme Rainfall Processes – Meteorological Aspects

Rainfall is a critical input to a region's hydrological cycle. Therefore, understanding spatial and temporal characteristics of rainfall, and especially extremes, is critical for water resource systems planning, design, and management. Regionally, rainfall can vary considerably in its amount, intensity, frequency, phase, and type. In general, rainstorms occur when atmospheric water vapour is lifted to a higher elevation in the atmosphere, condensing and eventually precipitating. However, different atmospheric processes can cause the lifting of moisture laden air, such as lifting triggered by local topography or by the release of convective potential energy. Heavy rainfall occurrence is typically favoured under conditions of warm and moist air. As air is lifted, it cools, becomes saturated, and its moisture either transforms into ice crystals or grows into small water droplets until gravity eventually overcomes the upward force and precipitation falls to the ground in the form of rain, graupel or snow. The intensity of rainfall reaching the ground depends on the amount of moisture in the air and the rate at which atmospheric lifting processes can convert this moisture into precipitation.

There are four predominant atmospheric processes that cause extreme rainfall events:

1. intense synoptic or low-pressure and frontal weather systems (sometimes called frontal systems);
2. convective or unstable atmospheric conditions;
3. tropical cyclones/hurricanes or their remnants; and
4. orographic or terrain-driven lifting.

The extreme rainfall events associated with these atmospheric processes can exhibit substantial differences in spatial and temporal variations, as well as seasonal variability.

4.2.1 | Synoptic processes

Synoptic and frontal systems produce heavy rainfall by lifting moist air into the mid to upper atmosphere through dynamical processes. Low-pressure systems can draw air inwards towards their centres, with this convergence forcing air upward. Air can also be lifted and cooled along cold and warm fronts in cold fronts, relatively cold air forms a wedge to lift warmer and lighter air masses. This lifting mechanism is typically stronger than in the case of warm fronts, where warm air slides above colder masses and is lifted more slowly. Consequently, cold fronts often bring more intense rainfall events in a short duration of time, while warm fronts produce light to moderate rainfall over longer periods, across wider areas. Additionally, convective processes can lead to intense thunderstorms forming along, or just ahead of, the cold front. In the case of a stationary front, where the warm and cold air masses are not advancing or retreating, heavy rainfall events usually require additional input from embedded convection.

An extreme rainfall event caused by a synoptic weather system or frontal process (i.e., large-scale weather systems) usually results in widespread, continuous rainfall over a large area. In many cases, the most extreme events associated with synoptic systems tend to be nearly stationary, low-pressure, frontal systems, often incorporating embedded convection. Hence, heavy synoptic rainfall events during the warm season are frequently enhanced by convection. Heavy rainfall from an incoming frontal system can also be intensified by strong onshore and upslope flows over terrain in coastal mountainous regions, resulting in prolonged heavy rain events lasting several hours. In other cases, a series of frontal systems occurring over a region can create antecedent saturated ground conditions, significantly increasing the region's vulnerability to flooding from subsequent storms.

In summary, for a given location, synoptic-scale systems tend to induce extreme rainfall events of long duration (typically lasting 12 hours or more) with a relatively uniform rainfall distribution throughout the storm duration. However, thunderstorms driven by convective processes and embedded within synoptic frontal systems can enhance rainfall, causing intense storms locally over shorter periods (a few hours). Moreover, synoptic-scale rainfall processes can affect wide areas ranging from a few hundred to 1000-km scale.

4.2.2 | Convective processes

Extreme convective rainfall is produced when unstable air rises vertically due to atmospheric instability through a deep atmospheric layer in response to a lifting-triggering mechanism. Typically, this mechanism is associated with solar daytime heating, accounting for the higher frequency of convective events during the warmest times of the year. In other cases, convective rainfall events can be triggered by remnants of earlier synoptic features or augmented by regional topographic features and local circulations, such as lake and sea breezes.

Convective processes have different characteristics compared to synoptic processes as they are much more localized, of shorter duration and higher intensity. Convective events often lead to storms of 2 to 6 hours duration with rainfall intensities upwards of 100 mm per hour. Extreme convective rainfall events are typically associated with severe thunderstorms and small scale “organized” convective events (10–100 km horizontal extent), causing disasters such as flash floods and landslides.

4.2.3 | Tropical cyclones, hurricanes, and typhoons

Tropical cyclones typically occur over warm subtropical and tropical oceans, and may include hurricanes and typhoons when they are particularly intense. These cyclones can result in very large rainfall events because they carry warm, moist tropical air and intense lifting and convection from their source region. Tropical cyclones dissipate when the conditions that maintain their energy are removed, e.g when they move away from warm water sources or land on continents and are weakened by increased surface roughness and friction. In North America, these tropical systems primarily occur during the late summer and autumn along the east and sometimes the west coasts.

In summary, tropical cyclone systems can result in long-duration rainfall events (12+ hours) with high rainfall intensities (>100 mm in a few hours). These tropical systems are closer to synoptic systems in horizontal extent (up to 500 km).

4.2.4 | Topographic and orographic processes

Orographic rainfall refers to the precipitation produced by the lifting of air and moisture over terrain, especially in the presence of a mountain range or barrier. Mountainous features can also influence the development of synoptic rainfall systems on their drier, leewardside, leading to high frequencies of newly formed synoptic lows in the lee regions of major mountains (e.g., the Rocky Mountains in Alberta or the Alps in Europe). In other cases, higher elevations can heat more rapidly than the surrounding valleys during the warm season, resulting in an increased incidence of upslope motions and convective events. For example, the Rocky Mountains of North America and the European Alps exhibita pronounced peak in summer convective storm frequency, induced by upslope and high elevation heating. Large bodies of water, such as the Great Lakes, can also impact the tracking and intensification of weather systems. For instance, low pressure systems tend to intensify as they track over the warm waters of the Great Lakes in winter. Some of Canada's heaviest rainfall rates for durations greater than 6 hours result from synoptic weather systems intensified by onshore and upslope flows overthe Pacific coastal mountains.

4.3 | Overview of changes in extreme hydrologic processes

Global warming can significantly affect the global hydrologic cycle, by altering the Earth's water and energy budget, in turn, affecting the dynamical and thermodynamical characteristics of the general atmospheric circulation. Hydrological impacts can also be modulated at regional to local scales by forcings such as complex topography, coastlines or inland bodies of water. This section presents a brief discussion of changes in the hydrologic cycle emerging from both, historical observations, and model projections for the 21st century. General Circulation Models, also known as Global Climate Models (GCMs), typically present historical simulations and projections of future climate change based on various future forcing scenarios, which include greenhouse gases (GHGs), aerosols, and land-use change. For example, the fifth phase of the Coupled Model Intercomparison Project (CMIP5) was an internationally coordinated effort that produced a multi-model ensemble of climate projections. Specific results for Canada were generated using outputs from 29 CMIP5 GCMs, considering three scenarios: a low emission scenario (RCP2.6), a medium emission scenario (RCP4.5), and a high emission scenario (RCP8.5) (Zhang et al., 2019).

4.3.1 | Extreme hydrological processes and water engineering design

In the design of water infrastructure, practicing engineers often need to perform frequency analyses of extreme hydrologic processes, such as maximum precipitation, peak discharge, and low flows. The purpose of frequency analysis is to analyze past records of extreme hydrologic variables to estimate future occurrence probabilities. Frequency analysis can be performed using single-site data, regional data, or a combination of both. It may also consider historical extreme events and physical constraints (World Meteorological Organization, 2009).

Extreme hydrological phenomena are characterized by variability, randomness, and uncertainty. It is important to note that statistical analysis of historical hydrologic data does not provide a definitive answer. Uncertainty in frequency analysis arise from several sources, including the representativeness of the analytical method, the selection of the probability distribution model, and estimation of the model parameters.

In the case of extreme events, the primary interest is not merely what has occurred, but rather what is the likelihood that similar extreme and damaging events will occur in the future. Many extreme hydrologic events cannot be forecasted with sufficient skill and lead time on the basis of deterministic information. In such cases a probabilistic approach should be employed to account for the effects of these uncertainties in decision-making. However, if events can be assumed to be independent in time (i.e., the timing and magnitude of an event bears no relation to preceding events), then frequency analysis can be employed to estimate the likelihood of any one or a combination of events over the time horizon of interest. For example, extreme rainfall data used for frequency analysis are typically available in the form of annual maximum series (AMS), which represents the largest rainfall in each complete year of record. Accordingly, it is assumed that these annual maxima are independent. An alternative data format for precipitation frequency studies is partial duration series (PDS), also referred to as peaks over threshold data, which consist of all large precipitation amounts above a selected threshold. Consequently, in the case of PDS, there may be a lack of independence between consecutiveevents occurring in close sequence (Willems et al., 2012). Owing to its simpler structure, the AMS-based method is more popular in practice.

Further information regarding frequency analyses methods for extreme hydrologic variables such as extreme precipitation and peak flow processes can be found in the guideline by the World Meteorological Organization (2009). The current design and management procedures, however, have been primarily based upon historical data that do not account for the potential impacts of climate change. The absence of appropriate information and decision support for the design and management of critical water infrastructure under a changing climate poses significant risk. Major weather events, such as extreme floods and storms, can cause extensive damage and loss of life, costing billions of dollars.

4.3.2 | Observed and projected changes in temperature extremes

Temperature extremes are expected to shift or change in distribution at daily to seasonal scales. Therefore, an increase in mean temperature is already expected to lead to an increase in temperature extremes. According to the recent IPCC report (IPCC, 2021), global temperatures have risen by apprximately 1.07°C since the late 19th century. As a result, observations show that hot extremes and heatwaves have become more frequent and intense, while cold extremes have decreased across most continental areas.

Climate projections indicate that this trend will continue as global warming persists, with the extent of the increase in extremes dependent on the magnitude of the warming. In some scenarios, temperature conditions are predicted to increase well beyond current extremes. For example, some studies show that in the most extreme scenario (RCP8.5) the temperatures experience in summer of 2003 across Europe, which in some areas was 4 standard deviations from the current mean, may become the norm, and even hotter summers would be likely to occur. Marine heatwaves are also projected to increase with increased warming.

Model projections also show that the warming would not be uniform across the continental surfaces. Areas, called "hot-spots", will warm faster than the global average. The most prominent hot-spot is the Arctic, which is warming at more than double rate of the global average due to the ice-albedo feedback mechanism. Other prominent hotspots, mostly associated with reduced precipitation and cloudiness, and thus increased solar insolation and reduced evaporative cooling, are the Mediterranean basin, a portion of the Amazon Basin, Southern Africa, central America and the southwestern United States.

Under climate change, a warming climate is expected to lead to increases in atmospheric moisture, and consequently increases in extreme precipitations. As a result, infrastructure designed with historical extreme values may be at greater risk of damage or failure. It has been argued that the increase in mean precipitation in a climate warmed by rising GHGs is energetically constrained to $\sim$2% per °C, while, in the absence of other influences (e.g., changes in large-scale circulation, local storm dynamics, etc.) extreme precipitation could be free to intensify closer to the theoretical Clausius-Clapeyron (CC) rate ($\sim$7% per ^{0}C). Expressing the relative change in precipitation extremes as a function of warming is commonly referred to as “temperature scaling”. Given that projections of temperature change are felt to be more reliable than those for extreme precipitation, temperature scaling serves as the basis for providing guidance to engineers on future changes in rainfall extremes in Australia (Ball et al., 2016) and in Canada (CSA, 2019).

4.3.3 | Observed and projected changes in precipitation extremes

Global warming can profoundly affect the characteristics of precipitation in a multiplicity of ways. First, changes in the global circulation can alter storm trajectories and thus the spatial patterns of precipitation. For example, one of the circulation responses to warming is the expansion of the Hadley cell, which in turn induces a poleward shift of the mid-latitude jet streams. This shift results in a consequent increase in precipitation at mid to high latitudes, e.g. the central and northern portions of

Europe, North America and Asia, and a decrease in subtropical areas, e.g. the Mediterranean and central America, southern Africa and southern Australia. This pattern of precipitation change is evident in both model projections and, to a lesser extent, in observations.

A second response of the hydrologic cycle to global warming is the so-called "Intensification of the Hydrologic Cycle". A warmer atmosphere contains more energy and, in accordance with the Clausius-Clapeyron law, holds more water vapor (about 7% per degree of warming). Therefore, when precipitation is triggered, the precipitation intensity tends to increase with climbing temperatures. A ubiquitous increase in precipitation intensity, along with associated frequency and intensity of extremes, is consistently shown in model projections for all scenarios, including the future occurrence of events of unprecedented intensity. Observed increases in heavy precipitation since 1950 have been identified in extensive regions of Asia, Northern Europe, North America, North Australia, and Southern Africa (and to a lesser extent, South America).

Simultaneously, model experiments indicate that global warming induces a decrease in the frequency of precipitation events and an increase in the duration of dry periods. This, in combination with increasing temperatures, leads to an elevated risk of drought. Such responses are widespread in future model projections, and have been observed over the past decades in areas of Western and Southern Europe, West and East Asia, Southern Australia, western North America and northeastern South America. The occurrence of compound extremes, (e.g., drought and heat waves) can further increase the impacts of such events.

Global warming can also influence the characteristics of regional circulations, such as monsoons. Monsoon precipitation is projected to increase due to the higher moisture in the atmosphere; however, observed trends remain unclear due to the competing regional effects of aerosols and greenhouse gases. Underwarming conditions, interannual variability of precipitation is expected to increase, along side the proportion of intense tropical cyclones (categories 4 and 5) experienced, and the peak wind speeds of the most intense cyclones. These cyclone trends have already been observed in the historical record.

4.3.4 | Observed and projected changes in sea level

Global warming increases sea levels through the melting of continental glaciers and ice sheets, as well as through the thermal expansion of warming waters. This, in turn, presents a substantial risk to coastal infrastructure. Global sea levels have risen by approximately 20 cm since the beginning of the 20th century; however, sea level can show pronounced regional variability due to additional factors such as changes in ocean and atmospheric currents and local subsidence. Global sea level projections indicate a rise of 0.28–0.55 meters for the lowest GHG scenario (SSP1-1.9) and 0.63–1.01 meters in the highest scenario (SSP5-8.5). However, there remains significant uncertainty in undertsanding and modeling of certainice processes affecting the Greenland and West Antarctica ice sheets, whereby these estimates could increase significantly. Further, sea level rise will likely continuefor several centuries beyond 2100 due to the intertia of the slow components of the climate system.

4.4 | Strengths, limitations, and uncertainties associated with different approaches for climate change projections

4.4.1 | General

General Circulation Models, also known as Global Climate Models (GCMs), are the primarytools available today to produce projections of climate change and associated hydroclimatic regimes and extremes. Modern GCMs include various components of the climate system, such as the oceans and cryosphere, and achievehorizontal grid spacings of the order of 80-100 km. While GCMs can reasonably reproduce the general characteristics of the global circulation and its main modes of internal variability (e.g. ENSO and NAO), they are limited by their coarse spatial resolution in simulating regional and local climatesTo address this limitation, both dynamical and empirical/statistical downscaling techniques are employed to refine the GCM outputsand achieve finer scale climate information (Nguyen and Giorgi, 2022). The followingsections will briefly discuss these modeling techniques as applied to the generation of climate projections.

4.4.2 | Interpreting projections from GCMs and RCMs

Climate projections are affected by a number of sources of uncertainty. One such source is related to the use of different GHG concentration scenarios, which is generally addressed by performing projections across a range of such scenarios developed by the IPCC. Once the GHG scenarios are input into the GCMs, different models generally produce a range of corresponding climate responses. This is measured, for example, by the Equilibrium Climate Sensitivity (ECS), which is the global temperature response to doubling of carbon dioxide concentration. Current GCMs exhibit an ECS ranging from 2.0 to 4.5 ^{0}C, a range that has remained relatively stable over several generations of models. The climate sensitivity of a model is intrinsically determined by the unique numerical representations of dynamical and physical processes within a model. Among these, the representation of clouds and precipitation processes, and in particular tropical convection, greatly contributes to the ECS. The representation of cryosphere processes is another important factor. The presence of a range of ECS values implies that climate change information cannot rely on a single model, but needs to employ an ensemble that encompasses the full ECS range of GCms. Various techniques have been developed to reduce inter-model uncertainty by weighting GCMs according to their performance in reproducing different climate characteristics or by constraining climate projections with observations. Additionaly, GCMs are characterized by long term internal variability associated with the slow components of the system (e.g. the oceans) this variability can be explored by carrying out projections using different initial ocean conditions (or different "realizations" of the same scenario).

Similar considerations apply when using RCMs to downscale GCM outputs. It is not sufficient to downscale a single GCM projection; instead„ a range of GCM simulations covering (to the extent possible) the full GCM ECS range and the GCM internal variability must be downscaled. This presents a considerable computational challenge, making it feasible only to downscale a sub-set of available GCMs. Therefore, the selection of GCMs for downscaling must be undertaken very carefully. Furthermore, different RCMs have their own representations of dynamical and physical processes, resulting in different simulations even when driven by the same GCM boundary conditions. For this reason, a suitable matrix of GCM/RCM pairs is needed to suitably interpret uncertainties in projections.

The use of large ensembles is particularly important when considering extreme events, which are, by definition, rare. Additonally, simulated meteoclimatic events must be carefully interpreted considering systematic biases in the models (e.g. over- or underestimation of intensities). Bias correction techniques are often applied to model outputs before use in impact studies. These techniques correct the model output to reduce biases compared to observation datasets, assuming that the model bias in reproducing present-day climate persist in the simulation of future climates.

4.4.3 | Downscaling methods

As mentioned above, tools for generating high-resolution climatic inputs required for modelling extreme hydrologic processes at a given location or over a watershed area are needed. “Downscaling” approaches have subsequently emerged as an efficient means of relating large-scale atmospheric predictor variables to local- or station-scale hydrologic processes (Nguyen and Giorgi, 2022). In general, downscaling methods can be grouped into three broad categories: (i) Dynamic Downscaling (DD) methods using RCMs; (ii) Empirical/Statistical Downscaling (ESD) procedures based on the relationships between coarse-scale predictor climate variables (e.g., atmospheric circulation indices) and at-site predict and surface parameters (e.g., precipitation); and (iii) Downscaling approaches based on Machine Learning (ML) methods.

Compared with GCMs (whereby current GCMs are run at resolutions of the order of 100 km), RCMs can model the physical dynamics of the atmosphere with horizontal resolution in the order of 20–50 km.

The resolution of these RCMs is thus more suitable for coupling with hydrologic models to evaluate the impacts of climate change on hydrologic regime. However, there are several acknowledged limitations of DD using RCMs. The main limitation is that RCMs require considerable computing resources, which restricts the number of experiments and the duration of climate simulations. Furthermore, the climate scenarios produced by RCMs are sensitive to the choice of boundary conditions used to initiate the experiments. DD methods cannot correct the large-scale GCM model inaccuracies. Finally, for many hydrologic applications, it is still necessary to downscale the spatially average results from RCMs to smaller spatial scales or individual sites for local impact studies.

Empirical/Statistical Downscaling (ESD) methodologies are typically classified into three categories, according to the computational techniques used [8]: weather typing approaches; stochastic weather generators; and regression methods. In general, these ESD methods require three common assumptions: (i) surface local-scale parameters are a function of synoptic forcing; (ii) the GCM used for deriving downscaled relationships is valid at the scale considered; and (iii) the derived relationships remain valid under changing climate conditions. Among the three ESD categories, the regression and stochastic weather generator methods are the most popular because the weather classification schemes are somewhat subjective. Several features distinguish DD and ESD methods. DD methods contain more complete physics than ESD techniques; however, the more complete physics significantly increases computational cost, which typically limits the simulation of a climate by these models toa single realization. Alternatively, ESD approaches are relatively fast and less expensive than the computationally intensive DD methods. These convenient features of the ESD allow users to develop expansive climate realizations, and thus quantify the confidence interval of simulated climate variables. Additionally, ESD methods can directly account for the observed climate and weather data available at alocal study site, producing results that are consistent with local climate conditions as described by observations. Finally, many downscaling approaches are based on the combination of more than one of the above-mentioned downscaling methods.

The most recent downscaling approaches are based on machine learning (ML) methods such as Artificial Neural Networks (ANNs) and Support Vector Machines (SVMs). Thus far, the direct application of these state-of-the-art ML methods to statistical downscaling have not been found to provide a significant improvement over the traditional regression-based ESD procedures. The key challenge in this statistical downscaling work remains the identification of climate predictors provided by climate models that significantly affect the temperature and precipitation characteristics at a given local site. However, the use of ML methods may offer a more efficient and robust procedure for selecting these significant climate predictors.

4.5 | Concluding remarks

Hydraulic infrastructure must be designed and operated to ensure safety for people and the environment, while also being economically viable. This requires the accurate prediction of extreme hydrologic processes over the operational lifespan of these infrastructures in the context of a changing climate. However, the uncertainty in climate change projections and increasing climate variability makes this task particularly challenging.

In summary, this guideline has demonstrated that, while significant progress has been made in advancing the accuracy and reliability of global/regional climate modeling, outputs from these GCMs/RCMs remain unstuiable for the assessment of climate change impacts on hydrologic regime at small spatial and short time scales. To address this challenge, several dynamical and statistical downscaling methods have been proposed in scientific and technical literature. Despite limitations, these methodologies have demonstrated value as useful tools for assessment of the potential impacts of climate change in practice.

However, downscaling methods still depend upon accurate and reliable outputs of GCMs/RCMs to develop realistic scenarios that describe potential changes in hydrologic processes under changing climate conditions. Therefore, given their distinct natures and associated skills, it is recommended that employing a combination of both dynamical and statistical downscaling methods is the best approach to develop physically plausible climate scenarios for impact and adaptation studies at local sites or over awatershed. Furthermore, given the high uncertatinty of climate model simulations, it is highly recommended to employ an ensemble ofdifferent climate model projections (a multi-model ensemble approach), particularly when considering extreme events for hydraulic design purposes.

References

1 | Ball, J., Babister, M., Nathan, R., Weeks, W., Weinmann, E., Retallick, M., &Testoni, I. (Eds.) (2016). Australian Rainfall and Runoff: A Guide to Flood Estimation, Commonwealth of Australia.

2 | CSA. (2019). Technical guide: Development, interpretation, and use of rainfall intensity-duration-frequency (IDF) information: Guideline for Canadian water resources practitioners, CSA PLUS 4013:19, Canadian Standard Association, Toronto, Ontario, Canada, 126 pages.

3 | Hershfield, D.M. (1961). Rainfall frequency atlas of the United States for durations from 30 minutes to 24-hours and return periods from 1 to 100 years, Technical Paper 40, U.S. Weather Bureau, Washington, D.C.

4 | IPCC (Intergovernmental Panel on Climate Change) 2021. Climate Change: The Physical Science Basis. Sixth Assessment Report, Geneva, 3949 pages.

5 | Nguyen, T-H. and Nguyen, V-T-V. (2020). Linking climate change to urban storm drainage system design: An innovative approach to modeling of extreme rainfall processes over different spatial and temporal scales. Journal of Hydro-environment Research, 29: 80-95. DOI:10.1016/j.jher.2020.01.006.

6 Nguyen, V-T-V., and Giorgi, F. (2022), Climate change projections for impact and adaptation studies at the urban watershed scale, Special Issue on Climate Change, International Association for Hydro-Environment Engineering and Research, *Hydrolink*, Vol. 2022/3, pp.72–76.

7 NRCC (National Research Council of Canada) (1989). Hydrology of floods in Canada: a guide to planning and design, Ottawa, Canada, 245 pp.

8 Willems, P., Olsson, J., Arnbjerg-Nielsen, K., Beecham, S., Pathirana, A., Bulow Gregersen, I., Madsen, H., and Nguyen, V-T-V. (2012). Impacts of Climate Change on Rainfall Extremes and Urban Drainage Systems, International Water Association Publishing, 238 pages.

9 World Meteorological Organization (1982). Manual for estimation of probable maximum precipitation, Operational Hydrology Report No. 1, WMO No. 332, Geneva, Switzerland, 269 pp.

10 World Meteorological Organization (2009). Guide to hydrological practices, Chapter 5, Vol. II, WMO No. 168, Geneva, 302 pages.

11 Zhang, X., Flato, G., Kirchmeier-Young, M., Vincent, L., Wan, H., Wang, X., Rong, R., Fyfe, J., Li, G., Kharin, V.V. (2019): Changes in Temperature and Precipitation Across Canada; Chapter 4 in Bush, E. and Lemmen, D.S. (Eds.) Canada's Changing Climate Report. Government of Canada, Ottawa, Ontario, 444 p., https://changingclimate.ca/CCCR2019/.

CHAPTER 5

Climate Change Risk Assessment

Inigo J. Losada

Director of Research at IH Cantabria IHCantabria- Institute of Environmental Hydraulics of University of Cantabria, Santander, Spain. E-mail: losadai@unican.es

5.1 | Introduction

The water sector has been dealing with risks over centuries. Risk assessments and risk management have been built upon historical observations of climate and meteorological indicators and, more recently, upon the combination of in situ or remote observations and numerical data sets like hindcasts and reanalysis. The main motivation for this work has been dealing with disaster risk reduction or prevention. Only about a decade ago, risk assessments for disaster risk management and climate change associated impacts started to converge. For the latter, one of the main characteristics is the use of scenarios (plausible description of how the future may develop based on a coherent and internally consistent set of assumptions about key driving forces and relationships for different future horizons (IPCC, 2021). This implies representing the hazards in terms of climate projections which are providing a 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.

Assessing risks of climate change impact is the first step in adaptation planning. Therefore, adopting a robust assessment framework is of outmost importance to accelerate adaptation.

5.2 | Climate change risk assessment framework: terms and definitions

Even if the climate change research community has not achieved a fully developed framework for risk assessment, since the IPCC special report on extreme events and disasters (IPCC, 2012), the IPCC risk framework presented therein and the latter modifications in the 5th and 6th Assessment Reports (AR5 and AR6) cycles has been taken as the most accepted and extended climate change risk assessment methodology. According to the AR5 and AR6 reports climate risks emerge from the interaction between 3 components: climate hazards, exposure and vulnerability. In the following, terms and definitions are based on IPCC (2021).

Risk 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 (including extreme weather/climate events) with the exposure and vulnerability of the affected human or ecological system. In the context of climate change responses, risks result from the potential for such responses not to achieve the intended objective(s) or from potential trade-offs or negative side-effects (IPCC, 2021).

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. It must be noted that impacts may be referred to as consequences or outcomes and can be adverse or beneficial.

To illustrate this definition, we may say that changes in precipitation and potential evaporation are the main climatic drivers controlling impacts on freshwater resources, but not only, whereas changes in extreme sea level, including different combinations of changes in mean sea level, storm surges and waves, is the main driver of coastal flooding. However, when assessing hazards, it is to be noted that there are other non-climatic drivers that may contribute to enhance similar consequences. For water resources, changing land-use, like increasing urbanization may increase flood hazards and decrease groundwater recharge while the construction of new port infrastructures or dams may contribute to reducing coastal sediment transport becoming a major driver of coastal erosion.

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. In short, exposed elements are the impact receptors induced by changes in the relevant climate drivers. Population and infrastructure located at an inland or coastal flooding area; mangroves affected by changes in freshwater discharge; operations in hydroelectric power stations impacted by changes in the precipitation patterns or the supply chain of a corporation affected by increasing frequency of droughts are some examples of exposed assets and operations.

However, for a given hazard (intensity and/or frequency), the impact on exposure may be different depending on the exposed elements' vulnerability. Vulnerability is the propensity or predisposition to be adversely affected. It does encompass a variety of concepts and elements, including sensitivity or susceptibility to harm and lack of capacity to cope and adapt. Exposed elements with a higher sensitivity will show a higher degree of affection, either adversely or beneficially, to climate variability or

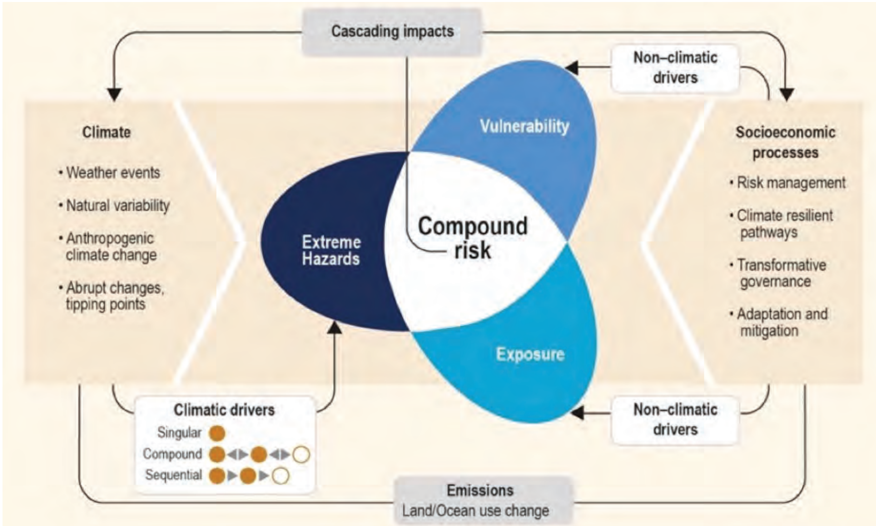


Figure 5.1 | Risk Framework (Source Collins et al., 2019).

change. Whereas exposed elements with a higher coping or adaptive capacity will have a higher ability to address, manage and overcome adverse conditions or to adjust to potential damage. Initially, levees in the early stages of its useful life or with a high standard of maintenance will be able to sustain extreme flooding events better than those at final stages or without maintenance.

In this case, Figure 5.1 is used to highlight part of the complexity inherent to risk assessment if, for example, compound risks arise from the interaction of hazards which can be characterized by: singular extreme events (extreme precipitation), compound events (combination of storm surge and large waves causing extreme water levels) or sequential events that interact with exposure and vulnerability at a given location, like a sequential impact of hurricanes in the same geographic area during a hurricane season.

5.3 | Risk assessment preparation

5.3.1 | Setting the context, objectives and expected results

Context, scope, objectives, and final outcomes expected are unique to each risk assessment and need to be defined as an initial step in the process.

Nowadays the context, objectives and expected results may vary considerably. Over the last decade risk assessments have been mostly driven by the public sector as a first pillar for the development of their adaptation policies. The formulation of national adaptation plans (NAPs), a commitment established under the Cancun Adaptation Framework by the countries engaged with the United Nations Framework Convention on Climate Change (UNFCCC), has boosted the formulation of risk assessments at national and subnational scale. Most of them do include water related sectors to evaluate climate change impacts on water security, water resources, freshwater ecosystems, coastal areas, agriculture, hydropower and many others. Beyond this directly related sectors, there are many others that need to be addressed when dealing with impacts associated to water related acute, (heavy precipitation, extreme sea levels, flooding, drought) and chronic hazards, such as sea level rise, change in precipitation patterns or salt water intrusion.

Beyond the above, only recently the private sector is starting to demand extensive information on climate risks, mostly driven by new regulations, such as the EU Taxonomy (Regulation (EU) 2020/852 of June 2020), reporting needs and, especially to have a better access to the financial system. Water related sectors and water related drivers of risks across sectors have become critical in this developing process.

Having a clear understanding of the context, objectives, expected results and who are the relevant stakeholders and recipients of the risk assessment results is essential to determine the scope and method to be applied. National risk assessments are usually developed to inform high level adaptation strategies and policies whereas local risk assessment is the main pillar in the development of adaptation measures implementation projects. Different context, objectives and expected results but while both may rely on the same risk framework (Figure 5.1), the way in which the framework is applied may vary substantially.

It is important to note that risks should be assessed considering a systemic approach. Therefore, once the geographic extension has been set, it is important to characterize the different subsystems and their interrelations and connections within this geographic extension and beyond. As a first approximation, the characterization may be built by assessing the natural, for example, geomorphology, ecosystems and ecosystem services and the socioeconomic subsystems, such as population, economic sectors, built environment, regulations, and all the components and processes therein. Please note that they are not decoupled but, most of the different sources of information to be used, are usually strongly sectorial.

This part of the assessment will be essential to describe the exposure and, later, its vulnerability, and usually relies on historical information. However, future changes in the system or subsystems, such as demographic changes, changes in territorial planning, the building of new infrastructures or an expected increase in water demand may introduce changes in exposure or in other risk components and should be accounted for.

Once the different assets and processes have been characterized, the next step is to identify the hazards of climatic origin that could affect the system at risk and the main climatic variables and indicators that need to be used to quantify the potential impact to be expected. This needs to be done for selected time horizons and emissions scenarios. The best way to start with is by building a sensitivity matrix relating to a set of climate hazards with each of the different assets and processes. As has been previously stated, it is also important to include other hazards of non-climatic origin that may contribute to exacerbating or reducing the effects of climate change. Usually, this kind of sensitivity matrix relies on expert judgement and on historical information on how the different exposed elements have been impacted by climate/weather events.

This initial exercise does not need a high level of spatial granularity or the use of climate projections, but it is highly recommended starting point for the development of a well-developed risk assessment.

5.3.2 | Selection of time horizons and scenarios

To decide what are the relevant time horizons and scenarios to be considered there is a need to reconcile the risk assessment objectives with the availability of data, especially climate projections.

The risk assessment objectives, the timescales of the decision-making level, the lifetime of the system under assessment or the lead time for the emergence of critical climate change impacts can be used to set the time horizons. Different countries have already established what are the minimum time horizons to be addressed with standard recommended time horizons for less than 10 years from the baseline, for the short-term, the period 2040–2060 for the medium term and a latter period or 2100 for the end of the century. Horizons less than 10 years from present are typical for the evaluation of climate risks on several investments. Technical Guidance on the Climate Proofing of Infrastructure in the period 2021–2027 (2021/373/01) recommends assessing the risk throughout the operational lifetime of the project. Therefore, this may vary depending on the type of infrastructure such as dams, ports or irrigation systems, but usually beyond 30 years. The consideration of the implementation of nature-based solutions for coastal protection such as wetland restoration or mangrove restoration, may require assessments with longer time horizons considering that the lead time for nature base solutions to provide the adaptation service they are design for, may be longer.

The selection of time horizons and scenarios are mostly constrained by the availability of climate projections. While for time horizons under 10 years from the baseline the assessment may be carried out using historical data sets or decadal predictions, beyond that time horizon evaluating the hazards using climate projections is a must. Climate projections depend on an emission/concentration/radiative forcing scenario, which is in turn based on assumptions concerning, for example, future socioeconomic and technological developments that may or may not be realised. They are provided by the Coupled Model Intercomparison Project (CMIP) which is a climate modelling activity from the World Climate Research Programme (WCRP), which coordinates and archives climate model simulations based on shared model inputs by modelling groups from around the world. Within the CMIP projections are generated using General Circulation Models (GCM), which are a numerical representation of the atmosphere–ocean–sea ice system based on the physical, chemical and biological properties of its components, their interactions and feedback processes. There are also projections stemming from Regional Circulation Models (RCMs) which are climate models at higher spatial resolution over limited geographic areas.

One aspect that needs to be highlighted is that, for both the GCMs and RCMs, projections are provided as a collection of comparable datasets coming from different models and settings, useful to reflect part of the uncertainties that will cascade from the hazards to the calculation of risk. However, in many risks assessments hazard is characterized by model ensembles to provide a more robust estimate of the underlying behaviour. Sometimes risk analysis is carried out with the selection of one single model, which introduces a high level of uncertainty in the assessment.

The 5th Assessment Report (AR5) completed in 2014, relied heavily on four main scenarios, known as Representative Concentration Pathways (RCPs) which are scenarios that include time series of emissions and concentrations of the full suite of greenhouse gases (GHGs) and aerosols and chemically active gases, as well as land use/land cover: Meinshausen et al., 2011; van Vuuren et al., 2011), and simulation results from CMIP5. RCPs were named after the approximate radiative forcing reached at the year 2100, resulting in an increased energy flux of 2.6, 4.5, 6.0 to 8.5 W m^{-2}. A large set of RCMs were developed during the AR5 cycle providing downscaled information of higher quality for impact modelling and risk assessment. This is the main reason why most risk assessments and adaptation plans are mainly based on AR5 RCPs scenarios.

The 6th Assessment Report (AR6) is based on model simulations from CMIP6 (Eyring et al., 2016) using a new range of scenarios based on Shared Socio-economic Pathways (SSPs; O'Neill et al., 2016). The set of SSPs recognizes that global radiative forcing levels can be achieved by different pathways of CO_2, non-CO_2 greenhouse gases (GHGs), aerosols (Amann et al., 2013; Rao et al., 2017) and land use. Therefore, the set of SSPs establishes a matrix of global forcing levels and socio-economic storylines that are combined with RCPs to provide the most recent working scenarios. Table 5.1 provides an overall view of the most relevant combinations and a short description of the storylines behind.

Projections of future global climate change in CMIP6 include simulations, spanning time horizons from the near-term (2021–2040), mid-term (2041–2060), and long term (2081–2100) out to the year 2300. One important aspect to be highlighted is that changes in climate variables are assessed relative to both the recent past (1995–2014) and the (1850–1900) approximation to the pre-industrial period.

Consequently, it can be concluded that hazard scenarios to be considered in risk assessments will be limited by the existing RCPs in AR5 or SSPs-RCPs combinations in AR6. Few climate models provide continuous time series of climate relevant data for impact assessment and therefore, an additional

Table 5.1 | Description of the most relevant scenarios presented in the IPCC 6th Assessment Report.

SSP-RCP	WARMING LEVEL (approx.)	DESCRIPTION
SSP1-1.9	1.5°C in 2050	Most optimistic IPCC scenario. Global CO_2 emissions are reduced to zero around 2050. Societies shift to more sustainable practices, moving from economic growth to general well-being. Extreme weather events are more frequent, but the world has dodged the worst impacts of climate change. Only one that meets the Paris Agreement target of keeping global warming to around 1.5° C above pre-industrial temperatures. Reaches 1.5° C but then declines and stabilizes at around 1.4°C by the end of the century.
SSP1-2.6	1.8°C in 2100	Following best-case scenario, global CO_2 emissions are reduced drastically, but not as rapidly, reaching zero emissions after 2050. Socioeconomic changes towards sustainability equivalent to SSP1-1.9. Temperatures stabilize at around 1.8°C above pre-industrial levels by the end of the century.
SSP2-4.5	2.7°C in 2100	Intermediate scenario. CO_2 emissions hover around current levels before beginning to decline by mid-century, but do not reach zero by 2100. Socioeconomic factors follow their historical trends, with no noticeable change. Progress toward sustainability is slow, and development and income grow unevenly. In this scenario, temperatures rise by 2.7°C by the end of the century.
SSP3-7.0	3.6°C in 2100	Emissions and temperatures are rising steadily, with CO_2 emissions roughly doubling from current levels by 2100. Countries become more competitive with each other, focusing on national security and securing their own food supply. By the end of the century, the average temperature will have risen by 3.6°C.
SSP5-8.5	4.4°C in 2100	A future to be avoided at all costs. Current levels of CO_2 emissions will roughly double by 2050. The world economy is growing rapidly, but this growth is fueled by the exploitation of fossil fuels and energy-intensive lifestyles. In 2100, the average global temperature is 4.4°C above pre-industrial values.

restriction exists in the selection of the time horizons limiting risk evaluations to the time slices in which projections are provided. However, it must be acknowledged that individual research centres or private data providers have already developed downscaled or continuous time series of AR6-GCM projections available on demand or for a fee.

In this regard, one last point to be made is that simulations in GCMs and RCMSs do provide most of the relevant atmospheric climate variables needed for assessing risks. However, sea level rise projections are a combination of the results of climate models and a set of additional components not modelled and an important source of uncertainty. For that reason, risk assessments for coastal applications may usually require additional scenarios related to very low probability but extremely high impacts, to account for deep uncertainties in several processes contributing to sea level rise (for example, using expert elicitation assessment for the loss of Greenland and Antarctic ice-sheets). Additionally, since the IPCC is not providing projections for storm surges and sea surface waves, usually a time lag exists between the availability of new IPCC climate projections and the development of global or down-scaled projections of sea surface dynamics required for coastal risks. Initiatives like the Coordinated Ocean Wave Climate Project (COWCLIP), an international collaborative research project, have been established to overcome said limitation.

Finally, it should be acknowledged here that GCMs and RCMs have limitations and results are highly dependent on resolution and process parameterization. Accordingly, risk assessments should keep track of uncertainties and limitations associated to the use of GCMs and RCMs.

5.3.3 | Selection the scope and methodology: a multilevel approach

Considering that the risk framework in Figure 5.1 is the one to be used, once context, objectives, expected results, time horizons and scenarios have been set, it is possible to select the scope and methodology that best applies for each risk assessment exercise. An essential recommendation is using an approach proportional to the needs of the assessment and the quality and quantity of the resources available. Major divergences between the needs and availability of data sets may require a large preliminary effort in acquiring new data sets. Therefore, the selection of the final approach to be followed should be made after having explored the availability and quality of hazard, exposure and vulnerability.

Following a multilevel approach including progressive steps moving from a qualitative to more advanced quantitative or hybrid methods is highly recommended. A multilevel approach for a specific risk assessment may include:

Level I:

- **Assessing the perceived risk by** developing questionnaires or a participatory process to engage the relevant stakeholders and communities. To guide the process the assessment can start with assessing the perceived risk for the past and present climate; identify the relevant impacts; introduce a sensitivity analysis based on projections or thresholds or assess levels of tolerable or admissible risks and critical thresholds that may lead to tipping points in the stakeholders' and communities' perceptions.
- **Screening risks using expert elicitation**. In order to use limited amounts of resources, avoid the collection or large amounts of data and large calculations or when dealing with high uncertainty, developing an expert elicitation process is an excellent way to gain a deep understanding of the system, subsystems, interconnections, climate drivers, impacts and impact chains, consequences and relevant thresholds, among others. The amount, quality and type of information used to guide the process may change on a case-by-case basis. For example, expert elicitation may or may not use climate projections or may rely on observed trends or low-resolution projections.

Depending on the objective and scope, the assessment may end here. Knowledge gained and results of Level I are used as a foundation for the next levels of assessment.

Level II:

- **Quantitative or semi-quantitative approaches**. In this set of approaches quantitative information is used, usually in terms of indicators providing information for the different risk components and, in general, making use of climate projections with varying scales of resolution. Spatial resolution of the different indicators can be adjusted depending on the scope and existing data sets. Impacts are calculated with simplified semi-empirical formulations or setting thresholds. Lack of information or high level of uncertainties can be overcome with expert elicitation. Results are provided in terms of quantitative risk/consequences indicators discretely distributed in space or aggregated, for example, by hazard, sector, or geographic area.

The assessment may end here if the objectives have been addressed consistently. Level II can be skipped if Level III is required and sufficient resources, technical capacity and time is available.

Level III:

- **Advanced quantitative approaches**. This set of approaches applies to highly demanding assessments used, for example, to select and implement adaptation options or if risk assessments are carried out at a local scale and the necessary resources are available. They provide a high-resolution mapping of risks and consequences based on downscaled projections and, ideally making use of advanced impact modelling.

Tables 5.2 and 5.3 provide a summary of the criteria to be used to decide the most appropriate Level to apply.

5.4 | Risk assessment implementation

5.4.1 | Identifying impacts, impact chains and relevant climatic and non-climatic drivers

Independently of the level of risk assessment selected, after the preliminary screening, implementation requires a detailed identification of the potential climate change impacts and other non-climatic driven impacts they may interact in the systems under consideration. Therefore, if the sensitivity matrix has not been built, as suggested in Section 5.3., it must be developed as a first step in the implementation process. Depending on the level of assessment, for each subsystem, sector, asset or process of the system at risk it is required to identify potential climate-related impacts, the main climatic driver and potential consequences. A second phase screening should also be devoted to identifying non-climatic driven impacts.

Once this process has been completed, there is a need to develop impact chains. Impact chains are essential to understand and visualize how hazards can induce direct and indirect impacts and how they cascade across the system. It has to be noticed that presently, only few risk assessments are accounting for cascading or indirect risks in the water sector. Figure 5.2 shows a diagram of the impact chain for hydrological drought.

Beyond including the impact chains and cascading effects, there is currently an important discussion on how to add complexity to climate change risk assessments in order not to underscore interactions among multiple drivers of climate change risk and how to account for compounding and cascading risks. (Simpson et al. 2021).

Figure 5.3, presents the complex interactions that generated risk to infrastructure during the 2018 heatwave.

One significant difference between Figures 5.1 and 5.3 is the fact that in the latter one it is recognized that risks can arise from climate change impacts and from responses to climate change. During the 2018 heatwave several regions across Europe experienced multiple heat extremes compounded with

Table 5.2 | Relationship between levels of approach in risk assessment and several relevant selection criteria.

Level	Approach	Spatial scale	Decision level	Data req.	Initial Resolution	Results	Quality	Uncertainty	Technical resources	Economic resources	Time (1)
I	Qualitative	Any	Build awareness. Exploratory assessments. Set priorities	Low	Low	Qualitative on risk components and consequences. Risks based on colour codes.	Low to medium	Varies depending on the quality of experts and information used	Low	Low	< 2 months
II	Quantitative Hybrid	Regional to national	Identify risk priorities. Calculate costs of inaction. Adaptation strategies or plans	Medium	Depending on the geographic extension of the system	Risk levels based on discrete ranges. Risk maps with discrete information on risk components and consequences or aggregated socioeconomic indicators or Key Perfomance Indicators selected.	Medium	Medium-high	Medium	Medium	3 to 6 months
III	Advanced quantitative	Local to regional	Identify risk priorities. Calculate costs of inaction.. Adaptation plans. Implementation of adaptation measures.	High	High	Detailed mapping of risk components, risks and consequences. Aggregated socioeconomic indicators or Key Perfomance Indicators selected..	High	Lowest	High	High	6 to 18 months

(1) Depending on the size of the team and resources available.

Table 5.3 | Suggested use of climate, exposure, vulnerability and risk information for different levels of risk assessment.

Level	Climate information	Impact modelling	Exposure	Vulnerability	Risk
I	Projections not strictly required. Sensitivity analysis based on thresholds or "stress-tests". Analysis of observed trends or low-resolution projections.	No modelling. Based on expert judgement and historical information.	Level of definition varies with expert knowledge and information available	Based on expert judgement or pre-defined thresholds based on historical information or existing guidelines.	Expressed in terms of consequences with a qualitative risk scale (i.e. low to high) or colour code based on experts criteria. Mostly, in terms of changes with respect, present risks for different scenarios.
II	Projections needed. Downscaled projections if available. If not use of RCMs or GCMS with increasing uncertainty.	Based on thresholds, impact indicators or semi-empirical approximations	Exposure provided in terms of indicators from international, regional or national data sets. Information associated to a geospatial reference system. Projections if available	Used of social, economic and environmental vulnerability indicators. Thresholds based on historical information or existing guidelines and recommendations. Damage functions may be used but representative of homogeneous subsystems or geographic areas within the systems. For example, damage functions for urban vs rural areas in the domain.	Discrete maps or aggregated information of risk indicators are usually expressed in terms of consequences. May present changes with respect to the baseline period or future risks for different scenarios
III	High resolution downscaled projections required. Times slices or times series depending on the impact modelling approach.	Advanced process- based models if possible	High resolution exposure on a geospatial reference system. High resolution DTM.	Combination of thresholds based on historical observations or recommendations. Damage and fragility curves in literature or based on the combination of pre-existing general curves and observations. Each of the assets and processes within the system hase their own damage functions or thresholds.	High resolution maps or aggregated information of risk indicators usually expressed in terms of consequences. May present changes with respect to the baseline period or future risks for different scenarios

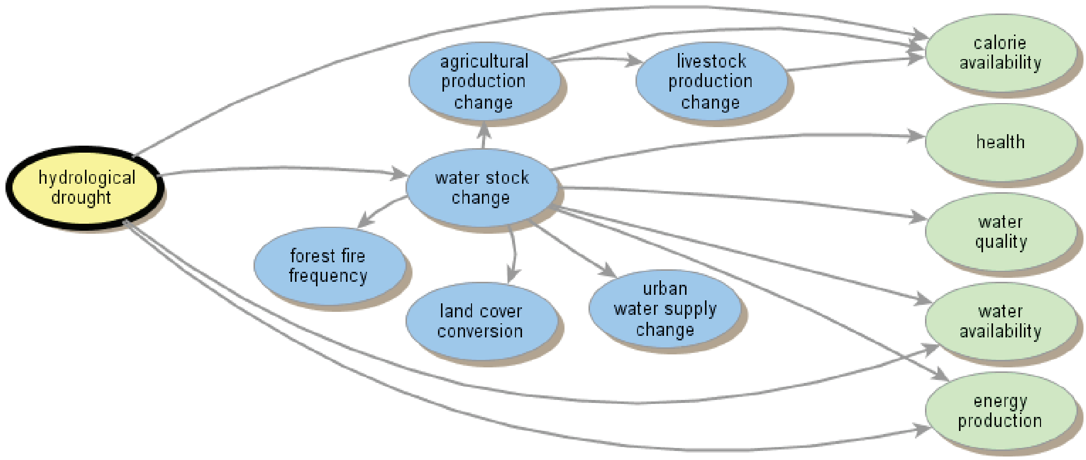


Figure 5.2 | Impact chain for hydrological drought (Source: The Climate Impacts: Global and Regional Adaptation Support Platform (ci:grasp 2.0)).

drought conditions leading to restrictions for shipping in rivers with consequent losses for industry; shut down of nuclear power plants because of insufficient water for cooling; crop yield reduction or railway lines buckled under heat, among other impacts (Simpson et al. 2021).

5.4.2 | Selecting the appropriate data for hazards, exposure and vulnerability

The main sources of data for risk assessments will be climate observations and models (hindcasts and reanalysis), socioeconomic data sets from different kinds of geospatial sources, statistics, censuses, or surveys, from local to international sources, and environmental data sets. Additional information of observed damages or losses due to extreme climate/weather events, climate variability such as ENSO, or long-term changes is also essential and useful to establish thresholds or damage functions or to relate modelled impacts with economic losses. This information will be required for setting the baseline or reference period. It is important to note that collecting information on existing risk reduction measures or adaptive capacity in the system is needed to avoid risk overestimation.

For future time horizons and scenarios, modelled climate projections or decadal predictions will be required. As per exposure and vulnerability, demographic projections, expected land use changes or potential changes modifying the hazards, exposure and vulnerability need to be accounted for. In the lack of detailed information different scenarios can be built for exposure and/or vulnerability to be combined with emissions-related climate scenarios.

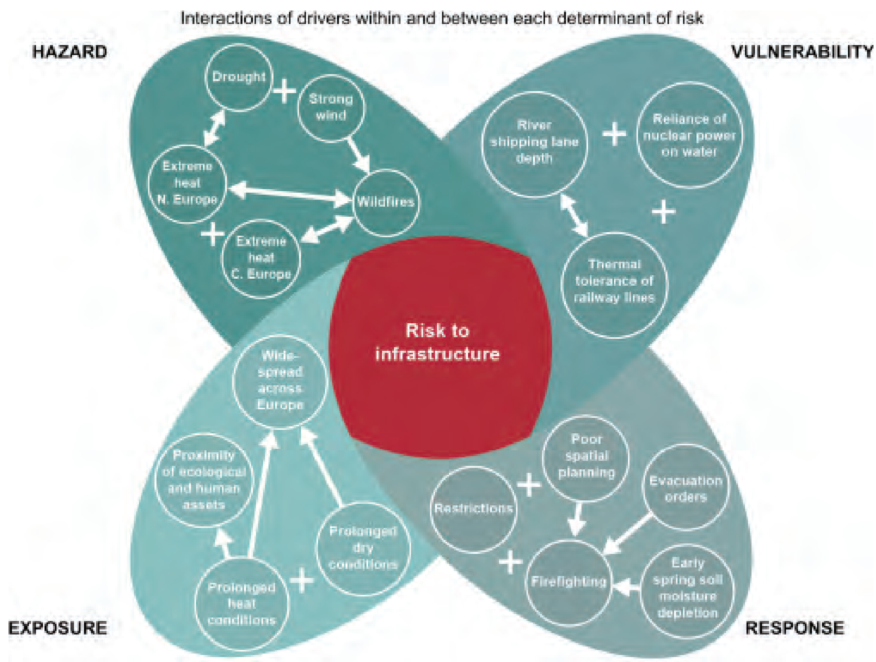


Figure 5.3 | Complex interactions that generated risk to infrastructure during the 2018 heat wave (Source: Simpson et al. 2021).

However, and as summarized in Tables 5.1 and 5.2, the final data to be gathered will depend on the level of risk assessment to be applied.

5.4.3 | Impact assessment methods

Impact assessment methods will also depend on the level of complexity of the risk assessment and, therefore, the set of criteria proposed in section 3.3. The three main approaches are (see link with the different assessment levels in Tables 5.1 and 5.2):

Expert elicitation: Expert elicitation is a well-known practice. No real modelling is applied and based on different well-established approaches assess impacts or sensitivity for different drivers and thresholds on different levels of subsystem or sectorial disaggregation. Experts may assign, beyond impact intensity levels, expected frequency or confidence levels. The selection of experts, the base-line information provided and a proper methodology to enforce comprehensiveness and unbiased judgement is essential.

Indicators-based: Once a selection and evaluation of the relevant risk component indicators has been made, impacts can be calculated by setting hazard proxies and thresholds, such as increase in total water level above a given threshold for flooding or annual number of hours of wind speed above a given threshold for wind damage or by developing impact indicators, like developing an indicator for coastal structures overtopping based on a semi-empirical formulation. The latter may require assumptions regarding the exposed asset characteristics that may need to simplify the assessment based on typologies or for a limited number of representative assets. Thresholds may also apply to assess impacts on processes, operations or on ecosystems' damages. Indicators-based impact modelling may require a higher degree of uncertainty due to the need for simplifying assumptions in the assessment. However, it provides a relatively easier way to obtain quantitative estimates of risk with less resources and data demand, usually applied to large and complex systems. Besides, since calculations are usually less time consuming, this approach favours the use of a higher number of scenarios and time horizons or even considering several GCMs or RCMs for a given scenario.

Advanced modelling-based: This approach is based on standard hydraulic engineering praxis and relies on the use of a variety of models simulating relevant physical or other kind of processes. Hydrological, flooding, coastal erosion, fluid-interaction, water quality, CFD... models can be applied but rather than working with extreme events return periods based on historical information, they must be fed with climate projections. The level of complexity of the modelling approach and the computational time will rule the number of scenarios, time horizons and number of GCMs and RCMs that can be used for the assessment. Even for a given hazard like flooding, there is a need to find the trade-offs between using a simple bathtub approach, allowing a high number of scenarios and climate models to be used at low-cost and the application of process-based models with a better representation of the relevant physical processes, a higher demand in the quantity and quality of input data and more robust and confident results but at a higher computational cost.

5.4.4 | Calculating risk and consequences

Independently of the level of approach selected, risks are calculated as the integration of hazard, exposure and vulnerability. Once the information of hazard, exposure and vulnerability has been produced, the objectives, scope and results expected, together with the volume of information that has been produced will determine how risks are to be calculated and the kind of outcomes to be produced.

Figure 5.4 shows a flowchart of a multi-sectoral, high-resolution assessment of climate change risks of coastal flooding in a coastal area (Toimil et al. 2017). The method corresponds to a level 3 approach

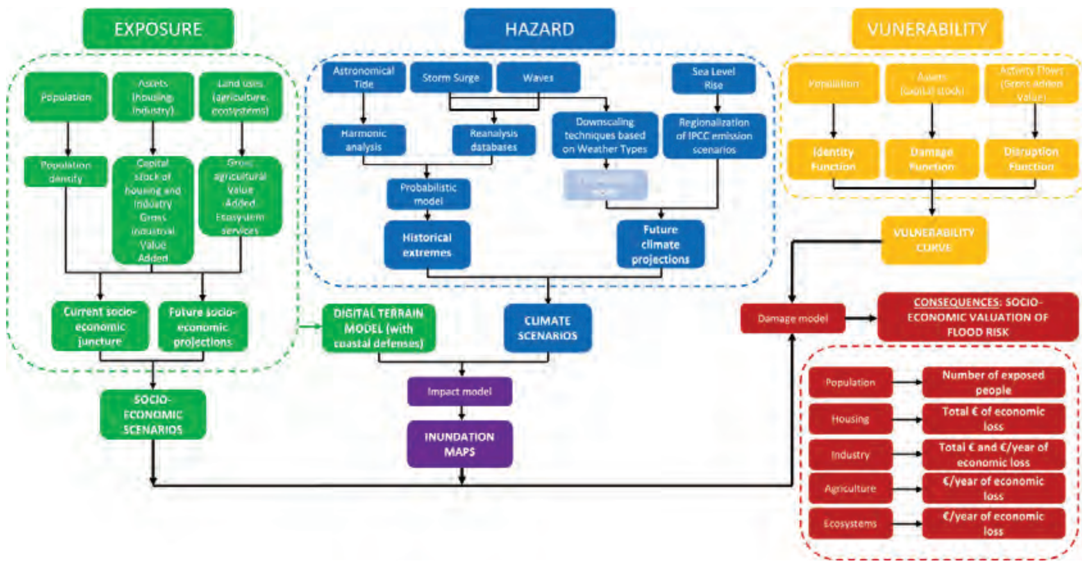


Figure 5.4 | Flowchart of a multi-sectoral, high-resolution assessment of climate change risks of coastal flooding in a coastal area (Source: Modified from Toimil et al. (2017)).

since hazard and exposure were determined for several time horizons and emission scenarios using high spatial resolution data sets and a process-based model (RFSM-EDA, Jamieson et al. 2012) to obtain flooding maps in a coastal stretch 350 km long. The assessment did only address coastal flooding driven by changes in projected extreme water levels which were obtained by compounding sea level rise projections, with storm surge, wave run-up and riverine discharge projections. Due to the variations induced by the local bathymetry on the water level components, extremes of total water levels, used as an input for the flooding model, needed to be projected for different scenarios and time horizons with high resolution. Additionally, a high-end scenario was considered for sea level rise to account for deep uncertainties in its projections.

Exposure represented at a (5 m x 5 m) geographic grid included population, the built environment (residential capital for individual buildings, industrial capital stock and gross value added (GVA), critical infrastructures, agricultural GVA and flow of coastal ecosystem services. Challenges dealing with data sources with different spatial resolution and baseline periods are always diverse and require building homogeneity. Population projections were used for the different time horizons and as a proxy to calculate changes in the capital stock and GVA. Vulnerability was represented in different ways, an identity function for population, depth-damage functions for individual buildings from HAZUS (FEMA, 2003).

To assess the impact on the activity flows, a disruption period related to the duration of the flood event was considered, and the expected disrupted activities were computed as economic losses. Depth-disruption functions were developed based on historical coastal flood events.

Consequences were calculated for mid and the end of the century for an RCP8.5 emission scenario including both permanent flooding due to SLR scenarios and extreme events using a series of socioeconomic indicators as shown in Figure 5.4. To make consequences comparable at different time scales a discount rate is usually applied. Selecting a proper discount rate is still today a controversial issue.

Risk assessment results may be presented with different levels of aggregation. In the previous case, results have been aggregated by sector or by municipality, even if consequences were calculated with a very high level of spatial resolution. However, the level of complexity of the assessment may require normalization of indicators and different means for aggregation. This is especially relevant in urban areas when dealing with multihazard assessments (riverine, coastal or heavy precipitation flooding, heat waves, extreme winds…) also including other natural non-climatic drivers such as tsunamis, earthquakes or slides.

5.4.5 | Assessing uncertainties

Risk assessment seeks to account for the full range of potential unwanted or “bad” outcomes even when they are very uncertain (and very unlikely) (Sutton, 2019). Unless they are carried out using a Level I approach, future projections of risks, are mainly developed using top-down approaches (Levels II and III). These means undertaking a sequence of steps that include selecting emission or concentration scenarios and climate models (GCMs or RCMs), correcting models bias, applying downscaling methods (via statistical or dynamical downscaling approaches), and implementing impact models to obtain results that will be transformed into economic, social or environmental consequences. The information involved in this modelling chain cascades (Wilby and Dessai, 2010) across steps, and so does related uncertainty (both intrinsic or knowledge-related, Toimil et al. 2021a), which accumulates in the final results of the risk assessment.

Figure 5.5 shows a generic sequence of comprehensive steps followed in top-down assessments of climate change-driven coastal erosion and associated sources of uncertainty. Similar representations of the cascade of uncertainty in climate change modelling could be elaborated for other applications in the water sector.

Even if there are still practical, and conceptual barriers in how to approach uncertainty sampling across the entire top-down approach, risk assessments must include specific sections to describe the

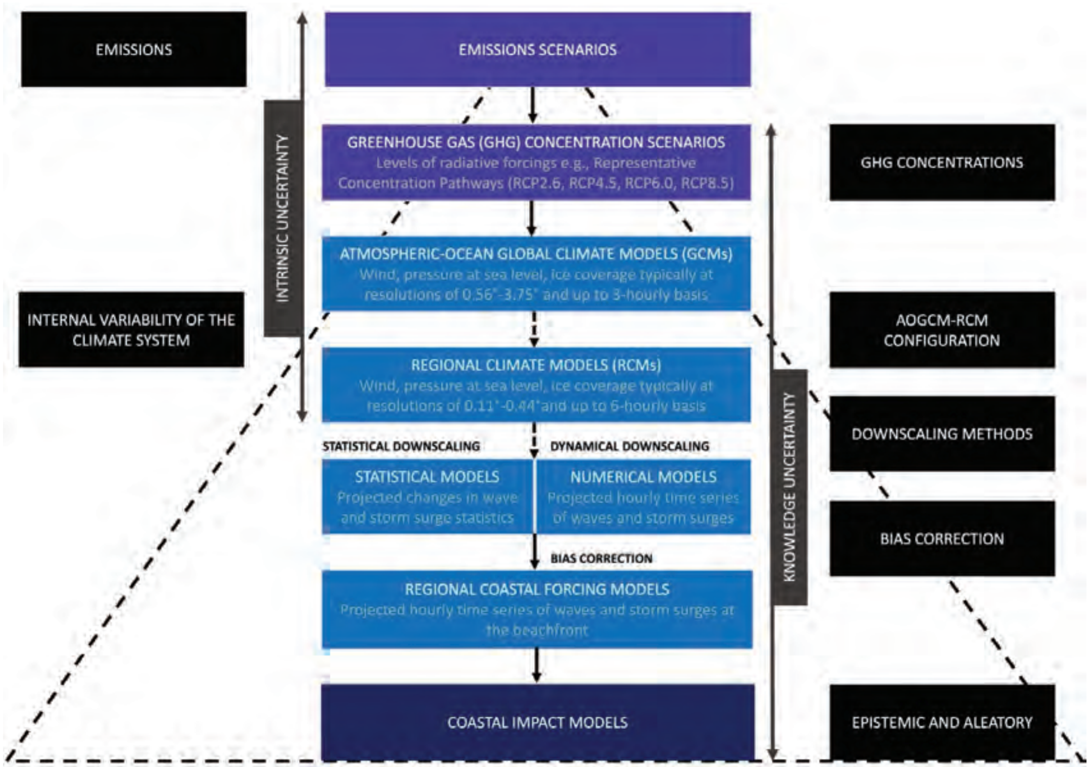


Figure 5.5 | Generic sequence of comprehensive steps followed in top-down assessments of climate change-driven coastal erosion and associated sources of uncertainty that cascade through the whole process (Source: Toimil et al. (2020)).

different sources and type of uncertainties along the process as well as actions that have been taken to map or reduce them. The use of several scenarios, GCMs or RCMs; the introduction of biased correction; the use of high-end scenarios for sea level rise to deal with deep uncertainty in its projections or several others in the selection of the impact models or input parameters, are some of the actions to be applied. Still, uncertainties need to be highlighted to help the receptor in decision-making.

It has to be pointed out that within the climate change community, there are a series of emerging decision-making processes particularly useful when addressing the uncertainties of risk projections such as adaptation pathways or dynamic adaptive policy pathways (Barnett et al, 2014, Hasnoot et al. 2012, Hasnoot et al. 2013, Toimil et al. 2021b).

5.4.6 | Risk communication

Once the risk assessment outcomes have been analysed and reviewed, results have to be communicated to the relevant incumbents, stakeholders and public at large. The communication method (technical reports, summaries for decision-makers, policy briefs, risk maps, videos, oral speeches or participatory workshops…) will largely depend on the context, objectives, scope and expected results but, in general, there is no method or specific content that is able to fit the large variety of interested entities or individuals. This is especially the case for risk assessments developed for the public sector when developing risk assessments at national or subnational scales. Beyond the overall assessment, administrations may be interested in developing sectorial reports for coastal areas, such as water resources, agriculture or industrystemming from the global assessment, as well a synthetic, easily understandable summaries for the public at large.

References

1 | Amann, M., Z. Klimont, and F. Wagner, 2013: Regional and Global Emissions of Air Pollutants: Recent Trends and Future Scenarios. Annual Review of Environment and Resources, 38(1), 31–55, doi: 10.1146/annurev-environ-052912-173303.

2 | Barnett, J., Graham, S., Mortreux, C., Fincher, R., Waters, E., Hurlimann, A., 2014. A local coastal adaptation pathway. Nat. Clim. Change 4 (12), 1103–1108. https://doi.org/10.1038/nclimate2383.

3 | Collins M., Sutherland, M., Bouwer, L., Cheong, S.-M., Frölicher, T., Jacot Des Combes, H., Roxy, M. Koll, Losada, I.J, et al., 2019:. Extremes, Abrupt Changes and Managing Risk. In: IPCC Special Report on the Ocean and Cryosphere in a Changing Climate [H.-O. Pörtner, D.C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegriía, M. Nicolai, A. Okem, J. Petzold, B. Rama, N.M. Weyer (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 589–655. https://doi.org/10.1017/9781009157964.008.

4 | Eyring, V. et al., 2016: Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization. Geoscientific Model Development, 9(5), 1937–1958, doi: 10.5194/gmd-9-1937-2016.

5 | European Commission, 2021:. Commission notice – technical guidance on the climate proofing of infrastructure in the period 2021-2027; https://op.europa.eu/en/publication-detail/-/publication/23a24b21-16d0-11ec-b4fe-01aa75ed71a1/language-en.

6 | Federal Emergency Management Agency (FEMA), 2003: Multi-hazard loss estimation methodology, flood model, HAZUS, technical manual. Department of Homeland Security, Emergency Preparedness and Response Directorate, FEMA, Mitigation Division, Washington, D.C.

7 | Haasnoot, M., Middelkoop, H., Offermans, A., Beek, E.V., Deursen, W.P.A.V., 2012: Exploring pathways for sustainable water management in river deltas in a changing environment. Clim. Change 115(3–4), 795–819.

8 | Haasnoot, M., Kwakkel, J.H., Walker, W.E., ter Maat, J., 2013: Dynamic adaptive policy pathways: A method for crafting robust decisions for a deeply uncertain world. Glob Environ. Change 23(2), 485–498.

9 | IPCC, 2012: Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change [Field, C.B., V. Barros, T.F. Stocker,D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen, M. Tignor, and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, UK, and New York, NY, USA, 582 pp.

10 IPCC, 2014: Summary for Policymakers. In: *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA

11 IPCC, 2021: Annex VII: Glossary [Matthews, J.B.R., V. Möller, R. van Diemen, J.S. Fuglestvedt, V. Masson-Delmotte, C. Meíndez, S. Semenov, A. Reisinger (eds.)]. In Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Peían, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekći, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 2215–2256, doi:10.1017/9781009157896.022.

12 Jamieson S., Lhomme J., Wright G., Gouldby B., 2012: Highly efficient 2D inundation modelling with enhanced diffusion-wave and sub-element topography. Proc. Inst. Wat. Man 165(10):581–595.

13 Meinshausen, M. et al., 2011: The RCP greenhouse gas concentrations and their extensions from 1765 to 2300. Climatic Change, 109(1–2), 213–241, doi: 10.1007/s10584-011-0156-z.

14 O'Neill, B.C. et al., 2016: The Scenario Model Intercomparison Project (ScenarioMIP) for CMIP6. Geoscientific Model Development, 9(9), 3461–3482, doi: 10.5194/gmd-9-3461-2016.

15 Rao, S. et al., 2017: Future air pollution in the Shared Socio-economic Pathways. Global Environmental Change, 42, 346–358, doi: 10.1016/j.gloenvcha.2016.05.012.

16 Simpson, N. P., Mach, K.J, Constable, A., Hess, J. Hogarth, R., Howden, M. et al., 2021: A framework for complex climate change risk assessment. Perspective. One Earth, Vol. 4, Issue 4, p. 489–502- https://www.cell.com/one-earth/fulltext/S2590-3322(21)00179-2.

17 Sutton, R. T., 2019: Climate science needs to take risk assessment much more seriously. Bull. Am. Meteorol. Soc. 100, 1637–1642. doi: 10.1175/bams-d-18-0280.1

18 The Climate Impacts: Global and Regional Adaptation Support Platform (ci:grasp 2.0). https://www.pik-potsdam.de/cigrasp-2/ic/hd/hydrological_drought.html. Accessed: March 2023.

19 Toimil, A., Losada, I.J., Diaz-Simal, P., Izaguirre, C., Camus, P., 2017: Multi-sectoral, high-resolution assessment of climate change consequences of coastal flooding. Climatic Change 145, 431–444.

20 Toimil, A., Camus, P., Losada, I. J., Le Cozannet, G., Nicholls, R. J., Idier, D., et al., 2020: Climate change-driven coastal erosion modelling in temperate sandy beaches: methods and uncertainty treatment. Earth Sci. Revi. 202:103110. doi:10.1016/j.earscirev.2020.103110

21 Toimil, A., Camus, P., Losada, I. J., Alvarez-Cuesta, M., 2021a: Visualising the uncertainty cascade in multi-ensemble probabilistic coastal erosion projections. Front. Mar. Sci., 24, Sec. Coastal Ocean Processes, Vol. 8. https://doi.org/10.3389/fmars.2021.683535

22 Toimil, A., Losada, I.J., Hinkel, J., Nicholls, R.J., 2021b: Using quantitative Dynamic adaptive policy pathways to manage climate change-induced coastal erosion. Climate Risk Management 33, 100342.

23 van Vuuren, D.P. et al., 2011: The representative concentration pathways: an overview. Climatic Change, 109(1–2), 5–31, doi: 10.1007/s10584-011-0148-z.

24 Wilby, R. L., and Dessai, S., 2010: Robust adaptation to climate change. Weather 65, 180–185.

CHAPTER 6

Nature Based Solutions for Climate Change Adaptation

Talita Silva

Department of Hydraulic Engineering and Water Resources, Universidade Federal de Minas Gerais, Brazil. E-mail: talita.silva@ehr.ufmg.br

Bregje van Wesenbeeck

Deltares, P.O. Box 177, 2600 MH Delft, The Netherlands.

Delft University of Technology, Faculty of Civil Engineering and Geosciences, P.O. Box 5048, 2600 GA Delft, The Netherlands.

Giovanna Grossi

University of Brescia, Dept. of Civil, Environmental, Architectural Engineering and Mathematics.

6.1 | Introduction

6.1.1 | What are Nature Based Solutions?

Nature-based Solutions (NbS) are becoming increasingly popular across the globe. They are generally defined as actions to protect, sustainably manage, and restore natural or modified ecosystems, addressing societal challenges effectively and adaptively, while simultaneously providing human well-being and biodiversity benefits (Cohen-Shacham et al., 2016). In addition to providing a certain design function, they inherently deliver a range of co-benefits, such as biodiversity, water purification and tourism. With respect to climate change, they support mitigation by sequestering CO_2, and contribute to adaptation by reducing the impact of climate-driven events, such as floods, droughts, and heatwaves. NbS can be applied in a multitude of sectors and landscapes, from mountainous regions in the form of peat areas and grasslands that store and delay water, to deltas and coasts, where mangroves and marshes dampen waves and trap sediment. For their use in hydraulic engineering, evidence on their effectiveness, resilience and long-term robustness is growing, but is not yet considered standardized.

6.1.2 | Background

“Nature-based Solutions” is a relatively recent term in environmental management, first emerging in the 2000s (i.e. World Bank, 2008). It gained significant prominence in 2015 (Escobedo et al. 2019) in the context of Horizon 2020, a research and innovation program of the European Union (Maes and Jacobs 2017). Since then, the term has spread amongst policy-makers, environmental organizations and researchers (Fernandes and Guiomar 2018), especially in the context of coastal management (Sutton-Grier et al. 2015, urban planning and management (Castellar et al. 2021; Frantzeskaki 2019) and climate change adaptation (Kabisch et al. 2016; Calliari, Staccione, and Mysiak 2019). In the European Union and in the United States, there has been a push towards replacing aging hydraulic structures, such as dams and levees, with NbS systems to restore natural flow regimes and improve ecosystem health (Chambers et al., 2023; Sutton-Grier et al., 2018).There is a growing interest in NbS in river restoration by making use of natural river dynamics for flood risk reduction, with examples in dam removal (https://damremoval.eu/), Room for the River (https://www.rijkswaterstaat.nl/en/projects/iconic-structures/room-for-the-river) and Natural River Management (https://www.adb.org/publications/guidelines-mainstreaming-natural-river-management). Because NbS share many similarities with traditional approaches, many studies have sought to clearly define the concept of NbS in order to avoid misunderstandings, rework, loss of opportunities and eventually, a potential failure of the idea (Nesshöver et al. 2017; Dorst et al. 2019).

NbS have previously been reported to be related to Green-blue Infrastructures, Ecosystem Approach, Ecosystem-based Approach, Ecosystem Services, and Natural Capital and Urban Forests (Escobedo et al. 2019; Nesshöver et al. 2017; Dorst et al. 2019). While the details of similarities and differences between these approaches are beyond our scope, there is a consensus that NbS have the potential to be an umbrella concept (Nesshöver et al. 2017; Albert, Spangenberg, and Schröter 2017; Castellar et al. 2021) which encompasses all similar approaches, gathering knowledge and experience from them and providing a common language to experts from different disciplines and sectors (Dorst et al. 2019).

6.1.3 | Nature Based Solutions and the Sustainable Development Goals

NbS can strongly contribute to the achievement of the Sustainable Development Goals and targets of the 2030 Agenda. Namely, NbS can act for:

- Zero hunger (SDG2) by promoting sustainable agriculture;
- Healthy lives (SDG3) by regulating waterborne human diseases and parasites;
- Sustainable energy (SDG7) by improving water quality and therefore reducing energy requirements for subsequent water treatment;
- Inclusive and sustainable economic growth, full and productive employment and decent work for all (SDG8) for the positive effects between economic growth and the environment;

- Building resilient infrastructure (SDG9) by contributing to build overall system resilience and adaptive capacity;
- Making cities and human settlements inclusive, safe, resilient and sustainable (SDG11) since they address water management objectives in urban settlements;
- Ensuring sustainable consumption and production patterns (SDG12) by promoting sustainable consumption of resources (such as chemicals, fertilizers and land in farming);
- Addressing climate change (SDG13) by helping mitigate climate change through improved sequestration of carbon;
- Life below water (SDG14) and Life on land (SDG15) by promoting the conservation, restoration and sustainable use of ecosystems.

6.1.4 | Nature Based Solutions in the world: examples

6.1.4.1 | *Rain garden in Belo Horizonte city (Brazil)*

Belo Horizonte is the capital of Minas Gerais state, in southeast Brazil (Figure 6.1c). Very urbanized and densely occupied, in 2020 the city had an estimated population of 2.5 million inhabitants distributed

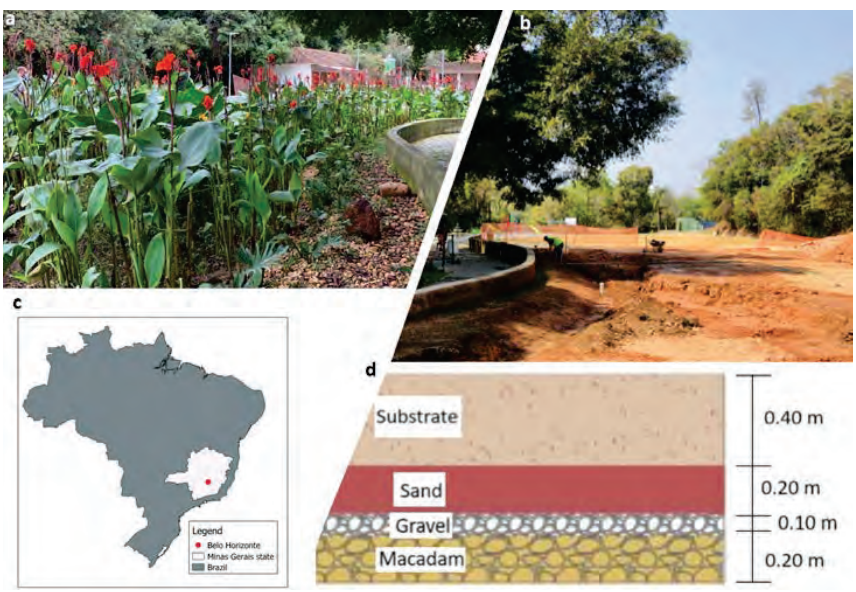


Figure 6.1 | Rain garden in the park Fazenda Lagoa do Nado (Belo Horizonte, Brazil) (a), construction phase (b), (c) location and (d) rain garden layers (figure adapted from Codas (2021)).

over 331 km^2. With a tropical climate, the mean annual air temperature is 21.1°C and the average of total annual precipitation is 1,464 mm. During the warm rainy season from October to March, approximately 90% of the total annual precipitation occurs, mainly originating from the South Atlantic Convergence Zone and from convective rain events. High intensity rainfall, associated with notable soil imperviousness and steep slopes, are at the origin of urban floods which strike the city every year.

A partnership between the municipality of Belo Horizonte and the ICLEI - the Local Governments for Sustainability global network brought the implementation of a rain garden in the urban park Fazenda Lagoa do Nado through the INTERACT-Bio project, funded by the German Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection. Rain gardens are constructed depressions in the ground which receive runoff and whose surface is vegetated with native species, grasses, shrubs, rushes or small trees. These NbS may also have a mulch over the ground withtheir substrate composed of a mixture of soil, sand and organic matter. Besides retaining runoff, rain gardens improve water quality through physico-chemical and biological processes which take place both in the surface and in the soil, and through plant uptake.

The rain garden of park Fazenda Lagoa do Nado was designed to retain a design storm of a 25-year return period, considering a concentration time of 10 minutes and a drainage area of 0.82 ha. Runoff arrives at the NbS either through a bioswale (a shallow, sloped channel filled with vegetation that help to slow runoff) or through a cobble stone channel, finally passing through a buffer area to dissipate energy and reduce flow velocity. The rain garden itself is composed of a set of layers, from the bottom to the surface, as follows (Figure 6.1d): macadam (0.20 m height), gravel (0.10 m height), sand (0.20 m height) and substrate (0.40 m height). With a surface area of 69 m^2, the rain garden will store the runoff over a 0.20-meter depth depression which corresponds to storage of 15.44 m^3, in addition to the volume available in the voids of the macadam and gravel layers. Plant species (Figure 6.1a) from the local biomas, Cerrado and Atlantic Forest, were selected based on their adaptability in dry and wet land conditions, and on their attractiveness to pollinators.

The rain garden of Park Fazenda Lagoa doNadois located in a non-prone flood area, serving primarily as a demonstration project aimed at raising awareness among the population and municipal technicians about sustainable alternatives for urban drainage. The construction of the rain garden (Figure 6.1b) started in August 2021, and its inauguration was in February 2022.

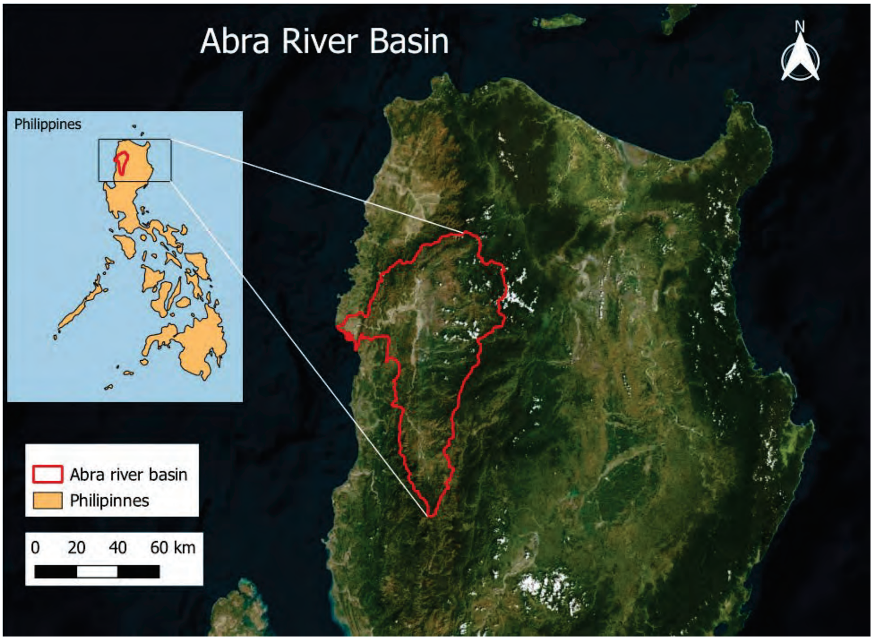


Figure 6.2 | Abra river basin location.

6.1.4.2 | *NbS for reducing riverbank erosion and flooding in Abra river basin (Philippines)*

The Philippines is an archipelagic country in Southeast Asia consisting of 7,641 islands, which are highly vulnerable to natural disasters, such as flooding, due to their geographical location. Abra river basin is located in Luzon, the largest and most populated island in the Philippines, situated in the northern portion of the archipelago. The region is home to the country's capital, Manila and to the most populous city, Quezon City (Figure 6.2). The watershed has a drainage area of approximately 5,125 km^2 covering the provinces of Abra, Ilocos Sur, Mountain Province and Benguet with altitudes as high as 2,500 m above sea level in its eastern portion. Mean annual rainfall is 3,000 mm and the area has two well-marked seasons, a dry period from November to April and a wet period from May to October (DENR, 2015). The population was 487,651 inhabitants in 2015 and estimates for 2050 reach 680,000 inhabitants (ADB, 2022).

Natural hazards in the watershed include soil erosion, floods, landslides, typhoons and drought. Flood risk is greater in the middle and lower basins, where the population concentrates in large villages. Bank erosion has been leading to the lateral displacement of Abra River and constantly evolving braided channels, exposing people settled in between them to flooding and erosion risk. Additionally, flooding and erosion hazards are aggravated by quarrying activities which artificially change watershed geomorphology (van Wesenbeeck et al., 2020). The Philippine Government is preparing flood risk management projects for the main basins in the country and the Asian Development Bank (ADB) provided technical assistance for integrating nature-based solutions to flood risk management strategies in three pilot river basins, including Abra River basin.

The proposed NbS for riverbank erosion and flooding in the Abra river basin involve interventions that create "*room for the river*" like removing or setting-back dikes and levees. This approach allows for natural river meandering, braiding, and channel movement, as well as enabling the river to overflow onto flood plains during high flows. Natural river meander will reduce flow speed and carrying capacity, thereby minimizing the risk of bank erosion. This strategy will require reducing asset vulnerability to flooding by implementing building code and resettlement of vulnerable communities. Quarrying activities which are important for the basin's economy but are currently performed in an uncontrolled manner, exacerbating flooding and erosion hazards, can become an ally through proper management. Strategic quarrying by the private sector, government, and local communities can be encouraged to divert river channels away from vulnerable assets. These smart quarrying practices can be used to facilitate the desired morphological river development and should be followed by a long-term hydrological monitoring program. Smart quarrying is also expected to provide job opportunities and improve livelihoods of households, potentially resulting in a decrease in deforestation and in the adoption of unsustainable agricultural practices (ABD, 2022; van Wesenbeeck et al., 2020).

6.2 | Nature Based Solutions for water engineering in a changing climate

6.2.1 | Nature Based Solutions for Climate Mitigation and Adaptation

Nature-based solutions can play a large role in mitigation of climate change by sequestering and storing carbon (Raymond et al., 2023). Vascular plants trap CO_2 from the atmosphere, sequestering it to oxygen and storing carbon in their tissue. In wetlands, dead plant material can get buried below water or under layers of sediment and thereby create a large base of carbon storage under anoxic conditions that inhibit carbon to oxidize toward carbon dioxide again. Riverine and coastal wetlands play a globally relevant role in carbon sequestration and storage (Raymond et al., 2023), hence their restoration and conservation are important to mitigate climate change. In addition, these ecosystems also increase resilience against climate change effects. In Table 6.1, the function of ecosystems in climate change adaptation from a hydraulic engineering perspective is summarized.

Table 6.1 | Ecosystem functions for climate change adaptation from a hydraulic engineering perspective.

Climate change effect	Ecosystem	Function
Coastal erosion	Vegetated wetlands	Trapping sediment, consolidating soil, reducing current and wave impacts
Increasing precipitation intensity	Forests	Decreasing run off speeds and increasing infiltration capacity
Increasing frequency and severity of heavy storms	Green urban infrastructures (e.g. green roofs or green walls)	Decreasing surface runoff volumes and peak flows
Sea level rise	Beach and dunes	Blocking surges and floods
Higher waves	Salt marsh, dunes, mangroves, coral reefs	Breaking and attenuating waves

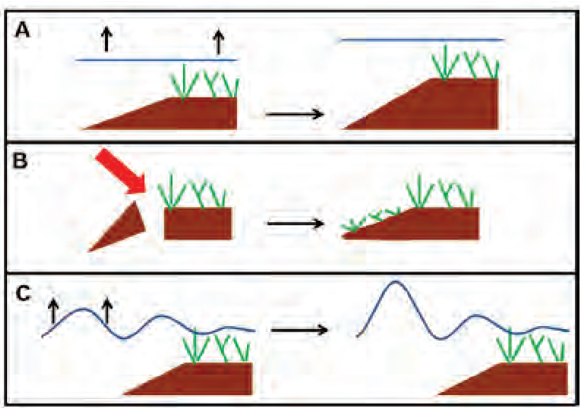


Figure 6.3 | Conceptual drawing showing three adaptive features of ecosystems that can contribute to flood risk mitigation. A) Accretion with rising water levels. B) Self-repair (resilience) after small disturbance events. C) Reduction of waves with different heights to almost similar heigh. *Source*: van Wesenbeeck et al. (2017).

Nature-based Solutions are considered extremely useful in light of climate change adaptation as they are considered flexible and easy to adapt to changing boundary conditions and external drivers (see van Wesenbeeck et al 2017, Grossi et al., 2020). They can repair themselves after disturbances, grow with rising water levels by trapping sediments, and can reduce waves of different heights to a similar level (Figure 6.3) (van Wesenbeeck et al. 2017).

6.2.2 | Nature Based Solutions: an ecological perspective

Nature-based solutions often target functional requirements for mitigation of natural hazards and adaptation to climate change. However, they should also achieve natural benefits, such as increasing biodiversity and habitat connectivity. In many initial NbS projects these benefits were poorly, if at all, monitored. Generally, pre-project baseline surveys are lacking, hence the supplemental effects on biodiversity and natural values are difficult to assess. Overall, from a natural perspective it is more important to consider that biodiverse and healthy ecosystems deliver the most benefits, are most productive and most resilient against perturbations (Seddon et al. 2019). On the other hand, transition to healthy soils is the main goal of the European Union Soil Deal for Europe. In fact, several research and innovation projects are being funded by the European Commission to promote the culture of healthy soils. (e.g. LOESS project, Literacy boost through an Operational Educational Ecosystem of Societal actors on Soil health, https://loess-project.eu/)

Restoration and protection of ecosystems is a separate discipline which is well elaborated and documented. Healthy and biodiverse ecosystems need suitable abiotic conditions; hence, hydraulic infrastructure needs to be aware not to modify these conditions in undesirable directions. However, hydraulic engineering also offers opportunities to enhance and restore natural processes in directions benefiting ecosystem presence and health. Especially in areas where previous disturbances have deteriorated ecosystem presence and quality, restoration of connections and flows offer opportunities for large-scale restoration of natural landscapes and ecosystems. For example, restoring connectivity between the river and its floodplains can reduce sediment surplus and dredging effort in the river, but also increase sedimentation in the floodplain, thereby offering opportunities to increase bed level, restore nature and improve food production (Fischer et al., 2021).

6.2.3 | What do we know about the efficiency of Nature Based Solutions?

Strong ongoing evidence on NbS efficiency for promoting climate change adaptation and mitigation is of paramount importance to disseminate its implementation and guide science advance and public policies. Despite the increasing number of studies focusing on assessing NbS benefits, knowledge gaps are still far from being filled and understanding on trade-offs and synergies between NbS for climate change mitigation/adaptation, biodiversity, human health, social and economic aspects is incomplete (Kabisch et al. 2016). Furthermore, though a reasonable evaluation of NbS short-term performance is found in the literature, long-term effectiveness assessment will require a greater effort for monitoring and collecting data over long periods.

Because nature-based solutions rely on a broad, interdisciplinary and multi objective approach, assessing their benefits is a challenging task. In the last years, many frameworks have been proposed to identify NbS benefits, prove their effectiveness (e.g. Calliari, Staccione, and Mysiak 2019; Raymond et al. 2017; Sowińska-Świerkosz and García 2021) and mathematical models and monitoring are the most common adopted strategies (Vojinovic et al. 2021; Kumar et al. 2021). Defining indicators of performance for NbS is also a fundamental need and according to Kabisch et al. (2016) they should consider (i) integrated environmental performance, (ii) human health and well-being, (iii) citizen involvement and (iv) transferability aspect.

6.3 | Recommendations for Nature Based Solutions Implementation

A number of manuals, practical guides and similar documents have been published in recent years listing implementation steps of NbS aiming at different objectives such as, flood protection, disaster risk-management, natural river management, sustainable urban drainage and coastal defense (Green-Gray Community of Practice, 2020; van Wesenbeeck et al., 2019; World Bank, 2017, 2018). While these NbS implementation steps do not largely distinguish themselves from the good practices of traditional engineering projects, they require reinforcement of some directives to cope with NbS particularities. First, public sector is incapable to fully supervise the functioning of many NbS structures and their success will rely on the willingness and ability of the local community to operate, maintain, preserve, and live in harmony with them. Very often NbS implementation reverberates on land use and management, enters private properties, and extrapolates administrative boundaries (World Bank, 2018). For these reasons, supporting community and stakeholders' engagement to NbS solutions has a vital role in all steps of Nbs implementation.

Second, standards and guidelines for designing and constructing NbS are currently under development and there are gaps within the assessment of their effectiveness, especially under extreme conditions and at long term (Green-Gray Community of Practice, 2020; World Bank, 2017). Strategies to overcome the lack of standardized design and performance evaluation include (i) the use of numerical models based on conservative estimations of parameters related to the nature performance, (ii) the adoption of risk management approach meaning to work with a set of solutions aiming at both reduce hazard as well as reduce exposure and vulnerability and; (iii) the embracement of adaptive management, *i.e.* to refine management strategies as the outcomes from current and future actions are better acknowledged (World Bank, 2017).

After these considerations, implementation of NbScould be arranged into three main steps (van Wesenbeeck et al., 2019) namely, (i) identification, (ii) preparation and (iii) implementation, whose actions (World Bank, 2018) are schematically presented in Figure 6.4.

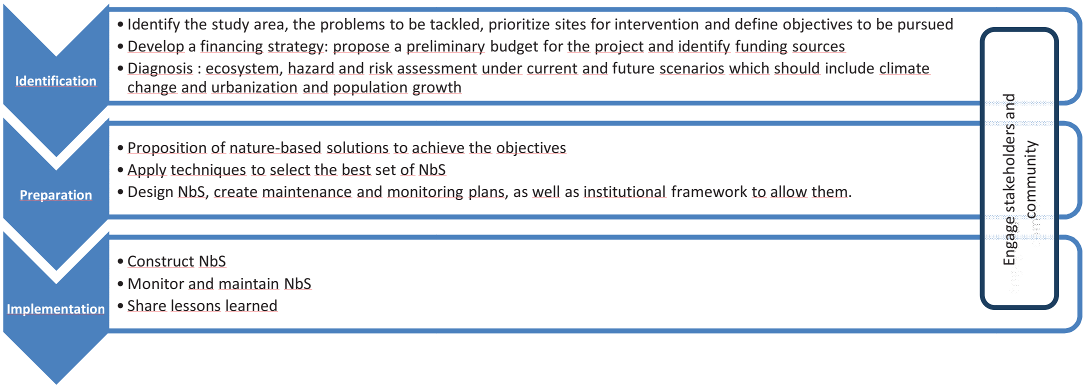


Figure 6.4 | Implementation steps for NbS.

6.4 | Conclusions

By favoring nature and ecosystem restoration, nature-based solutions are expected to play a major role in climate change adaptation. Namely, they offer opportunities for infrastructure optimization while preserving nature and community well-being. On the other hand, by mitigating the effect of land use change, NbS bring back some natural and healthy features (flexibility and resilience) to the environment and consequently make it less vulnerable to climate risk.

The nature-based approach stems from previous similar 'green' or 'sustainable' approaches, but further pushes technical solutions in the direction of promoting an active rehabilitation of natural ecosystem services, as well as the participation of local communities and stakeholders in their planning, monitoring, and management activities. Infact, NbS include a plethora of different technical solutions, but the level of the benefits each of them can provide (independently or in combination) depends on the local geomorpho-climatic features, as well as on the adopted maintenance procedures.

Especially in the last decade they have been suggested in several frameworks: at the international level by the UNESCO World Water Program and the European Environment Agency, but in many countries also at the national, regional and local levels. In most cases their contribution to reaching the UN Sustainable development goals is outlined to overstep socio-political barriers and support sustainable development in several sectors. Provided that they bring not only environmental benefits, but rather a spectrum of co-benefits including societal and economic ones, their implementation always requires a detailed and holistic analysis of the situation and a shared decision on which solution can better suit the local conditions.

Local climatic trends and future expected scenarios need to be considered to ensure a robust design of these solutions, while maintenance plans need to be co-developed with all the stakeholders, including civil society, to ensure their long-lasting effects.

References

1 ADB–Asian Development Bank (2022). Nature-based solutions for Flood Risk Management: Revitalizing Philippine rivers to boost climate resilience and enhance environmental sustainability. 13 p.

2 Albert, C., J. Spangenberg, and B. Schröter. 2017. "Nature-Based Solutions: Criteria." Nature 543: 315. https://doi.org/10.1038/543315a.

3 Calliari, Elisa, Andrea Staccione, and Jaroslav Mysiak. 2019. "An Assessment Framework for Climate-Proof Nature-Based Solutions." Science of the Total Environment 656: 691–700. https://.

4 Castellar, J. A. C., L. A. Popartan, J. Pueyo-Ros, N. Atanasova, G. Langergraber, I. Säumel, L. Corominas, J. Comas, and V. Acuña. 2021. "Nature-Based Solutions in the Urban Context: Terminology, Classification and Scoring for Urban Challenges and Ecosystem Services." Science of the Total Environment 779: 146237. https://doi.org/10.1016/j.scitotenv.2021.146237.

5 Chambers, M. L.; van Rees, C. B.; Bledsoe, B. P.; Crane, D.; Ferreira, S.; Hall, D. M; Lammers, R. W.; Landry, C. E.; Nelson, D. R.; Shudtz, M.; Suedel, B. C. Nature-based solutions for leveed river corridors, Anthropocene, Volume 44, 2023, 100417, https://doi.org/10.1016/j.ancene.2023.100417.

6 Codas, B. Relatório Técnico – Bacias de Contribuição (2021). Guajava Arquitetura e Urbanismo. GEASA. Personal communication. Belo Horizonte (Brazil), 26 p.

7 Cohen-Shacham, E., Walters, G., Janzen, C. and Maginnis, S. (eds.) (2016). Nature-based Solutions to address global societal challenges. Gland, Switzerland: IUCN. xiii + 97pp. http://dx.doi.org/10.2305/IUCN.CH.2016.13.en

8 DENR–Department of Environment and Natural Resources (2015). Formulation of Integrated River Basin Management and Development Master Plan of Abra River Basin. Final Report. Volume 1. Quezon city (Philippines): 57p.

9 Dorst, Hade, Alexander van der Jagt, Rob Raven, and Hens Runhaar. 2019. "Urban Greening through Nature-Based Solutions – Key Characteristics of an Emerging Concept." Sustainable Cities and Society 49 (January): 101620. https://doi.org/10.1016/j.scs.2019.101620.

10 Escobedo, Francisco J., Vincenzo Giannico, C. Y. Jim, Giovanni Sanesi, and Raffaele Lafortezza. 2019. "Urban Forests, Ecosystem Services, Green Infrastructure and Nature-Based Solutions: Nexus or Evolving Metaphors?" Urban Forestry and Urban Greening 37 (March 2018): 3–12. https://doi.org/10.1016/j.ufug.2018.02.011.

11 Fernandes, João Paulo, and Nuno Guiomar. 2018. "Nature-Based Solutions: The Need to Increase the Knowledge on Their Potentialities and Limits." Land Degradation and Development 29 (6): 1925–39. https://doi.org/10.1002/ldr.2935.

12 Fischer,S., Greet, J., Walsh, C. J., Catford, J. A. Restored river-flood plain connectivity promotes woody plant establishment, Forest Ecology and Management, Volume 493, 2021, 119264, https://doi.org/10.1016/j.foreco.2021.119264.

13 Frantzeskaki, Niki. 2019. "Seven Lessons for Planning Nature-Based Solutions in Cities." Environmental Science and Policy 93 (October 2018): 101–11. https://doi.org/10.1016/j.envsci.2018.12.033.

14 Green-Gray Community of Practice. (2020). Practical Guide to Implementing Green-Gray Infrastructure.

15 Grossi, G., Barontini, S., Berteni, F. Balistrocchi, M., Ranzi, R. 2020. "Nature-based solutions as climate change adaptation and mitigation measures in Italy" in Climate Change-Sensitive Water Resources Management, CRC Press, ISBN9780429289873.

16 Kabisch, Nadja, Jutta Stadler, Horst Korn, and Aletta Bonn. 2016. "Nature-Based Solutions to Climate Change Mitigation and Adaptation in Urban Areas. BfNSkript 446." Ecology and Society 21 (2): 39.

17 Kumar, Prashant, Sisay E. Debele, Jeetendra Sahani, Nidhi Rawat, Belen Marti-Cardona, Silvia Maria Alfieri, Bidroha Basu, et al. 2021. "Nature-Based Solutions Efficiency Evaluation against Natural Hazards: Modelling Methods, Advantages and Limitations." Science of the Total Environment 784. https://doi.org/10.1016/j.scitotenv.2021.147058.

18 Maes, Joachim, and Sander Jacobs. 2017. "Nature-Based Solutions for Europe's Sustainable Development." Conservation Letters 10 (1): 121–24. https://doi.org/10.1111/conl.12216.

19 Nesshöver, Carsten, Timo Assmuth, Katherine N Irvine, Graciela M Rusch, Kerry A Waylen, Ben Delbaere, Dagmar Haase, et al. 2017. "The Science, Policy and Practice of Nature-Based Solutions: An Interdisciplinary Perspective." Science of the Total Environment 579: 1215–27. https://doi.org/10.1016/j.scitotenv.2016.11.106.

20 Raymond, Christopher M., Niki Frantzeskaki, Nadja Kabisch, Pam Berry, Margaretha Breil, Mihai Razvan Nita, Davide Geneletti, and Carlo Calfapietra. 2017. "A Framework for Assessing and Implementing the Co-Benefits of Nature-Based Solutions in Urban Areas." Environmental Science and Policy 77 (July): 15–24. https://doi.org/10.1016/j.envsci.2017.07.008.

21 Raymond, C.M., Lechner, A.M., Havu, M. et al. Identifying where nature-based solutions can offer win-wins for carbon mitigation and biodiversity across knowledge systems. npj Urban Sustain 3, 27 (2023). https://doi.org/10.1038/s42949-023-00103-2

22 Seddon, N., Turner, B., Berry, P. et al. Grounding nature-based climate solutions in sound biodiversity science. Nature Clim Change 9, 84–87 (2019). https://doi.org/10.1038/s41558-019-0405-0.

23 Sowińska-Świerkosz, Barbara, and Joan García. 2021. "A New Evaluation Framework for Nature-Based Solutions (NBS) Projects Based on the Application of Performance Questions and Indicators Approach." Science of the Total Environment 787. https://doi.org/10.1016/j.scitotenv.2021.147615.

24 Sutton-Grier, A.E.; Gittman, R.K.; Arkema, K.K.; Bennett, R.O.; Benoit, J.; Blitch, S.; Burks-Copes, K.A.; Colden, A.; Dausman, A.; DeAngelis, B.M.; et al. Investing in Natural and Nature-Based Infrastructure: Building Better Along Our Coasts. Sustainability 2018, 10, 523. https://doi.org/10.3390/su10020523

25 van Wesenbeeck, B.K., de Boer, W., Narayan, S. et al. Coastal and riverine ecosystems as adaptive flood defenses under a changing climate. Mitig Adapt Strateg Glob Change 22, 1087–1094 (2017). https://doi.org/10.1007/s11027-016-9714-z

26 van Wesenbeeck, Bregje K, van IJzendoorn, Christa, Sanchez, Ana Nunes (2019). Guidelines for mainstreaming natural river management in ADB water sector investments. Asian Development Bank, Delft, The Netherlands: Deltares.

27 van Wesenbeeck, Bregje K; Schasfoort, F.; Castillo, G. (2020). Regional: Protecting and Investing in Natural Capital in Asia and the Pacific. Technical Assistance Consultant's Report 9461 for the Asian Development Bank. Quezon city (Philippines): 110p.

28 Vojinovic, Zoran, Alida Alves, Jose Patiño Gómez, Sutat Weesakul, Weeraya Keerakamolchai, Vorawit Meesuk, and Arlex Sanchez. 2021. "Effectiveness of Small- and Large-Scale Nature-Based Solutions for Flood Mitigation: The Case of Ayutthaya, Thailand." Science of the Total Environment 789: 147725. https://doi.org/10.1016/j.scitotenv.2021.147725.

29 World Bank (2008). Biodiversity, climate change and Adaptation: nature-based solutions from the World Bank Portfolio. Washington (USA), 112 p.

30 World Bank. 2017. Implementing nature-based flood protection: Principles and implementation guidance. Washington, DC: World Bank.

31 World Bank. 2018. Nature-based solutions for disaster risk management. Washington, DC: World Bank.

CHAPTER 7

Adaptations for Urban Drainage

Kenichiro Kobayashi

Graduate School of Science and Engineering, Saitama University, Japan.
E-mail: kkobayashi@mail.saitama-u.ac.jp

Giovanna Grossi

Department of Civil, Environmental, Architectural Engineering and Mathematics, Universitaà degli Studi di Brescia. E-mail: giovanna.grossi@unibs.it

Guinevere Nalder

New Zealand. E-mail: nalder_gv@yahoo.com

Talita Silva

Department of Hydraulic Engineering and Water Resources, Universidade Federal de Minas Gerais, Brazil. E-mail: talita.silva@ehr.ufmg.br

Van-Thanh-Van Nguyen

McGill University, Canada. E-mail: van.tv.nguyen@mcgill.ca

7.1 | Introduction

This chapter provides an overview of urban drainage in 5 regions, namely Japan, the Pacific Ocean (especially New Zealand), Latin America and the Caribbean (especially Brazil), Italy, and Canada. First, the expected climate change in each region is briefly summarized, then the expected effect on urban drainage in each country is also briefly explained.

The general resolution of present day GCM/RCM is typically 60/20 km, where, in the most detailed cases, versions may downscale to 1 km, largely without single/multi model ensembles. This resolution is much coarser than the typical urban drainage system, where, for example, in Japan more than 90 % of drainage areas are less than 2 km^2 (Ministry of Land, Infrastructure, Transport and Tourisms; hereafter MLIT, 2020a). This disparity makes the design of urban drainage systems based on strict climate science difficult. While meteorologists will continue to improve climate models, at this moment practical solutions to consider the effect of climate change on the design of drainage systems are still needed.

One current approach is to increase the design rainfall intensity with a factor obtained from GCM/RCM or any theoretical/empirical formula. This is being done in some countries as introduced in this chapter. Likewise, detailed research has begun in cooperation with the local government on how to incorporate the climate change effect on urban drainage. This chapter further discusses the importance of non-stationarity in rainfall/flood frequency analysis. These activities are largely in the beginning stages, especially in practice, however a body of up-to-date research is being steadily accumulated. The importance of considering the cumulative effect of all flood prevention activities at a catchment level is also considered,including the use of green infrastructure. The consideration of the effect of climate change on drainage design must include many factors among climate science, civil engineering practice, and budget constraints. Each section of this chapter introduces such activities of each study region.

7.2 | Regional Impact of Climate Change

7.2.1 | Japan

7.2.1.1 | *Expected Climate Change across Japan*

In Japan, efforts to estimate the effect of global climate change on discharge and inundation with multi-model ensembles have been carried out (e.g. Hirabayashi et al.), with these works having contributed to the IPCC. However, the consideration of climate change effect on the actual practice of river planning/drainage system did not start in Japan until recently. This has led to the development of the ensemble climate change projections called d4PDF(database For Policy Decision making for Future climate change). In d4PDF, global warming simulations were performed using an atmospheric global model at 60km resolution (hereafter AGCM; Mizuta et al. 2017). Additionally, regional downscaling simulations at 20 km resolution for the entire Japan area were carried out using a regional climate model (hereafter RCM). Four sets of experiments are performed by the AGCM.

- historical climate simulation: 1951–2010, 100 members
- non-warming simulation: 1951–2010, 100 members
- +2K future climate simulation: 2031–2090, 54 members
- +4K future climate simulation: 2051–2110, 90 members

The dynamical downscaling simulations by the RCM from AGCM were conducted as follows for the entire Japan region.

- historical climate simulation: Sep 1950-Aug 2011, 50 members
- $+2$K future climate simulation: Sep 2030-Aug 2091, 54 members
- $+4$K future climate simulation: Sep 2050-Aug 2111, 90 members

The historical climate simulation consists of 50 member ensembles for 60 years, thus there are $60 \times 50 = 3000$ years data. The 2K and 4K future climate simulationswere performed based on six different SSTs by CMIP5 models (CCSM4, GFDL_CM3, HadGEM2_AO, MIROC5, MPI-ESM-MR, MRI-CGCM4) assuming that the climates are 2K and 4K warmer than the pre-industrial climate. The 4K future climate was simulated for 60 years as well. There are 90 members (6 SST distributions $\times$ 15 perturbation), thus resulting in $90 \times 60 = 5400$ years data.

In the $+4$K simulations, climatological SST warming patterns (ΔSSTs) were added to the observational SST. The concentration of the greenhouse gases is given by the value of the RCP8.5 scenario for 2090. In the $+2$K simulation, 9-member ensemble experiments were conducted for each of the six Δ SSTs by the aforementioned CMIP5 model, giving a total of 54 members. The duration of the simulation was 60 years, thus there exists $60 \times 54 = 3240$ years of data. The concentration of the greenhouse gases is givenby the value in 2040 of the RCP8.5 scenario.

For further details of d4PDF, see https://diasjp.net/ds2022/dataset/. Likewise, further downscaling of d4PDF down to 5km was carried out and the data is available at (https://diasjp.net/ds2022/dataset/ds16.html, Kawase et al., 2023). This 5 km dataset is based originally on the results of a global climate model with a 60km grid from a large-scale ensemble experiment and is dynamically downscaled to 5 km for 732 years (61 years $\times$ 12 perturbation) for each climate (historical, $+2$k, $+4$k) for all of Japan using a regional climate model.

An initial analysis was done for the whole of Japan by Kobayashi et al. (2020) focusing on the discharge and flood hazards using d4PDF. An analysis by Kobayashi et al. (2021) focusing on Arakawa River in Tokyo Metropolitan area hasshown the stability of the frequency analysis using d4PDF.

On the other hand, MILT has conducted a rainfall analysis using the aforementioned d2PDF and d4PDF and made a recommendation regarding the climate change policy for Japanese river planning (MLIT, 2019: NILIM, 2022). The entirety of Japan was divided into several regions which have similar rainfall patterns, and then the rainfall increase ratio for each region was calculated. Currently, the $+2$K future simulation is expected to be used for actual river planning when the return period of the flooding on the river is more than 200 years. The recommended rainfall increase ratio of the MILT published is as shown in Table 7.1. The short term in $+4$K change in the table indicates the recommended factor

Table 7.1 | Increasing ratio of rainfall using d4PDF by MLIT (2019).

Region	+2K change	+4K change	
			Short term
Hokkaido North and South	1.15	1.4	1.5
Kyushu North West	1.1	1.4	1.5
Other area (including Okinawa)	1.1	1.2	1.3

when the rainfall duration is more than 3 hours and less than 12 hours. This increase ratio is applied for rainfall areas greater than 100 km^2, though it can be applied to areas below 100 km^2 with careful attention to ensure the increase ratio can be higher than the value in the table for such small areas. These factors are currently often simply multiplied with the design rainfall.

7.2.2 | The Pacific

7.2.2.1 | *Expected Climate Change Across the Pacific especially New Zealand*

The dominant features of the Pacific Ocean climate are the El Niño Southern Oscillation and the Walker Circulation. The Walker Circulation is caused by easterly trade winds along the Pacific equatorial belt. Sea water is forced westwards and as it warms in the process it leads to an area of warm surface water. The warm wet air above this rises, leading to clouds and precipitation. Once sufficiently dry, the air flows back across the Pacific. Once over the colder sea surface the air falls, completing the circulation.

This circulation leads to a pressure gradient across the Pacific. Measurements have shown a negative correlation between pressures at Darwin, in Australian and Tahiti. However, this pressure gradient undergoes variation. In extreme situations it can change direction altogether. This variation is called the Southern Oscillation. When this pressure differential weakens the easterly trade winds weaken and the sea surface temperature rises in the eastern Pacific. i.e. the Walker Circulation is reversed with region of maximum rainfall shifting eastward. This is the classic El Nino situation and leads to the general designation – El Nino Southern Oscillation or ENSO. In contrast a strong pressure differential enhances the trade winds and enhances the normal Walker Circulation. In contrast this extreme is called La Nina. The ENSO is the result of the interaction of air movement and sea surface temperature. Hence global warming can be expected to have strong influence on the ENSO structure. Recent modelling suggests that extreme El Nino and La Nina events will increase in frequency with global warming. As tropical cyclones require a minimum water surface temperature of 27 °C to develop, the increase in water surface temperature due to climate global warming can be expected to lead to more frequent and more intense tropical cyclones. Extreme rainfall will shift eastwards during an El Nino and westward during a La Nina.

A background paper for the UN Asia-Pacific Human Development Report[37][3] indicates that in the 100 years to 2017 there was a net temperature rise of 0.6^{o}C leading to a sea level rise of 17 cm across the Pacific and there was an acceleration in these rises in the last 10 – 15 years. For the following 100 years, temperatures were expected to rise 1.4 – 3.7^{o}C and this was expected to cause sea level rise of 120 – 200 cm by the year 2100.

The Paper also indicates that there has been a 'measurable drop in sea surface pH' (i. e., increasing acidity) leading to bleaching and degradation of coral reefs.

New Zealand's climate is governed primarily by the Walker Circulation. Like the rest of the Pacific, the main climate change effect is expected to be extremes of flood and drought becoming more extreme. For urban drainage, main factors are changes in mean precipitation and an increase in frequency and magnitude of extreme events both wet and dry.

In New Zealand, Climate Change modelling is carried out by the National Institute of Water and Atmospheric Research (NIWA) at the request of local governments and the central government usually the Department of the Environment. Following the release of the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report, NIWA carried out a modelling programme with four Representative Concentration Pathways (RCPs) RCP 2.6, 4.5, 6.0 ,and 8.5 corresponding to increasing radiative forcing by greenhouse gases.(Radiative Forcing is a measure of the change in the balance of energy flowing through the atmosphere.) (18).

The models were

- RCP 2.6: Radiative forcing of 2.6 watts per square metre (W.m^{-2}), with removal of some of CO_2 presently in the atmosphere
- RCP 4.5: Radiative forcing of 4.5 (W.m^{-2}), with atmospheric CO_2 concentration stabilized at the level at the time of commencement of modelling
- RCP 6.0: Radiative forcing of 6.0 (W.m^{-2}), with same stabilization pathway as RCP 4.5.

[3]Nunn P D Climate Change and Pacific Island Countries (2017), Asia-Pacific Human Development Report Background Papers Series 2012/07.

- RCP 8.5: Radiative forcing of 8.5 (W.m^{-2}), with no stabilization pathway ('Business as usual') and anticipated very high greenhouse gas levels in 2100 and beyond.

A summary of the results is in Table 7.2.

Following the release of IPCC 6th Report, NIWA carried out further modelling with models based on Shared Socioeconomic Pathways (SSP). At time of writing the results were being analysed prior to being released on the NIWA website, https://niwa.co.nz/climate-and-weather.

Table 7.2 | New Zealand climate change projections for 2040 and 2090 (Ministry for the Environment, 2018).

Climate variable	Direction of change	Magnitude of change	Spatial and seasonal variation
Mean temperature	Progressive increase with concentration. Only for RCP2.6 does warming trend peak and then decline.	By 2040, from +0.7˚C [RCP2.6] to +1.0˚C [RCP8.5]. By 2090, +0.7˚C to +3.0˚C. By 2110, +0.7˚C to +3.7˚C.	Warming greatest at higher elevations. Warming greatest summer/autumn and least winter/spring.
Minimum and maximum temperatures	As mean temperature.	Maximum increases faster than minimum. Diurnal range increases by up to 2˚C by 2090 (RCP8.5).	Higher elevation warming particularly marked for maximum temperature.
Daily temperature extremes: frosts	Decrease in cold nights (minimum temperature of 0˚C or lower).	By 2040, a 30% [2.6] to 50% [8.5] decrease. By 2090, 30% [2.6] to 90% [8.5] decrease.	Percentage changes similar in different locations, but number of days of frost decrease (hot day increase) greatest in the coldest (hottest) regions.
Daily temperature extremes: hot days	Increase in hot days (maximum temperature of 25˚C or higher).	By 2040, a 40% [2.6] to 100% [8.5] increase. By 2090, a 40% [2.6] to 300% [8.5] increase.	
Mean precipitation	Varies around the country and with season. Annual pattern of increases in west and south of New Zealand, and decreases in north and east.	Substantial variation around the country (see section 4.6.1), increasing in magnitude with increasing emissions.	Winter decreases: Gisborne, Hawke's Bay and Canterbury. Winter increases: Nelson, West Coast, Otago and Southland. Spring decreases: Auckland, Northland and Bay of Plenty.
Daily precipitation extremes: dry days	More dry days throughout North Island, and in inland South Island.	By 2090 [8.5], up to 10 or more dry days per year (~5% increase).	Increased dry days most marked in north and east of North Island, in winter and spring.

Table 7.2 | *Contd.*

Climate variable	Direction of change	Magnitude of change	Spatial and seasonal variation
Daily precipitation extremes: very wet days	Increased moderately extreme daily rainfalls, especially where mean rainfall increases.	More than 20% increase in 99th percentile of daily rainfall by 2090 [8.5] in South West of South Island. A few percentage decrease in north and east of North Island.	Increase in western regions, and in south of South Island. Decrease in extremes in parts of north and east of North Island.
Very extreme precipitation events: greater than 2-year average recurrence interval	Increase.	Percentage increases *per degree of warming* range from 5% for 5-day duration events to 14% for 1-hour duration events.	Little robust regional variability. Possibly larger increases in the very north and very south of the country.
Snow	Decrease.	Snow days per year reduce by 30 days or more by 2090 under RCP8.5.	Large decreases confined to high altitude or southern regions of the South Island.
Drought	Increase in severity and frequency.	By 2090 [8.5], up to 50mm or more increase per year, on average, in July–June PED.	Increases most marked in already dry areas.
Circulation	Varies with season.	Generally, the changes are only a few hectopascals, but the spatial pattern matters.	More northeast airflow in summer. Strengthened westerlies in winter.
Extreme wind speeds	Increase.	Up to 10% or more in parts of the country.	Most robust increases occur in southern half of North Island, and throughout the South Island.
Storms	Likely poleward shift of mid-latitude cyclones and possibly also a small reduction in frequency.	More analysis needed.	See section 4.7.
Solar radiation	Varies around the country and with season.	Seasonal changes generally lie between -5% and +5%. (See section 4.9.1.)	By 2090 [8.5], West Coast shows the largest changes: summer increase (~5%) and winter decrease (5%).
Relative humidity	Decrease.	Up to 5% or more by 2090 [8.5], especially in the South Island. (See section 4.9.1.)	Largest decreases in South Island in spring and summer.

7.2.3 | Latin America and the Caribbean

7.2.3.1 | *Expected Climate Change Across Latin America and the Caribbean especially Brazil*

Although climate, ecosystems, human population distribution and cultural traditions are very diverse over Latin America and the Caribbean (LAC), the region shares characteristics which lead to a similar context for urban drainage. For the most part under tropical climate marked by large rainfall intensities and volumes, LAC countries experienced a fast urbanization along with unregulated urban growth and a scarcity of investments for stormwater infrastructure and institutional framework. Not surprisingly, floods are the most common type of disaster in the region and Brazil is among the top 15 countries in world with the greatest population exposed to river flood risk (OCHA, 2020).

The occurrence of convergence zones, such as the Inter-tropical Convergence Zone and the South Atlantic Convergence Zone, together with monsoon systems and low level jets are determinant for the climate and precipitation patterns in LAC (Cavalcanti et al., 2009). Because most of the rainfall occurs in convergence zones or is restricted by topography, very distinctive rainfall spatial and temporal patterns are observed, for instance, the semi-arid region in northeast Brazil situated next to the humid Amazonia (Magrin et al. 2007). El-Niño Southern Oscillation is also a relevant phenomenon in the region and represents the main source of precipitation inter annual variability (Cavalcanti et al., 2009).

Unusual extreme weather events have been reported in LAC over recent years, such as the occurrence of Hurricane Catarina, the first tropical cyclone to hit Brazil.Changes in precipitation and increases in air temperature have been observed in the last decades. Regional studies on climate trends showed patterns consistent with a general warming, such as positive trends in daily minimum air temperatures, intense rainfall events and consecutive dry days. However, in some regions the lack of long time series of daily air temperature and rainfall prevents conclusions about trends (Magrin et al., 2007; IPCC, 2022). Assessment of Global Climate Models (GCMs) from the Coupled Model Intercomparison Project Phase 6 (CMIP6) over South America indicated that compared to a baseline period from 1971 to 2014, for 2100, median air temperature increases may reach 6°C in LAC (Ortega et al., 2020), with the highest values projected for Amazonia region (Almazroui et al., 2021). While temperature changes predicted by the models are robust in terms of sign and magnitude, projections for precipitation are much more uncertain and for most scenarios precipitation changes are within the baseline variability. A decrease is expected for annual rainfall in Central America, north-eastern and southern Andes and in Amazonia while an increase is likely to occur in winter rainfall in Tierra del Fuego and in summer rainfall in south-eastern South America (Almazroui et al., 2021; Christensen et al., 2007).

The results of the regional climate projections in Brazil suggest a warmer future across the country and an increase in extreme droughts, mainly in Cerrado (central Brazil), Caatinga (northeast Brazil) and Amazonia biomes. In the Amazonia region, air temperature increase of up to 6°C and a rainfall reduction of up to 45% are expected by the end of this century. In the northeast region of the country, air temperature is expected to heat up to 4.5°C and rainfall is forecast to decrease by up to 50% by 2100, which will severely aggravate the regional water deficit. In the central region of the country, seasonal variations are expected to become more pronounced; with air temperatures heating up to 5.5°C and rainfall dropping down to 45% in the late century. In the northeast, air temperature increase may reach 4°C along with a drop of up to 35% in rainfall by 2100. In western Brazil, expected air temperature increase will reach 4.5°C and rainfall will reduce 45% by 2100. Increases in rainfall volumes are expected only in the south (40% increase) and southeast (35% increase) regions, along with air temperature increase of up to 3°C (PBMC, 2013a).

Despite the high uncertainty concerning precipitation projections, climate change is expected to intensify hydrological extremes events, which in urban drainage context is translated as higher rainfall volumes in shorter periods. Studies focusing on the impacts of climate change on urban drainage in the region are still rare, but it is well acknowledged that Brazilian cities are vulnerable to climate changes, which already impose significant impacts, especially for urban poor, informal settlements. Climate change impacts include sea level rise threating coastal cities, heavy rains, loss of biodiversity and increase in the incidence of water-related diseases (PMBC, 2013b).

7.2.4 | Italy

7.2.4.1 | *Expected Climate Change Across Italy*

Italy is one of the most vulnerable European countries to climate change, featuring several climate types within about 300,000 km^2: in the Northern part the climate ranges from a humid subtropical climate (Cfa) to humid continental (Dfb), turning to cold continental (Dfc) in the highest elevation band, while in the rest of Italy the climate is similar to the Mediterranean type (Csa), including some transition types due to the effect of the Apennines (Grossi et al., 2020). The two main mountain chains (the Alps and the Apennines) from one side and the coastal areas on the other side are responsible for the high vulnerability of the country.

High-resolution global maps of the climate classification at a 1-km resolution for the present- day (1980–2016) and projected future conditions (2071–2100) under climate change were analyzed by Beck et al. (2018) for scenario RCP8.5. In the Northern hemisphere, the projected map shows a shift to the North of the climate types, also affecting the Italian mountainous areas.

Climatic trends observed in the last decade are described in the last assessment report on the climate indexes for Italy written by the National Agency for the Protection of the Environment (ISPRA, 2019). At the national level, the updated seasonal temperature trends show the highest positive rates for spring and summer, while the seasonal precipitation trends turn out to be insignificant. Concerning extreme events, the annual sum of the daily precipitation higher than the 95th quantile (R95) does not show any significant trend in the medium—long term (1970–2000), even if positive anomalies appear to be more than the negative ones in the last decade.

7.2.5 | Canada

7.2.5.1 | *Expected Climate Change Across Canada*

Environment and Climate Change Canada (ECCC) projects Canada to warm faster than the global average and predicts an increase in the frequency and severity of extreme weather events in coming years. The projected increasing trend in climate related catastrophes is already manifesting themselves and present a significant economic concern. In particular, in the past decade, flooding has emerged as the most costly natural disaster in the country, causing economic loss and a high potential for risk to the safety of Canadians across many regions. Floods can occur due to local intense rainstorms, rapid melting of snow, ice jams on rivers, storm surges and rising sea levels. In addition, current infrastructure design assumes climate stationarity, which may lead to an under estimation of extreme design rainfall, flood risk, and risk of failure of infrastructure systems. New climate adaptation measures are therefore needed to address flooding and ensure that urban drainage systems can help manage the current and future flood risks.

7.3 | Adaptation to climate change

7.3.1 | Japan

7.3.1.1 | *Japanese Approach to Climate Change Adaption*

To enhance the safety of river watersheds against water-related disasters, current Japanese river basin flood control (Ryuuiki Chisui) practice has started to be based upon the concept of comprehensive flood control (Sogo Chisui), e.g. Tsurumigawa River after 1980 (MLIT, 2024ab). In this concept, counter measures against water related disasters are considered at the entire basin level to create a society in which disaster prevention and mitigation become mainstream. Coping with the climate change is significant, thus levee maintenance, dam construction, paddy field dam, small reservoirs, green infrastructures etc. are all considered comprehensively to mitigate the water-related risks by all stakeholders in the river basin, from the catchment area to the flood area. One new approach in basin flood management is the newly-introduced land use regulation (Shiga Prefecture, 2014). Here it becomes possible, under some conditions, to prevent citizens living in high flood risk areas.

Likewise, the enhancement of rainwater drainage, as largely managed by cities, is promoted as a continuous activity and will also contribute to river basin flood control. For example, to cope with climate change, there will be an increase of the design rainfall intensity using the factor such as Table 7.1 (the value is modified slightly for the drainage but the details are omitted here since it is mostly similar, MLIT, 2024c).

The Sewer Sub-Committee of the Council for Social Infrastructure reported "The Way of Sewer at the New Era"in June 2007 (MLIT, 2007). As its mid-range target at focal areas e.g. the high level use area of underground space, business areas, and above floor level inundation prone area, the damage due to the inundation should be minimized by considering the historically maximum level rainfall. The hard counter measures for these areas should be designed for the 1:10 year rainfall level. This level should be applied against the1:5 year rainfall for the general land use area.

On the other hand, the construction of huge underground tunnels have been carried out at several places in Japan. For example, the Metropolitan Outer Area Underground Discharge Channel is a huge underground channel which receives overflow from Kuramastsu and Oootoshifurutone rivers, and then directs it to the Edogawa River using a 6.3km long tunnel at 50 m below ground level. The aim of the underground channel is to protect the eastern part of Saitama Prefecture and the north-eastern part of Tokyo (MLIT, 2020). There is also a huge underground river at Northern Neyagawa city in Kansai region, west Japan. This tunnel is still being extended. The total length is currently 14.3km with a storage volume of 26 million m^3. There are seven vertical shafts within Neyagawa city. 9.7km of the proposed total of 14.3km is already in use, while the rest, 4.6km, is now under construction (Osaka Prefecture, 2021).

The strategy for the promotion of green infrastructure was published by MLIT at 2019 (MLIT, 2019). In this strategy, response to climate change was listed as one of the 8 situations in which the promotion of green infrastructure is encouraged. Green Infrastructure includes rainwater storage and infiltration facilities such as the use of rainwater storage tanks, storm water infiltration inlets and water permeable paving, thus maximally utilizing the limited urban space available for flood control management.

Concrete activities to manage climate change effects on city level drainage management have been already started in some places such as Himeji-city, Hyogo-prefecture, west Japan (Himeji City, 2023). The first step was to follow the recommendation of MLIT by multiplying the design rainfall by the factor of rainfall-increases. However, if the increase ratio of the rainfall intensity leads to design values that are too high, the municipalities will not be able handle the situation easily due budget shortages. This is an example of how incorporation of climate change in drainage design needs to strike a balance between climate science, civil engineering practice and budget constraints.

7.3.2 | New Zealand

7.3.2.1 | *New Zealand Approach to Climate Change Adaption*

Engineering Response. In adapting urban drainage design for climate change the main relevant factors are the change in mean rainfall, higher frequency of floods or droughts, with storms being more intense and droughts lasting for longer.

When climate change modelling indicates a decrease in mean rainfall, the existing infrastructure may be adequate to deal with the quantity of runoff, but not adequate to deal with the quality. The decrease in runoff volume leads to less dilution of pollutants. This consequence can be managed by minor redesign of the existing infrastructure to incorporate pollution control structures, as subsequently described in Section 3.2.1.3.

Conversely, an increase in mean precipitation may lead to more frequent flooding which exceeds that for which the infrastructure was designed. An increase in flood extremes may also lead to greater erosion in receiving channels. While the increase in water volume may lead to greater dilution of contaminants, they are still there and need to be dealt with. An optimal engineering solution will be one that combines flood management along with pollution removal.

Upgrading Codes of Practice. In New Zealand, The Climate Change Commission, He Pou a Rangi, advises to central government on national response to climate change. However, given New Zealand's varying topography, detailed responses are the responsibility of local governments. This frequently includes rewriting local Codes of Practice to allow for climate change effects. Although, local authorities can commission detailed modelling for their area of responsibility from NIWA, most use the modelling commissioned by the Department of the Environment in response to the IPCC reports.

A typical example is the recently upgraded Code of Practice published by the Auckland Council using the results of the RCP modelling described above. This council is responsible for the largest urban area in New Zealand and as it is centred upon the isthmus between the Waitemata and Manukau Harbours the two main climate change effects it is concerned with are rising sea levels and changes in rainfall with its direct effect on urban drainage.

The basic document for stormwater runoff estimation is 'TP 108 Guidelines for Stormwater Runoff Modelling in the Auckland Region' issued in 1990. (Auckland. 1990) This contains a normalised 24 hour design storm with maps of 24 hour rainfall depth. This rainfall is then adjusted, if necessary, using supplied areal reduction factors. The Council has allowed for climate change by updating the 'Auckland Code of Practice for Land Development and Subdivision, Chapter 4 Stormwater'[4]. For primary systems (i.e. those designed for 10% AEP) a temperature increase of 2.1^{o}C is assumed and for secondary systems (1 % AEP) the increase is 3.5^{o}C. The revised Code includes a table of percentage increases in 24 hour rainfall depth for specified AEP and for each temperature increase. It also includes an updated normalised temporal rainfall intensity profile.

Upgrading Existing Infrastructure. Replacement of reticulation with larger pipes is unlikely to be feasible. Instead there are two smaller scale types of upgrade which can reduce the necessity for pipe replacement. These upgrades are

(1) Low Impact Urban Drainage Design (LIUDD)
(2) On site detention tanks.

Low Impact Urban Drainage Design. The basic principle of LIUDD is to use the natural process within soil and plants to control peak rate, volume, and quality of stormwater. LIUDD is based on the design of structures of varying sizes which provide treatment at source and volume control depending on the size of the structure.

Vegetated swales and rain gardens are two examples of small structures. Vegetated swales acts as a conveyance system that slows stormwater flows and thus provides some reduction in runoff while capturing some of the contaminants. The vegetation of the swale slows the velocity of the runoff which increases time of concentration and permits the deposition of suspended solids. Depending on the permeability of the soil, some runoff may be diverted into the groundwater store. Vegetation can also absorb some of the contaminants and use them for growth.

In contrast, rain gardens are bioretention structures. These consist of layers of planting soil topped by mulch with an underlayer of sand if necessary. The plantings in the garden such as trees, shrubs and grasses absorb nutrients from the inflow. The planting soil provides a store for runoff which is

[4] Auckland Council, The Auckland Code of Practice for Land Development and Subdivision Chapter 4: Stormwater Version 4.0, March 2024.

gradually released into the under drain. In areas with expected increase in mean rainfall, these small structures can be retrofitted to provide extra treatment.

Retention/TreatmentPonds. These are larger scale structures which are designed to provide substantial volume control as well as contaminant removal. These ponds are designed to have two unequal sized sections separated by a low bund. Inflow water comes into the smaller forebay, where larger sediments are deposited. It is usually designed to hold circa 15% of the total pond volume. A pond can be designed to have more than one forebay if inflow is coming from different directions. When the water level is sufficiently high, the water flows over the bund to the main pond which may be either wet or dry. Dry ponds are used only for retention. Wet ponds are designed to have a permanent volume of water to facilitate further sedimentation of contaminants. Plantings within and around the pond will aid treatment as well as making the pond look more natural. Detailed instructions for the design of these structures is given in the appropriate Auckland Council publication.

Onsite Detention. In onsite detention, small, individual tanks are placed on residential lots to collect runoff from impervious surfaces, primarily roofs. It is a method of controlling peak flow and is not designed as a method of improving the quality of the water, although some sedimentation can be expected to occur. Neither is it a method of collecting rainwater for reuse on the site. It is seen as an approach for high density housing with small section size and high impervious percentage. On-site detention is now compulsory in new constructions in New South Wales, although this system is not in general use in New Zealand. However, a study carried out for the Auckland Regional Council indicated that a whole of catchment approach needs to be taken, particularly for development of green field sites. An injudicious combination of developed subcatchment and undeveloped subcatchments can lead to peak flow in the receiving channel which is worse that the completely undeveloped case.

Where housing is less dense, collecting runoff for re-use may be feasible. While runoff can be directed back into the house for non-potable use it is expected that the main re-use would be for gardening and other outdoor activities. In areas with expected increase in mean rainfall, this option would become more attractive.

Design guidance for all these structures can be found in the Auckland Council Publication Stormwater Management Devices in the Auckland Region, https://knowledgeauckland.org.nz/media/1703/gd2017-001-stormwater-management-devices-in-the-auckland-region.pdf (19).

7.3.3 | Brazil

7.3.3.1 | *Brazilian Approach to Climate Change Adaption*

Brazilian policy on climate change dates back to 2009 and aims to reduce greenhouse gas emissions, conciliate economic and social development with the protection of the climate system, and implement adaptation measures to climate change impacts. The policy has a broad scope, however climate change impacts on urban drainage and respective adaptation and mitigation alternatives are not mentioned. Even the Brazilian Climate Change Impact Information and Analysis System (AdaptaBrasil MCTI) so far only includes indicators related to drought risk when it comes to climate change impacts on water resources.

In the absence of a national policy related to climate change impacts on urban drainage, it leaves the responsibility to the municipalities to provide urban drainage services, along with water supply, wastewater and solid waste management, to assess, propose and implement strategies for mitigation of impacts. Unfortunately, most municipalities have limited financial, technical and human resources to deal with the already established and widely recognized urban drainage problems. Adopting policies and implementing practices to reduce the adverse effects of climate change on urban drainage is, therefore, a reality for few Brazilian municipalities.

The municipality of Belo Horizonte is among the few Brazilian cities that had a planning of its occupation when it was created between 1894 and 1897. The capital of Minas Gerais state had many decades ago exceeded the initially planned population growth expectations and nowadays it counts 2.7 million inhabitants spread over an area of 331.4 km^2 frequently impacted by urban flash floods. The municipality has a climate change and eco-efficiency Committee and in 2016 developed an assessment of the climate change vulnerabilities in its territory, which identified that landslides, urban floods, dengue disease and heat waves would be the main impacts of climate change. The master plan of the municipality was updated in 2019 and presents the commitment with the adaptation to mitigate the consequences of climate change, which is performed through the mandatory inclusion of permeable areas in lots, or through the mandatory installation of rain barrels and the facultative implementation of green roofs or rain gardens. In order to foster the implementation of the master plan, in 2022, the municipality launched its manual for elaboration of drainage studies and projects, which provides guidelines for the design of runoff source control through nature-based solutions, encourages rainwater harvesting and promotes flood risk management. The manual was elaborated together with the Universidade Federal de Minas Gerais and is available at https://prefeitura.pbh.gov.br/obras-e-infraestrutura/informacoes/publicacoes/instrucao-estudos-e-projetos-de-drenagem.

7.3.4 | Italy

7.3.4.1 | *Italian Approach to Climate Change Adaption*

The adopted National Adaptation Strategy to Climate Change (MATTM, 2015) is consistent with the guidelines for national adaptation strategies set by the European Commission (2013) and includes sustainability principles contained in the Water Framework Directive and the Flood Risk Management Directive. Strategic actions are classified into specific soft, green, and grey measures.

Green measures differ from grey measures because they are "nature-based", that is, they use or sustainably manage natural "services", including the ecosystems ones, to mitigate the impact of climate change. The Italian National Adaptation Plan for Climate Change (MATTM, 2019) is being developed with the support of the Euro-Mediterranean Centre on Climate Change (CMCC). The intent is to provide institutional guidance to national and local authorities for developing regional strategies or plans and the integration of climate change adaptation within spatial and sectoral planning. Based on a robust climate, land, impact, and expected risk analysis for each of the key sectors reported in the strategy, it suggests preferential adaptation actions according to well-established criteria for each of the Italian climatic homogeneous regions.

Regional climate projections show a potential decrease in summer precipitation across the country, while the winter precipitation is expected to increase in the Northern regions. However, regional climate models do not agree on the effects of climate change on precipitation extremes, and detailed analysis of the local conditions is suggested to detect current and future trends.

In the previous decades, stormwater management in urban areas has been addressed by setting rules regionally, aiming mainly at controlling urban development. Regione Lombardia (Northern Italy) recently approved rules to account for the interaction between the two issues, briefly synthesized in the so-called ''hydraulic and hydrologic invariance" concept (BURL, 2017; BURL, 2018; BURL 2019). The ''hydraulic invariance" is ensuring that the peak flow of the surface runoff event is maintained at the pre-urbanization level, while the ''hydrologic invariance" is preserving the runoff event volume. Nature-based solutions are here suggested, together with multi-purpose solutions.

No climate change scenario is requested in the design procedures suggested by regional rules so far. Nevertheless, climatic trends are being investigated in some research projects dealing with sustainable urban drainage (e.g. the national research project URCA – urban resilience to climate change - https://prinurca.wordpress.com/), and high-resolution climate projections (https://www.cmcc.it/it/scenari-climatici-per-litalia) are being provided so that climate-sensitive urban drainage systems can be designed.

7.3.5 | Canada

7.3.5.1 | *Canadian Approach to Climate Change Adaption*

The key element in the design and management of urban drainage infrastructure in Canada includes rainfall intensity-duration-frequency (IDF) relations, which are used to estimate peak surface runoff rates (for sizing of drainage conduits, for instance); and design storm hyetographs (which are commonly used in the design of ponds and large-scale drainage works). ECCC provides standard IDF relations for over 600 climate stations across the country. In current practice, these IDF relations are estimated based on historical data and assume a stationary climate. In the case of coastal flooding, information on rising sea levels and the frequency and intensity of coastal storms is critical. Increasing sea levels may also increase vulnerability to tsunamis and extreme high tides, which will require some other special assessments. Hence, most studies to examine the effect of climate change on flooding in urban areas has focused on these IDF relations. The results predict that, due to the effect of warmer temperatures, there will be more water vapor in the atmosphere with intense precipitation and flooding expected to occur more frequently and with greater severity. The resulting IDF relations will have higher intensities and shorter return periods than those now in use. Increases in the number of flood events exceeding design conditions can result in increased stress to infrastructure and potential reduction in service life. Therefore, it is important to understand how extreme precipitations and, as a consequence, IDF values are changing, and to recognize the state of knowledge, uncertainties, and assumptions in projecting how these extreme events could change in the future.

In Canada, much of the existing urban drainage infrastructures can be broadly classified as providing primary functions of either flow conveyance or storage. Rainfall IDF information is hence a critical input to a number of modeling techniques (e.g., Rational Method; rainfall-runoff models) that are routinely used in the computation of runoff characteristics for the design and management of these conveyance and storage facilities. Traditionally, safely conveying peak flows resulting from extreme rainfall has been the primary focus of design for urban drainage infrastructures currently in use across Canada. More recently, significant efforts have been made to modernize this approach by applying a more holistic understanding of how to manage more effectively the runoffs produced by extreme rainfalls through the use of site infiltration, storage, and water re-use. These activities are essential for improving the system efficiency and resiliency in overall watershed management. In addition to traditional conveyance and/or storage infrastructures, a variety of other infrastructure types are also considered in modern stormwater management, especially in the context of a changing climate. Most of these infrastructures are commonly classified as low impact development (LID) or green infrastructures.

In summary, most urban drainage infrastructures designed in Canada using IDF to date has been designed and built using design information calculated from historical climate data. However, with any increase in the frequency and severity of intense rainfall events in the future, these design criteria may not hold over the planned lifespans of structures. Therefore, different methodologies to incorporate climate change into IDF information have been developed for engineering practice in Canada (CSA, 2019). These methodologies utilize global climate model outputs and are mainly based on dynamic and/or statistical downscaling approaches. In particular, the use of several climate model simulations (a multi-model ensemble approach) is recommended in practical applications in order to better assess the uncertainties inherent in these climate models. Another approach to estimating future extreme rainfall intensities is to apply a 'temperature scaling' factor based on the theoretical Clausius-Clapeyron (CC) relation (~7% per 1°C of warming). This temperature scaling approach is also used as the basis on future changes in rainfall extremes in Australia (Ball et al., 2016). In general, engineers should understand the scientific basis, strengths, and limitations of any given methodology, approach, or tool used to derive future IDF information.

References

1. MLIT(2020a).Water supply and sewerage, Committee on urban flooding countermeasures based on climate change, https://www.mlit.go.jp/mizukokudo/sewerage/mizukokudo_sewerage_tk_000659.html (in Japanese)
2. Hirabayashi, Y., Mahendran, R., Koirala, S., Konoshima, L., Yamazaki, D., Watanabe, S., Kim, H. and Kanae, S. (2013). Global flood risk under climate change, Nature Climate Change, volume 3, pages 816–821
3. Mizuta, R., Murata, A., Ishii, M., Shiogama, H., Hibino, K., Mori, N., Arakawa, O., Imada, Y., Yoshida, K., Aoyagi, T., Kawase, H., Mori, M., Okada, Y., Shimura, T., Nagatomo, T., Ikeda, M., Endo, H., Nosaka, M., Arai, M., Takahashi, C., Tanaka, K., Takemi, T., Tachikawa, Y., Temur, K., Kamae, Y., Watanabe, M., Sasaki, H., Kitoh, A.,Takayabu, I., Nakakita, E. and Kimoto M. (2017). Over 5000 years of ensemble future climate simulations by 60 km global and 20 km regional atmospheric models. Bull. Amer. Meteor. Soc. July 2017, 1383-1398
4. Kawase, H., Nosaka, M., Watanabe, S. I., Yamamoto, K., Shimura, T., Naka, Y., Wu Y.-H., Okachi, H., Hoshino, T., Ito, R., Sugimoto, S., Suzuki, C., Fukui, S., Takemi, T., Ishikawa, Y., Mori, N., Nakakita, E., Yamada, T. J., Murata, A., Nakaegawa, T. and Takayabu,I. (2023). Identifying Robust Changes of Extreme Precipitation in Japan From Large Ensemble 5-km-Grid Regional Experiments for 4K Warming Scenario. J. Geophys. Res. Atmos., 128, https://doi.org/10.1029/2023JD038513
5. Kobayashi, K., Tanaka, T., Shinohara M. and Tachikawa, Y. (2020). Analyzing future changes of extreme river discharge in Japan using d4PDF, Journal of Japan Society of Civil Engineers, Ser. B1 (Hydraulic Engineering), Volume 76 Issue 1 Pages 140–152 (in Japanese with English abstract)
6. Kobayashi, K., Tanaka, N., Maruyama, K., Tanaka, S., Watanabe, S. and Kitano, T. (2021). Simulation of Arakawa middle stream flood due to Typhoon 19 2019, Journal of Japan Society of Civil Engineers, Ser. B1 (Hydraulic Engineering), Volume 77 Issue 2 Pages I_1393-I_1398 (in Japanese with English abstract)
7. MLIT, Technical Study Group on Flood Control Plans Based on Climate Change(2019). Overview: Flood Control Planning Based on Climate Change, https://www.mlit.go.jp/river/shinngikai_blog/chisui_kentoukai/index.html(in Japanese)
8. National Institute for Land and Infrastructure Management (NILIM, MLIT) (2022). Technical Note on the Rate of Change in Heavy Rainfall Intensity for Flood Control Planning to Cope with Climate Change, Technical Note of NILIM, No. 1205 https://www.nilim.go.jp/lab/bcg/siryou/tnn/tnn1205pdf/ks1205.pdf (in Japanese)

9 MLIT (2024a). Design of Tsurumigawa River, https://www.ktr.mlit.go.jp/keihin/keihin_index019.html (in Japanese)

10 MLIT (2024b). Promotion of river basin flood control, https://www.mlit.go.jp/river/kasen/suisin/index.html (in Japanese)

11 Shiga Prefecture (2014). Shiga Prefecture Ordinance on Promotion of Basin Flood Control, https://www.pref.shiga.lg.jp/file/attachment/5374500.pdf(in Japanese)

12 MLIT (2024c). Measures against flooding by sewerage, https://www.mlit.go.jp/mizukokudo/sewerage/crd_sewerage_tk_000117.html (in Japanese)

13 MLIT (2007). Regarding the situation of recent rainfall and inland water damage, and the current status of sewerage development,. https://www.mlit.go.jp/mizukokudo/sewerage/content/001320996.pdf (in Japanese)

14 MLIT(2020b). The Metropolitan Outer Area Underground Discharge Channel, https://www.ktr.mlit.go.jp/ktr_content/content/000812778.pdf (in Japanese)

15 Osaka Prefecture (2021). Northern underground river of the Neya River, https://www.pref.osaka.lg.jp/o130360/ne/kouji/hokubu.html (in Japanese)

16 MLIT (2019).Overview of the Green Infrastructure Promotion Strategy, https://www.mlit.go.jp/sogoseisaku/environment/content/001613868.pdf (in Japanese)

17 Himeji City (2023). Himeji City Rainwater Management Comprehensive Plan, https://www.city.himeji.lg.jp/kurashi/0000023868.htm

New Zealand sections

18 Ministry for the Environment (2018). Climate Change Projections for New Zealand: Atmosphere Projections Based on Simulations from the IPCC Fifth Assessment, 2nd Edition. Wellington: Ministry for the Environment.

19 Auckland Council (2017). Stormwater Management Devices in the Auckland Region, https://knowledgeauckland.org.nz/media/1703/gd2017-001-stormwater-management-devices-in-the-auckland-region.pdfdownloaded June 2026

Latin America and the Caribbean, Brazil sections

20 Cavalcanti, I.F.A.; Ferreira, M.; Assunção, F. Da S.D.; Gertrudes, A.; Silva, J (2009). Tempo e Clima no Brasil. São Paulo: Oficina de Textos, p. 182. 2009.

21 Christensen, J.H., B. Hewitson, A. Busuioc, A. Chen, X. Gao, I. Held, R. Jones, R.K. Kolli, W.-T. Kwon, R. Laprise, V. Magaña Rueda, L. Mearns, C.G. Menéndez, J. Räisänen, A. Rinke, A. Sarr and P. Whetton, 2007: Regional climate projections. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B.Averyt, M. Tignor and H.L. Miller, Eds., Cambridge University Press, Cambridge, 847-940.

22 IPCC, 2022: Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Inter-governmental Panel on Climate Change [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegriía, M. Craig, S. Langsdorf, S. Löschke, V. Mo?ller, A. Okem, B. Rama (eds.)]. Cambridge University Press. Cambridge University Press, Cambridge, UK and New York, NY, USA, 3056 pp., doi:10.1017/9781009325844.

23 Magrin, G., C. Gay García, D. Cruz Choque, J.C. Giménez, A.R. Moreno, G.J. Nagy, C. Nobre and A. Villamizar, 2007: Latin America. Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.E. Hanson, Eds., Cambridge University Press, Cambridge, UK, 581–615.

24 OCHA, 2020. Natural Disasters In Latin America And The Caribbean 2000–2019. United Nations Office for the Coordination of Humanitarian Affairs, Panama: 20 p.

25 PBMC, 2013a. Executive summary: scientific basis of climate change - Contribution from Grupo de Trabalho 1 (GT1, acronym for the Working Group 1) to the Primeiro Relatoírio de Avaliacaoo Nacional sobre Mudancas Climaíticas (RAN1) of the Painel Brasileiro de Mudanc?asClimaíticas (PBMC) [Ambrizzi, T., Araujo, M. (eds)] COPPE. Universidade Federal do Rio de Janeiro, Rio de Janeiro, RJ, Brasil, 24 pp.

26 PBMC, 2013b. Executive Summary: Impacts, Vulnerability and Adaptation to Climate Change. Contribution from Grupo de Trabalho 2 (GT2 – acronym for the Working Group 2) to the Primeiro Relatoírio de Avaliacapo Nacional sobre Mudancas Climaíticas (RAN1) of the Painel Brasileiro de Mudancas Climaíticas (PBMC). [Assad, E.D., Magalhãpes, A. R. (eds.)]. COPPE. Universidade Federal do Rio de Janeiro, Rio de Janeiro, RJ, Brasil, 28 pp.

Italian sections

27 Beck, H.E., Zimmermann, N.E., McVicar, T.R., Vergopolan, N., Berg, A. & Wood, E.F. (2018) Present and future Köppen-Geiger climate classification maps at 1-km resolution. Scientific Data, 5, 180214. doi: 10.1038/sdata.2018.214.

28 BURL - Bollettino Ufficiale Regione Lombardia (2017) Regolamento Regionale 23 novembre 2017, n. 7: "Regolamento recante criteri e metodi per il rispetto del principio dell'invarianza idraulica ed idrologica ai sensi dell'articolo 58 bis della legge regionale 11 marzo 2005, n. 12 (Legge per il governo del territorio)", 48, suppl. del 27 Novembre 2017.

29 BURL - Bollettino Ufficiale Regione Lombardia (2018) Regolamento Regionale 29 giugno 2018, n. 7: "Disposizioni sull'applicazione dei principi dell'invarianza idraulica ed idrologica. Modifica dell'articolo 17 del regolamento regionale 23 novembre 2017, n. 7", 27, suppl. del 03 Luglio 2018.

30 BURL - Bollettino Ufficiale Regione Lombardia (2019) Regolamento Regionale 19 aprile 2019, n. 8: "Disposizioni sull'applicazione dei principi di invarianza idraulica ed idrologica. Modifiche al regolamentoregionale 23 novembre 2017, n. 7", 17, suppl. del 24 Aprile 2019

31 Grossi, G., Barontini, S., Berteni, F. Balistrocchi, M., Ranzi, R. 2020. "Nature-based solutions as climate change adaptation and mitigation measures in Italy" in Climate Change-Sensitive Water Resources Management, CRC Press, ISBN9780429289873.

32 ISPRA- Istituto Superiore per la Protezione e la Ricerca Ambientale (2019) Stato dell'Ambiente 88/2019, Gli indicatori del clima in Italia nel 2018, ISBN 978-88-448-0955-3

33 MATTM-Ministero dell'Ambiente e della Tutela del Territorio e del Mare-Direzione Generale per l'Energia e il Clima (2015) Strategia nazionale di adattamento ai cambiamenti climatici. Available from: http://www.pdc.minambiente.it/sites/default/files/allegati/Strategia_nazionale_adattamento_cambiamenti_climatici.pdf [Accessed 12th November 2019].

34 MATTM-Ministero dell'Ambiente e della Tutela del Territorio e del Mare-Direzione Generale per l'Energia e il Clima (2019) Piano nazionale di adattamento ai cambiamenti climatici. Available from: https://www.minambiente.it/sites/default/files/archivio_immagini/adattamenti_climatici/documento_pnacc_luglio_2017.pdf [Accessed 12th November 2019].

Canada Sections

35 Ball, J., Babister, M., Nathan, R., Weeks, W., Weinmann, E., Retallick, M., &Testoni, I. (Eds.) (2016). Australian Rainfall and Runoff: A Guide to Flood Estimation, Commonwealth of Australia.

36 CSA (Canadian Standard Association). (2019). Technical guide: Development, interpretation, and use of rainfall intensity-duration-frequency (IDF) information: Guideline for Canadian water resources practitioners, CSA PLUS 4013:19, Canadian Standard Association, Toronto, Ontario, Canada, 126 pages.

37 Nunn P D Climate Change and Pacific Island Countries (2017), Asia-Pacific Human Development Report Background Papers Series 2012/07.

CHAPTER 8

Adaptations for Dams and Reservoirs to Climate Change

Deghyo Bae
Dep. of Civil and Environmental Engineering, Sejong University, South Korea.
E-mail: dhbae@sejong.ac.kr

Hyun-Han Kwon
Dep. of Civil and Environmental Engineering, Sejong University, South Korea.
E-mail: hkwon@sejong.ac.kr

Yangwen Jia
Dep. of Water Resources, Institute of Water Resources and Hydropower Research, China.
E-mail: jiayw@iwhr.com

8.1 | Introduction

Water is a vital basic need for all living things, and managing existing water resources to meet the demand is crucial. Further, storing water is a necessity in many countries for water supply and flood management due to the spatial and temporal variability of the available water. For these purposes, dams and reservoirs were built to store and supply water in different sectors (i.e., domestic, industrial, hydropower, irrigation, and ecosystems). As climate conditions continue to shift due to climate change, the design and operation of dams and reservoirs face unprecedented challenges. These infrastructures are increasingly experiencing various operational and structural issues that lead to risks and vulnerabilities in how we handle water. Therefore, this chapter aims to guide us in the context of climate change on the retrofit of old dam designs and operations to address the current and future critical issues and challenges that many countries across the world may encounter.

This includes a summary of existing practices and projections for climate change, and the physical impact on the construction, maintenance, and functionality of dams in a changing climate. The risk associated with aging water storage infrastructure is one concern to investigate. Further, this chapter aims to develop frameworks and guidance documents for operators, owners, and policymakers to offer a general procedure to assess, plan, and design dams and reservoirs in consideration of climate change. Finally, the chapter explores recommendations for the following three components a) understanding gaps in current planning practice in a warmer climate, b) opportunities to improve planning and design concepts, and c) a research agenda for a way forward.

8.2 | Expected Climate Change

The global climate is manipulated and controlled by the dynamic interactions between oceans, land masses, and the atmosphere, and their corresponding contributions to changes in the distribution of heat flow (United Nations, 2013). Most heat changes occur in the oceans, and variations in sea surface temperatures (SSTs) are considered the direct indicator of climate change. Nonetheless, the 6th assessment report (AR6) of the Intergovernmental Panel on Climate Change (IPCC) declared that anthropogenic activities warmed the ocean, atmosphere, and land, due to greenhouse gases (GHG) (IPCC, 2021).

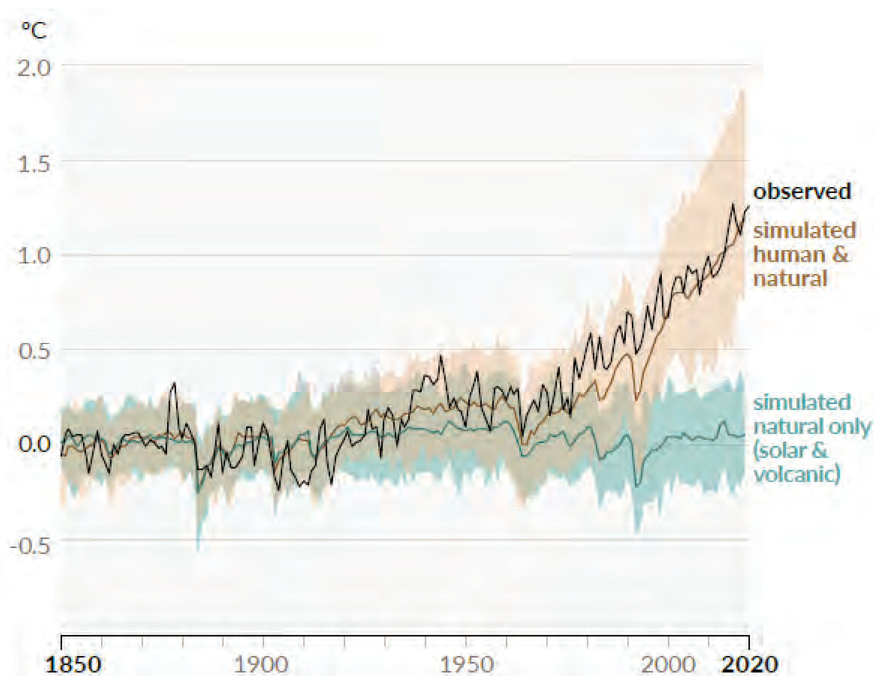


Figure 8.1 | Changes in observed and simulated (i.e., using human & natural and only natural factors) annual average global surface temperature from 1850–2020 (Source: IPCC, 2021).

The concentration of GHG in the atmosphere showed a continuous significant increase in 2019 compared to 2011:the mean annual concentrations of CO_2, CH_4, and N_2O increased from 19 ppm to 410 ppm, 63ppb to 1866 ppb, and 8 ppb to 332 ppb during 2011–2019, respectively (IPCC, 2021). Further, land and oceans absorb annually around 56% of CO_2 emitted from human activities. The global surface temperature (i.e., the sum of global mean surface temperature and global surface air temperature) has increased substantially during 1980–2020 compared to the rate in the 1850s. Global air temperatures over land surfaces have increased at about double that of the rate of the oceans' (Sivakumar and Stefanski, 2011). Moreover, the global surface temperature increased by 0.99° C and 1.09° C during the periods of 1980–2000 and 2000–2020, respectively, compared to the reference 1850–1900 period. Significantly, human intervention likely accelerates the increase in global surface temperature these days (Figure 8.1). Though the increase in surface temperature on land is more substantial than the increase in the sea surface temperatures (SSTs), anthropogenic activities caused an increase in SSTs between near-surface ocean layers (0 – 700 m) and an increase in salinity and acidity in the ocean waters (IPCC, 2021). Further, it is interesting that humans influence more strongly the melting of snow cover in the Northern Hemisphere compared to the Antarctic glacier cover. The melting of snow cover has led to global sea-level rise (SLR) and has been demonstrated to be increasing significantly at 1.3 mm/year, 1.9 mm/year, and 3.7 mm/year, with high significance during 1901 – 1971, 1971 – 2006, and 2006 – 2018, respectively (IPCC, 2021).

Precipitation has significantly increased since the 1950s, however the increasing rate of increase has declined slightly since the 1980s with moderate significance. Furthermore, the intensity and frequency of extreme rainfall has increased substantially. Interestingly, warming caused by GHG emissions has been shown to increase monsoon precipitation in South Asia, East Asia, and West Africa. Monsoon precipitation gradually decreases in response to increasing the emission of human-caused aerosols. Naveendrakumar et al. (2019) explored rainfall and temperature trends observed in South Asia and reviewed the methods used for the trend analysis. Further, compound extreme weather events such as heatwaves, floods, drought, and fire weather conditions have increased since the 1950s. Low-temperature extremes are less common in Europe because of the increase in heatwaves. The mean duration of summer heatwaves and the number of warm days in Western Europe have increased significantly (EEA, 2011). The duration of heat waves is also prolonged in South Asian regions (Sivakumar and Stefanski, 2011; Chandrasekara et al., 2021). The occurrence of tropical cyclones has been increasing since the 1980s, and the spatial occurrence of highly intensified tropical cyclones shifted from the western North Pacific to northward (IPCC, 2021).

8.3 | Climate Change Impacts on Dams and Reservoirs

8.3.1 | Hydrological Changes due to climate change

Monitoring climate change impacts over dams and reservoirs is essential where the frequent modification of water management strategies, including reservoir operation, is often required in a changing climate. The inflow from the Dez dam water basin, Iran, including sub-basins of Tire, Marbore, Sazar, and Bakhtiari sub-basins, experienced a significant decrease trend due to the reduction in summer rainfall based on the Nonparametric Mann-Kendal test, Pettit and Buishand test (Norouzi, 2020). Further, a considerable decrease in winter runoff was identified for the Yellow River in China (Hu et al., 2011) and Sanguwa rivers (Lee et al., 2014), impacting water availability. Jung and Kim (2017) identified water shortages during droughts in South Korea, and severe negative impacts were identified in the Boryeong Dam, South Korea.

Recent reviews of the South Asian monsoon system underscore the complex interplay between ocean-land temperature gradients, atmospheric circulation, and topographic influences. Climate change is projected to enhance total rainfall due to increased atmospheric moisture, yet concerns persist regarding a potential weakening of monsoon circulation. Such changes could significantly affect the hydrological cycle, especially in monsoon-dependent regions. Additionally, the role of aerosols and greenhouse gases introduces further variability in monsoon behavior, complicating water resource planning and reservoir operations. These dynamics highlight the urgency of refining climate models and observational tools to improve projections of extreme hydrological events and seasonal shifts (Fiaz et al., 2025).

Recent studies have highlighted the increasing vulnerability ofdams and reservoirs to floods due to increased extreme precipitation events. For instance, the EPA (2021) identified trends in the flow based on the indicator using the annual maximum discharge of a station, indicating a rise in peak flows associated with climate change. Yun et al. (2021) developed a model combining the hydrological variable infiltration capacity model and the reservoir module to understand the impacts of climate change on reservoir operations in the Lancang-Mekong River Basin, China. Interestingly, the study revealed that the upstream reservoirs were deficient in generating hydropower compared to the downstream reservoirs. Dam safety in the Himalayas regions is questionable because historical streamflow data on reservoir routing is not available to predict floods due to glacial melting (International Rivers, 2011).

Yasarer and Sturm (2016) stated that comprehensive studies had been undertaken from the perspective of climate change-induced water availability in reservoirs. Still, there is a limitation in studies that focus on climate change-influenced water quality degradation in reservoir waters. The sediments derived from stream bank erosion of Perry Lake, Kansas, could impact the degradation of reservoir water quality more than the sediments originating from surface soil (Juracek and Ziegler, 2009). Further, an increase in river bank and bed erosion can be associated with extreme rainfall under climate change (Seneviratne et al., 2012). More specifically, extreme rainfall events contribute more to erosion because high-intensity rainfall causes more erosion; for example, five extreme rainfall events in the Ohio watershed contributed to 66% of total erosion (Edwards and Owens, 1991). Additionally, sediment transportation increases during extreme rainfall events. For example, the seven storms observed in 2010 upstream of Kanopolis Lake, Kansas, related to 88% of total suspended sediments (Juracek, 2011).

In summary, climate change is likely to increase the severity, scale, and frequency of droughts and extreme precipitation. It is recommended to quantify hydrologic changes, including water inflows, flood and drought frequencies, and sedimentation in dams and reservoirs due to climate change using monitoring data. Parametric regression is a practical technique to track mean trends, but it ignores distributional changes at upper and lower tails, which are more effective than the mean trend in extreme climate studies. In this regard, a quantile regression has been used to provide a complete picture of long-term temporal trends (Uranchimeget al., 2018; Uranchimeget al., 2020). Moreover, parametric distribution approaches could be more efficient for normally distributed residuals, while the nonparametric approach is more robust, with residuals departing from normality (Kwon et al., 2007a; Kwon et al., 2007b; Kim et al., 2015; Lima et al., 2018).

8.3.2 | Structural Changes in dams and reservoirs due to climate change

The increased demand for water in dynamic water availability circumstances sparked the need to construct reservoirs and dams around the world. Hence, several dams were built more than 100 years ago (Figure 8.2), especially in the USA and Europe. Notably, most dams and reservoirs exceeded their active life span and have aged, causing numerous mechanical deformities and unsafety to living and non-living systems. Further, some dams and reservoirs were built for a certain life span where the impact of climate change was not considered while designing their life span. This could lead to massive economic, social and environmental risk to a country (Kraljevic, 2013).

Dams are structurally sensitive to most climate-related impacts. Notably,concrete dams, including arch-type dams, can be directly affected by changes in temperature, precipitation, and solar radiation

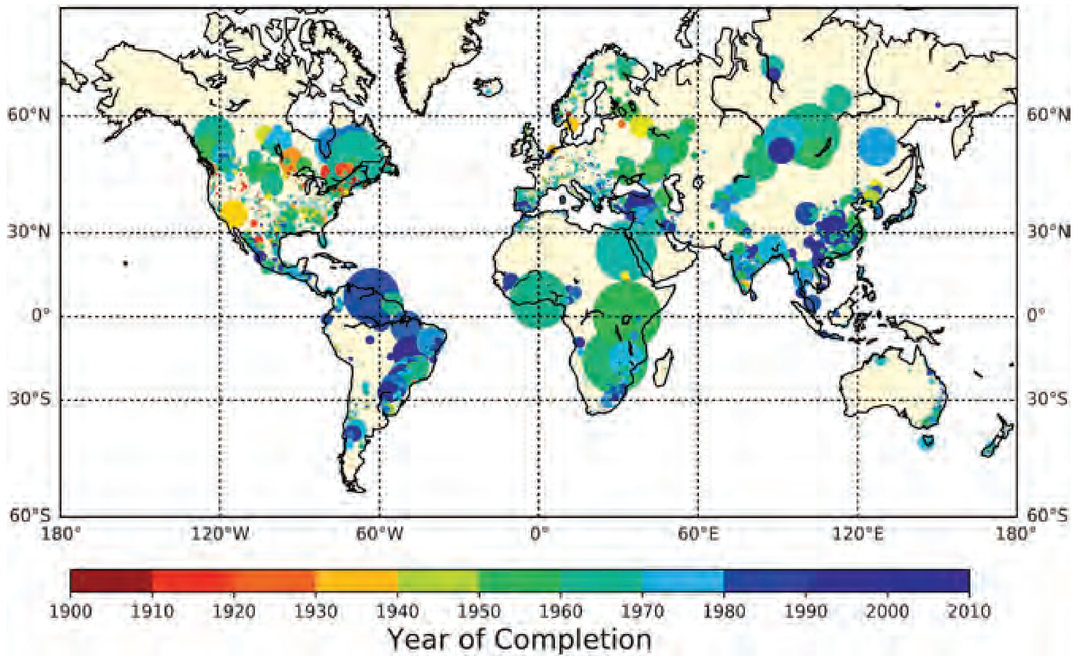


Figure 8.2 | The capacities and the year of dam completion for the dams which had been completed by 2010 in the world (The color shows the year of completion of the dams, and the size of the circle illustrates the capacity of the reservoir), Source: Lehner et al., 2011.

(FERC, 1999; Malm, 2016). Temperature is typically expected to increase under climate change and may have more significant impacts with more frequent extreme values (IPCC, 2021). Moreover, the potential variation in water storage in a reservoir can lead to increased exposure of the dam to solar radiation (both in duration and surface of exposure). In addition, an increase in temperature difference and maximum temperature is likely to affect damage to the surface of the concrete. More importantly, these issues can eventually expose the dam to mechanical stresses, thus making it more vulnerable to hydrostatic loads. In these circumstances, traditional stability analyses may be insufficient to assess whether increasing temperatures and solar radiation can influence the failure probabilities related to structural reliability, and more rigorous approaches should then be adopted. Similar concerns should be considered in other failure modes such as over topping and internal erosion) that can be influenced by climate change.

8.3.3 | Climate Change Impacts on Dams and Reservoirs

In addition to structural considerations (Section 8.3.2) and hydrological changes (Section 8.3.1), it is also crucial to synthesize the various ways in which climate change can impact dams and reservoirs. As summarized in Table 8.1, climatic factors, such as extreme temperature and precipitation events, droughts, floods, and glacial melting, can threaten the structural stability, operation, and reliability of water storage and hydropower facilities. For instance, precipitation variability can reduce inflows during dry spells, reducing water supply or hydropower generation while simultaneously causing damaging floods in wetter periods. Such variability exacerbates the challenge of determining design capacities, flood control.

Further, extreme temperature and precipitation events can threaten dam safety by intensifying erosion, sediment transport, and siltation in reservoirs, ultimately reducing their capacity and efficiency. These events can also precipitate over topping and structural damage in older earth-fill or smaller community-based dams that were never designed for higher runoff volumes. Meanwhile, glacial melting in colder regions adds additional uncertainty: melting ice accelerates sediment transfer into reservoir basins, leading to infrastructure wear and reduced storage capacity. Additionally, permafrost thaw in high-latitude regions can alter groundwater connectivity and release further sediment, posing new operational and engineering challenges.

Collectively, these climatic impacts highlight the need to adopt more adaptive and resilient strategies in designing, managing, and rehabilitating dams and reservoirs. Strategies might include integrating real-time monitoring to detect changing inflows, adopting innovative sediment management techniques, and upgrading dams and spillways for future flood extremes. Ultimately, recognizing the interconnected nature of these impacts, rather than treating each in isolation, can guide more robust approaches to reservoir safety, reliability, and ecological sustainability under a changing climate.

8.3.4 | Estimation of Climate Change Impacts on Dams and Reservoirs

The World Meteorological Organization (WMO) have recommended a) statistical method, b) generalized method, c) transposition method and d) moisture maximization method to calculate probable maximum precipitation (PMP) to investigate safety design standards at stationary climate. Chen and Hossain (2019) discuss the efficiency of PMP calculations for future dam safety. However, a stationary assumption on climate baselines is no longer suitable in a changing climate to assess dam safety (USACE, 2016). Interestingly, recently constructed dams and reservoirs have been built considering climate change, and therefore their life spans became different from historical ones (Arnell and Hulme, 2006). Therefore, frequent updating of the design flood calculation for new reservoirs is mandatory

Table 8.1 | Indicative climate change impacts on dams and reservoirs.

Climate change factors	Examples of impacts	Source
Precipitation variability	• Generation of hydropower declines due to a decrease in streamflow to the reservoir in low rainfall periods. • Loss of fish habitat and damage to the livelihood of the community	Cherry et al., 2017
Extreme temperature and precipitation events	• Difficulty in deciding construction and management criteria for reservoirs, such as design capacity, flood control, water spilling, and flood routine strategy. • Further, water wastage without using it for hydropower generation during extreme rainfall periods because of the spilling of reservoir water. • High sedimentation and siltation. Eutrophication due to sediment-bound nutrients. • Portioning of runoff into surface and groundwater • Older earth-fill dams that have erodible embankments tend to cause rainfall erosion during high rainfall events. Damages to downstream communities if dams break. • High temperatures may add additional mechanical stress to the concrete dams	Cherry et al., 2017; Vahedifard et al., 2017; Hughes and Hunt, n.d.; Sutton, 2019; Toniolo and Schultz, 2005; Rahman et al., 2025
Variabilityin air temperature	• Reduction of available water in reservoirs during following spring due to increase in autumn air temperatures in the Far North. Further, warming increases rain during winter and exceeds the capacity of the reservoirs in the northern reservoirs..	Cherry et al., 2017
Floods	• Exceeding the reservoir's existing capacity and emergency spillway may cause a devastating situation to downstream infrastructures and lives. Inundation impacts upstream infrastructures and lives. High GHG emissions such as methane from inundated vegetation. • Transporting catchment debris and vegetation may damage the outflow structures and spillways, and their performances • Deterioration of water quality in the reservoir, marginal vegetation conditions and fishery functions	Cherry et al., 2017; Hughes and Hunt, n.d.; Scherer and Pfister, 2016; Yasarer and Sturm, 2016; Kim et al., 2024
Droughts	• Generation of hydropower declines due to a decrease in streamflow to the reservoir. • Changes in micro-climate and increased evapotranspiration in reservoirs. • Heat-induced expansion of hydraulic structures	Cherry et al., 2017; Charalampos, S., et al. (2013); Kwon et al., 2016; Ho et al. (2017)
Glacial melting	• The discharge from the glaciers melt runoff is not even throughout the process and it is difficult to design and manage the hydropower reservoirs. Sometimes unexpected floods are also observable. • Discharge of large quantities of sediments leads to a reduction inthe storage capacity of a reservoir and wears off the hydrological structures. • Changes in pattern and frequency of the ice blockages and jams damage the hydrological structures. The melting of ice jams and associated flooding increase the quantity of water within the reservoir.	Cherry et al., 2017; Gurnell, 1995; Harrison et al., 1983; Gebre et al., 2013; Bergstrom et al., 2001; Prowse and Beltaos, 2002; US Department of Energy, 2017
Permafrost thaw	• An expected increase in subsurface storage and connectivity • High sediment release to the waterways due to thermal and water-driven soil erosion leads to a reduction of reservoir capacity and damage to hydrological structures	Cherry et al., 2017; Toniolo and Schultz, 2005; Gurnell, 1995
Polar amplification	• Accelerated warming in polar regions, especially the Arctic region, weakens the mid-latitude circulation and causes hot-dry extremes in mid-latitudes. These phenomena lead to heatwaves in the mentioned regions and may impact reservoirs and dams.	Coumou et al., 2018

in order to safeguard the safety of a dam. Further, simultaneous sensitivity analysis is also required to design floods for a future climate change scenario. The following section will explore in detail specific examples of such dams, and the methodologies employed to integrate climate resilience into their design and management.

8.3.4.1 | *Long-term Water Availability Evaluation*

Chung et al. (2011) identified that there would be negative changes in inflow and water storage in a group of multipurpose dams in the Han River due to climate change. Further, Gohari et al. (2014) predicted that water would be deficient for agriculture in Iran due to the reduction of available water in the Chadegan reservoir in the Zayandeh-Rud River basin, Iran. The future water capacity of the Gwanghye reservoir was evaluated based on RCP 4.5 and 8.5 climate change scenarios using the reservoir simulation process under two different conditions: a) before and b) after the heightening of the embankment (Lee and Shin, 2021). The study revealed that heightening the embankment can be an effective strategy to supply the irrigation water requirement in Korea.

The hydropower impact assessment for the USA was done using modeling of water availability by dynamically downscaling sub-daily atmospheric data under an ensemble of 10 IPCC AR5 GCM at RCP 8.5 scenario. GCM signals were downscaled using RegCM4 for both the historical (1966–2005) and future (2011–2050) periods. The Variable Infiltration Capacity hydrological model (VIC) is used to simulate future water availability for hydropower generation. The lumped Watershed Runoff–Energy Storage model was developed to analyze annual, multiannual, daily, and seasonal generation under different climate change scenarios. The study revealed an increase in winter and spring hydropower generation and a decrease in summer and fall generation (US Department of Energy, 2017).

In summary, studies on long-term water availability indicate a reduction in inflow and water storage. Some studies suggest heightening the dam as an alternative solution to the water supply shortage. Furthermore, these reductions due to climate change led to differences in seasonal hydropower generation.

8.3.5 | Flood-Risk Evaluation (or Dam Safety)

Risk assessment and water infrastructure design for extreme rainfall and flood mitigation have traditionally relied on calculating the Probable Maximum Precipitation (PMP) and Probable Maximum Flood (PMF). These methods typically assume a stationary climate when designing critical dam features for worst-case scenarios. However, climate change is increasingly challenging this assumption, as static PMP and PMF values no longer reflect evolving hydrological conditions (Visser et al., 2022).A study conducted in the Upper American, Owyhee, and Holston River watersheds, encompassing the Folsom, Owyhee, and South Holston dams, emphasized the need to re-evaluate older dams originally designed with fixed PMP and PMF standards. The research found that climate change and land-use alterations have already affected current PMP values, making the previous assumptions outdated. Further, it proposed employing a dynamic PMP approach in the design of future dams to better account for changing climatic and watershed conditions (Stratz and Hossain, 2014).

The design flood can be calculated using a) flood frequency approach with observed or simulated inflow series and b) precipitation-runoff method – design rainfalls from frequency analysis and their uses for estimating design floods from hydrologic models (Killingtveit and Saelthun, 1995; NVE, 2011). Nonetheless, the precipitation-runoff approach is more desirable than the flood frequency analysis because a) uncertainty is relatively low, and b) precipitation is easily interpolated and regionalized using established regional methods (Saelthun and Anderson, 1986). However, the reliability of these techniques depends on specific regional characteristics and data availability and quality. Lawrence et al. (2012) summarized the projected changes in quantity, seasonality, and uncertainties in floods in the Netherlands, Norway, and Sweden. Notably, many studies have revealed that projected flooding patterns are not uniform for the entire country, and regional differences in climate conditions and watershed characteristics have mainly influenced these differences (Veijalainen et al. 2010). Chernet et al. (2014) and Mailhot and Duchesne (2010) described the studies carried out to investigate the impact of climate change on hydrology using different methods. Reservoir simulation under varying climate change scenarios could be an efficient way to understand the corresponding changes in future water surface elevations in reservoirs. Sutton (2019) carried out a similar study for the Central Appalachian Ecoregion, West Virginia. Niu and Shah (2018) developed an optimal control model for Jinsha Dam and Aswan High Dam in China and Egypt, respectively, to design the optimal size of a dam under future climate change scenarios. The LISFLOOD model, which is a hydrological rainfall-runoff and channel routing model, can be used for flood forecasting under climate change scenarios. Further, it can assess river regulation measures and the effects of land-use changes on floods. The detailed simulation process of LISFLOOD is available in the manual prepared by the European Union (2013).

State-of-the-art methods for evaluating climate change impacts on dam safety now emphasize risk-based, comprehensive approaches that move beyond traditional stationary assumptions. Fluixa-Sanmartin et al. (2018) provide a succinct overview of contemporary assessment methods, including climate projections, downscaling techniques, fault-tree analyses, and revised flood routing and inundation models. They also underscore the importance of considering socio-economic consequences in a changing climate. Addressing the inherent uncertainties in modeling extreme events, researchers have increasingly adopted non-stationary flood frequency analysis and stochastic weather generators to capture non-independence and non-stationarity in hydrologic data. Such risk assessments are further refined by explicitly incorporating uncertainties from diverse sources, such as climate models, downscaling methods, and hydrological model structures.

Beyond advanced modeling, climate-driven processes that affect dam infrastructure also demand close attention. Sedimentation, a natural aging phenomenon in reservoirs, is highly sensitive to extreme weather events. As storms intensify, they accelerate sediment transport, hastening reservoir capacity loss. A recent UN warning suggests that the world's large dams may lose about a quarter of their capacity by 2050 due to climate change (The Guardian, 2023). Shifts in precipitation patterns and escalating extreme weather events introduce additional sediment—particularly following wildfires, which destabilize soils and multiply sediment loads. For example, post-fire erosion in a California watershed magnified sediment transport by three to four times after combined wildfire and flood events (East et al., 2024). Diminished storage capacity under these conditions imperils water supply, flood control, and ecosystem health, underscoring the urgency of planning dam management and design strategies that can withstand increasing flood risks.

Finally, effective dam-safety planning leverages both precipitation-runoff and flood event frequency analyses, each offering distinct strengths and limitations. Numerous studies apply hydrologic simulations under various climate scenarios to identify flood-risk dynamics and compute anticipated water-surface elevations in reservoirs. LISFLOOD, for instance, can evaluate the interplay of river regulation and land-use changes on floods. Socio-economic considerations of climate change and sedimentation must also be woven into these simulations to create holistic dam-safety policies. Notably, Wild (2014) demonstrated how alternative locations, designs, and operating policies could significantly enhance sediment passage through reservoirs in the Mekong River system, although these improvements can require considerable energy investments. Altogether, an integrated approach that combines robust hydrological modeling, infrastructure design, and socio-economic analyses is essential for maintaining dam resilience in the face of evolving climatic conditions.

8.4 | Recommendations for the Adaptation of Dams and Reservoirs to Climate Change

8.4.1 | Technical and Structural Adaptations

Adaptation to climate change could be defined as a process that governs the decrease of damage and understands the benefits associated with climate variability and climate change(Smitand Pilifosova, 2003). Though there are numerous adaptation strategies available for a changing climate, the adaptive capacity of the system determines the efficiency of the proposed adaptation strategy. Further, the adaptation strategies are categorized as either a) policy, planning, and assessment, b) design and construction, and c) operation and maintenance of the dams and reservoirs.

8.4.1.1 | *Reservoir Operation and Modeling Tools*

Adaptation options related to changing the operation of a reservoir has the potential to mitigate the impact of climate change on some dams and reservoirs. The application of a comprehensive modeling framework for reservoir operation could be helpful in understanding the effectiveness of adaptation measures for a certain climatic scenario. Examples of such models are VMod regional hydrological model (Lauri et al., 2012), LPJmL global hydrological model (Biemans et al., 2013), Hydrologic Simulation Program Fortran (HSPF) (Donigian et al., 1995), Agricultural Non-Point Source Pollution Model (AGNPS) (Young et al., 1989) and Soil and Water Assessment Tool (SWAT) (Douglas-Mankin et al. 2010). Yasarer and Sturm (2016) summarize the mathematical and statistical tools used to identify the impacts of climate change on reservoirs. Feldbauer et al. (2020) used the hydro-physical General Lake Model and identified that the withdrawal rate or stored volume of a reservoir affected the spatiotemporal variation of water temperature. Further, this study identified that the effectiveness of the withdrawal method depends on the withdrawal rate and downstream water. Therefore, an adaptation of an efficient withdrawal strategy would make the best thermal stratification in a reservoir and could minimize the water quality deterioration due to climate change. Gopalan et al. (2020) discussed previous studies on the application of hydrological models to determine adaptive strategies for dams and reservoirs to climate change. However, with limited available data, the complexity of the reservoir operational plans and new adaptive plans could drawback the application of hydrological models as a means of understanding adaptive measures for climate change.

The design criteria adopted for most of the recent reservoirs cannot bear the different regimes of streamflow due to climate change. Therefore, it is essential to consider different adaptation strategies, and a combination of reservoir operation and afforestation could be an effective adaptation strategy. Further, adapting modified structures or rehabilitation would also adapt dams and reservoirs for climate change (Gopalan et al., 2020). The increase in the height of the embankment of agricultural reservoirs was implemented in 2009 by the Korean Government of Korea to safely supply the required amount of water during dry seasons (Lee and Shin, 2021). The application of a comprehensive modeling framework for reservoir operation could be helpful in understanding the effective adaptation measures for a particular climatic scenario.

8.4.1.2 | *Structural and Material Design Enhancements*

To ensure future flexibility, design standards should incorporate non-erodible structures (e.g., concrete or masonry), to prevent the increased erosion of embankments due to extreme fluctuations in water levels, as well as physical changes such as erosion during extreme wet and hot weathers. Furthermore, the selection of construction materials, including concrete joints, aggregates, and derived products, must account for the proven effects of aging and climate change, particularly those caused by UV radiation and elevated temperatures (Atkins, 2013).

With regard to the issue of sedimentation, cost-effective frameworks for sediment removal in flood-prone reservoirs should be considered. The US Bureau of Reclamation and its collaborators are actively seeking new or improved techniques for reservoir sediment removal and transport that are cost-effective and preserve the operational objectives of the reservoir (US Bureau of Reclamation, 2022). Examples of reservoir reclamation include the use of an autonomous vessel capable of removing sediment from reservoirs or a dredging technology handling sediment and larger debris (WEDA, 2021).

Furthermore, reevaluation of spillway design estimates from PMP should be considered with climate extremes in mind. This includes upgrading and optimizing spillway design (Adamo et al., 2020). For example, the HöljesDam spillway design capacity was increased to accommodate an increase in anticipated discharge (Yang et al., 2019).

Future water infrastructure design should also consider the worst-case scenario with climate projections in estimating reservoir capacity and operational models while considering ecosystem and water quality.Adaptive dam design and best management practices should be flexible and balance the control of water for water supply, disaster risk mitigation, and ecological considerations (MacTavish, 2022).

8.4.2 | Understanding Gaps in Current Planning Practice in a Warmer Climate

Revising conventional design flood estimation methods to incorporate near-term climate projections is increasingly necessary yet remains challenging due to the uncertainties inherent in these projections. Additionally, longer design life spans, often exceeding 100 years, magnify the difficulty of predicting reliable flood estimates for dams located in data-scarce regions. In response, Wasko et al. (2021) propose employing alternative approaches that do not rely solely on conventional design floods in such complex contexts.

A central issue is the lack of consensus on standard methodologies for flood estimation under climate change, with dam safety guidelines often varying considerably by country or jurisdiction. For example, raising embankments at agricultural reservoirs in Korea did not fully account for future climate scenarios (Lee and Shin, 2021). This highlights how current design guidelines, including modifications to dam structures and management practices, remain insufficiently standardized for addressing changing climate conditions.

8.4.3 | Opportunities to Improve Planning Concept

Some institutions are developing and implementing more resilient decision-making guidance that incorporates climate change scenarios and updated risk components. Although a substantial amount of research has already examined the impacts of climate change on dams and reservoirs, practical application to dam safety remains limited. Further, adaptation plans should not be restricted to a particular administrative, instead, they need to be integrated into the national-level adaptation strategies and policies to ensure broader effectiveness.

Wasko et al. (2021) summarized various methodologies designed to address uncertainties in the decision-making process of design flood estimation, such as a) standard-based, b) risk-based, c) robust, and d) adaptive. Regularly revising these methodologies throughout the design life of dams and reservoirs—and during any major structural modifications—can help to minimize significant uncertainties related to evolving climate conditions. Potential review processes might employ a) Heuristic approaches based on physical reasoning, b) projections based on historical data, and c) projections based on global climate models. Selecting the most appropriate flood estimation technique is equally important. Wasko et al. (2021) recommend approaches such as a) flood frequency analysis, b) event-based approaches that use intensity-duration-frequency curves, c) continuous simulation, and d) probable maximum precipitation.

Wasko et al. (2021) further recommend openly acknowledging uncertainties, even if they are difficult to quantify precisely. Sensitivity testing within a credible range of possible outcomes is another valuable practice, enabling researchers and practitioners to explore the effects of varying parameters or assumptions on flood estimates. Such sensitivity analyses may be performed by considering multiple plausible scenarios, including “high” and “low” projections derived from several climate models or pathways.

In terms of designing new dams and reservoirs, the application of climate allowances is critical for coping with future climatic conditions. For instance, in the United Kingdom, designers must account for central allowances when planning dams expected to serve beyond 2060, and for structures lasting beyond 2100, a flood risk assessment must incorporate upper-end allowances at the 1% annual exceedance probability event (UK Gov., 2016). This strategy reduces vulnerabilities and enhances flood resilience. Additionally, the UK Environment Agency requires a 20% increase in the design flood volume for spillway designs to safeguard against climate change impacts (Atkins, 2013).

In Australia, updated Intensity-Frequency-Duration (IFD) curves and climate-model-based uncertainty assessments are being used to inform event-based design flood estimates. An adaptive approach to dam and levee construction is gaining traction, exemplified by the inclusion of additional capacity in levee foundations and the expansion of riverbank corridors to facilitate future embankment heightening or widening. Some projects already incorporate these measures to secure protection at a 1% annual exceedance probability level of flooding (Ball et al., 2019).

8.4.4 | Research Agenda for a Way Forward

Continuous and timely research is crucial to adapt and mitigate the future climate change impact on dams and reservoirs. Research advances the knowledge of climate resilience in dams and reservoirs, and the research process must be done systematically. Most studies assessed dam safety separately by only focusing on the direct impact of climate change on dams and reservoirs. Therefore, multi-disciplinary analyses of impacts on dams and reservoirs are recommended. Research on the indirect impacts of urbanization-associated problems, such as land-use change, pollution, riverbank encroachment, etc., must be considered simultaneously because anthropogenic activities may accelerate the impact of a changing climate. The teleconnections between atmospheric and ocean circulations, coupling climate research and forecasting with distributed hydrological models using radar technologies, could enhance the new findings toward raising the resilience of dams and reservoirs to climate change. Research on dynamic flood control and AI-based operation of dams and reservoirs would be another approach to mitigating climate change impacts on dams and reservoirs.

Ho et al. (2017) proposed a comprehensive research methodology for the effective and efficient research agenda for dams and reservoirs in the USA. The agenda includes several strategies to manage climate-induced flood and drought risks for dams and reservoirs in the USA. Most importantly, the agenda discusses analyzing climate change scenarios, institutional aspects to conserve water, and reliable management of water and its relevant infrastructures.

8.5 | Concluding Remarks

Dams and reservoirs have long been constructed to store water and meet growing demand, yet climate change has introduced new and significant stresses on these infrastructures. In response, researchers and stakeholders are increasingly focused on identifying and implementing adaptation measures that enhance the climate resilience of dams and reservoirs. These adaptation strategies generally include shifting from conventional, stationary approaches to dynamic, non-stationary methods that explicitly incorporate uncertainty; conducting comprehensive risk assessments that account for worst-case scenarios, such as increased sedimentation rates, structural aging, and ecosystem impacts; and implementing adaptive management practices that can respond effectively to the growing frequency and intensity of extreme weather events.

Despite these promising solutions, the practical challenges of adjusting dams and reservoirs to changing climate conditions persist. A key step in overcoming these hurdles is the establishment of uniform, globally recognized frameworks that integrate climate change projections into all aspects of dam design, construction, and operation. Encouragingly, many regions and institutions are developing new standards and guidelines that account for both emerging research and site-specific risks. Ongoing collaboration among engineers, policymakers, and researchers will be crucial for ensuring that dams and reservoirs continue to function safely, reliably, and sustainably amid increasing climate variability.

References

1 | Adamo, N., Al-Ansari, N., Sissakian, V., Laue, J., and Knutsson, S. (2020). “Dam Safety and Overtopping.” Journal of Earth Sciences and Geotechnical Engineering, 10(6).

2 | Arnell, N. W. and Hulme, M. (2006). Implications of climate changes for large dams and their management.” Thematic review II, World Commission on Dams, Cape Town, South Africa, 88.

3 | Atkins. (2013). Impact of Climate Change on Dams & Reservoirs. Department of Environment, Food and Rural Affairs, United Kingdom.

4 | Ball, B.M., Nathan, R., Weeks, W., Weinmann, E., Retallick, M., and Testoni, I. (2019). Australian Rainfall and Runoff: A Guide to Flood Estimation.

5 | Bergstrom, S., Carlsson, B., Gardelin, M., Lindstrom, G., Pettersson, A., and Rummukainen, M. (2001). Climate change impacts on runoff in Sweden – assessments by global climate models, dynamical downscaling and hydrological modeling, Climate Research, 16, 101–112.

6 | Biemans, H., Speelman, L.H., Ludwig, F., .Kabat, P. (2013). Future water resources for food production in five south Asian river basins and potential for adaptation-A modeling study. Science of the Total Environment, 468-469, S117-S131. https://doi.org/10.1016/j.scitotenv.2013.05.092

7 | Chandrasekara, S.S., Kwon, H.H., Vithanage, M., Obeysekera, J., and Kim, T.W. (2021). Drought in South Asia: A review of drought assessment and prediction in South Asian countries. Atmosphere, 12(3): 369.

8 Charalampos, S., Jean-Marie, M. and Jacques, G. (2013). Climate Change Impacts on Dams Projects in Transboundary River Basins. The Case of Mesta/Nestos River Basin, Greece. Available at: http://www.inweb.gr/twm4/abs/SKOULIKARIS%20Charalampos.pdf Accessed on 22nd October, 2021

9 Chen, X. and Hossain, F. (2019). Understanding Future Safety of Dams in a Changing Climate, American Meteorological Society, 1395.

10 Chernet, H.H., Alfredsen, K. and Midttomme, G.H. (2014). Safety of Hydropower Dams in a Changing Climate. Journal of Hydrologic Engineering, 1(3): 569–582.

11 Cherry, J.E., Knapp, C., Trainor, S., Ray, A.J., Tedesche, M. and Walker, S. (2017). Planning for climate change impacts on hydropower in the Far North. Hydrology and Earth System Sciences, 21: 133–151. DOI:10.5194/hess-21-133-2017

12 Chung, G.H., Jeon, M.H., Kim, H.S. and Kim, T.W. (2011). Adaptation capability of reservoirs considering climate change in the Han River basin, South Korea. Journal of Korean Society of Civil Engineers, 31: 439–447.

13 Coumou, D., Di Capua, G., Vavrus, S., Wang, L. and Wang, S. (2018). The influence of Arctic amplification on mid-latitude summer circulation, Nature Communications, 9: 2959. DOI: 10.1038/s41467-018-05256-8

14 Crown. (2009). FD2628 Impact of Climate Change on Dams & Reservoirs. Final Guidance Report, Department of Environment, Food and Rural Affairs' information.

15 Donigian, A Jr., Bicknell, B., Imhoff, J. and Singh, V. (1995). Hydrological simulation program-Fortran (HSPF). Computer models of watershed hydrology. p. 395–442.

16 Douglas-Mankin, K., Srinivasan, R. and Arnold, A. (2010). Soil and Water Assessment Tool (SWAT) Model: current developments and applications. T Am Ag Biol Eng. 53:1423–1431.

17 East, A.E., Logan, J.B., Dow, H.W., Smith, D.P., Iampietro, P., Warrick, J.A., Lorenson, T.D., Hallas, L., and Kozlowicz, B. (2024). "Post-Fire Sediment Yield From a Central California Watershed: Field Measurements and Validation of the WEPP Model." Earth and Space Science, 11(7). https://doi.org/10.1029/2024ea003575

18 Edwards, W. and Owens, L. (1991). Large storm effects on total soil erosion. Journal of Soil Water Conservation, 46:75–78.

19 EEA. (2011). European Environmental Agency.

20 EPA. (2021). Climate Change Indicators: River Flooding. Available at: https://www.epa.gov/climate-indicators/climate-change-indicators-river-flooding Accessed on 28th October, 2021.

21 European Union. (2013). LISVAP Evaporation Pre-Processor for the LISFLOOD water balance and flood simulation model. Revised User Manual, JRC technical report. Eds. Burek, P., van der Knijff, J. and Ntegeksa, V. European Union. ISBN 978-92-79-33199-2

22 Feldbauer, J., Kneis, D., Hegewald, T., Berendonk, T.U. and Petzoldt, T. (2020). Managing climate change in drinking water reservoirs: potentials and limitations of dynamic withdrawal strategies. Environmental Sciences Europe, 32: 48 https://doi.org/10.1186/s12302-020-00324-7

23 Fiaz, A., Rahman, G., and Kwon, H.H. (2025). Impacts of climate change on the South Asian monsoon: A comprehensive review of its variability and future projections. Journal of Hydro-Environment Research, 59: 100654.

24 Fluxia-Sanmartin, J., Altarejos-Garcia, L., Morales-Torres, A. and Escuder-Bueno, I. (2018). Review article: Climate change impacts on dam safety. Natural Hazards and Earth System Sciences, 18: 2471–2488. https://doi.org/10.5194/nhess-18-2471-2018

25 Fujihara, Y., Tanaka, K., Watanabe, T., Nagano, T. and Kojiri, T. (2008). Assessing the impacts of climate change on the water resources of the Seyhan River basin in Turkey: Use of dynamically downscaled data for hydrologic simulations. Journal of Hydrology, 353: 33–48.

26 Gebre, S., Alfredsen, K., Lia, L., Stickler, M., and Tesaker, E. (2013). Review of Ice Effects on Hydropower Systems, Journal of Cold Regions Engineering, 27, 196–222.

27 Gohari, A., Bozorgi, A., Madani, K., Elledge, J. and Berndtsson, R. (2014). Adaptation of surface water supply to climate change in Central Iran. Journal of water and Climate Change, 5: 391–407.

28 Gopalan, S.P., Hanasaki, N., Chanpathong, A. and Tebakari, T. (2020). Impact assessment of reservoir operation in the context of climate change adaptation in the Chao Phraya River basin. Hydrological Processes, 35(1): https://doi.org/10.1002/hyp.14005

29 Gurnell, A. M. (1995). Sediment yield from Alpine glacier basins, in: Sediment and Water Quality in River Catchments, Eds. Foster, I. D. L., Gurnell, A. M., and Webb, B. W., Wiley, New York, 407–435.

30 Harrison, W., Drage, B., Bredthauer, S., Johnson, D., Schoch, C., and Follet, A. (1983). Reconnaissance of the Glaciers of the Susitna River Basin in Connection with Proposed Hydroelectric Development, Annals of Glaciology, 4, 99–104.

31 Ho, M., Lall, U., Allaire, M., Devineni, N., Kwon, H.H., Pal, I., Raff, D. and Wegner, D. (2017). The future role of dams in the United States of America, Water Resources Research, 53: 982–998. DOI:10.1002/2016WR019905.

32 Hu, Y., Maskey, S., Uhlenbrook, S. and Zhao, H. (2011). Streamflow trends and climate linkages in the source region of the Yellow River, China, Hydrological Process, 25: 3399–3411.

33 Hughes, A.K. and Hunt, D. (n.d.). A guide to the effects of climate change in Dams. Available at: https://britishdams.org/2012conf/papers/3%20Risk-related%20aspects%20of%20reservoirs%20and%20their%20operation/Papers/3.7%20Hughes%20-%20A%20Guide%20to%20the%20Effects%20of%20Climate%20Change%20in%20Dams.pdf Accessed on 22nd October, 2021

34 International Rivers. (2011). Wrong Climate for Big Dams: DESTROYING RIVERS WILL WORSEN CLIMATE CRISIS, International Rivers, 2150 Allston Way, Suite 300, Berkeley, CA 94704.

35 IPCC. (2021). Summary of policymakers. In: Climate Change 2021: The physical science basis. Contribution of working group I to the sixth assessment report of the Intergovernmental Panel on Climate Change. Eds. Masson-Delmotte, V., Zhai., P., Pirani, A., Connors, S.L., Pean, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M.I., Huang, M., Leitzell, K., Lonnoy, E., Matthews, J.B.R., Maycock, T.K., Waterfield, T., Yelekci, O., Yu, R. and Zhou, B. Cambridge University Press. In Press.

36 Jung, W. and Kim, Y. (2017). Evaluation of Boryeong Dam Water Supply Capacity and Proposal of a drought policy. ChungNam Rep., 278, 1–16.

37 Juracek K, and Ziegler, A. (2009). Estimation of sediment sources using selected chemical tracers in the Perry lake basin, Kansas, USA. International Journal Sediment Research, 24:108–125.

38 Juracek, K.E. (2011). Suspended-sediment loads, reservoir trap efficiency, and upstream and downstream channel stability for Kanopolis and Tuttle Creek lakes, Kansas, 2008-10. Reston (VA): US Geological Survey 2011–5187.

39 Killingtveit, Å. and Saelthun, N. R. (1995). Hydrology. Vol. 7 of hydropower development, Norwegian Institute of Technology, Division of Hydraulic Engineering, Trondheim, Norway.

40 Kim, K.B., Kwon, H.H., and Han, D. (2015). Bias correction methods for regional climate model simulations considering the distributional parametric uncertainty underlying the observations. Journal of Hydrology, 530: 568–579.

41 Kim, Y.T., Yu, J.U., Kim, T.W., and Kwon, H.H. (2024). A novel approach to a multi-model ensemble for climate change models: Perspectives on the representation of natural variability and historical and future climate. Weather and Climate Extremes, 44: 100688.

42 Kraljevic, A., Meng, J-h. and Schelle, P. (2013). Seven sins of dam building. WWF International - Freshwater Programme & WWF-Germany, Switzerland.

43 Kwon, H.H., Lall, U., and Khalil, A.F. (2007b). Stochastic simulation model for nonstationary time series using an autoregressive wavelet decomposition: Applications to rainfall and temperature. Water Resources Research, 43(5).

44 Kwon, H.H., Lall, U., and Kim, S.J. (2016). The unusual 2013–2015 drought in South Korea in the context of a multicentury precipitation record: Inferences from a nonstationary, multivariate, Bayesian copula model. Geophysical Research Letters, 43(16): 8534–8544.

45 Kwon, H.H., Moon, Y.I., and Khalil, A.F. (2007a). Nonparametric Monte Carlo simulation for flood frequency curve derivation: An application to a Korean watershed 1. JAWRA Journal of the American Water Resources Association, 43(5): 1316–1328.

46 Lauri, H., de Moel., H., Ward, P.J., Rasanen, T.A., Keskinen, M. and Kummu, M. (2012). Future changes in Mekong river hydrology: Impact of climate change and reservoir operation on discharge. Hydrology and Earth System Sciences, 16, 1603–4619.

47 Lawrence, D., Graham, L. P. and Besten, J. (2012). Climate change impacts and uncertainties in flood risk management: Examples from the North sea Region." Rep. No. 2012:5, Norwegian Water Resources and Energy Directorate (NVE), Oslo, Norway, ⟨http://www.webby.nve.no/publikasjoner/rapport/2012/rapport2012_05.pdf⟩ (Mar. 21, 2012).

48 Lee, A., Cho, S., Kang, D.K. and Kim, S. (2014). Analysis of the effect of climate change on the Nakdong river stream flow using indicators of hydrological alteration, Journal of Hydro-Environment Research, 8: 234–247.

49 Lee, J. and Shin, H. (2021). Assessment of Future Climate Change Impact on an Agricultural Reservoir in South Korea. Water, 13, 2125. https://doi.org/10.3390/w13152125

50 Lehner, B., and Coauthors (2011). Global Reservoir and Dam Database, Version 1 (GRanDv1): Reservoirs, Revision 01. NASA Socioeconomic Data and Applications Center (sedac), https://doi.org/10.7927/H4N877QK.

51 Lima, C.H., Kwon, H.H., and Kim, Y.T. (2018). A local-regional scaling-invariant Bayesian GEV model for estimating rainfall IDF curves in a future climate. Journal of Hydrology, 566: 73–88.

52 MacTavish, L., Bourgeois, G., Lafleur, C., and Ristic, E. (2022). Climate Change Adaptation for Dams. National Research Council Canada.

53 Mailhot, A. and Duchesne, S. (2010). Design Criteria of Urban Drainage Infrastructures under Climate Change. Journal of Water Resources Planning And Management, 136(2): 201–208.

54 Naveendrakumar, G., Vithanage, M., Kwon, H.H., Chandrasekara, S.S.K., Iqbal, M.C.M., Pathmaraja, S., Fernando, W.C.D.K. and Obeysekera, J. (2019). South Asian perspective on temperature and rainfall extremes: A review. Atmospheric Research, 225(1): 110–120

55 Niu, Y. and Shah, F.A. (2018). Design and Management of Multi-purpose Dams under Climate Change. 2018 Agricultural & Applied Economics Association Annual Meeting, Washington, D.C., August 5–August 7.

56 Norouzi, N. (2020). Climate change impacts on the water flow to the reservoir of the Dez dam basin, Water Cycle, 1: 113–120.

57 NVE. (2011). Retningslinjer for flomberegninger (Guidelines for flood calculations). Rep. No. 04/2011, Oslo, Norway.

58 Prowse, T. D. and Beltaos, S. (2002). Climatic control of river ice hydrology: a review, Hydrological Processes, 16, 805–822. DOI:10.1002/hyp.369, 2002.

59 Rahman, G., Jung, M.K., Kim, T.W., and Kwon, H.H. (2024). Drought impact, vulnerability, risk assessment, management and mitigation under climate change: A comprehensive review. KSCE Journal of Civil Engineering, Article ID 100120.

60 Saelthun, N. R. and Andersen, J. H. (1986). New procedures for flood estimation in Norway. Nordic Hydrol., 17(4–5), 217–228.

61 Scherer, I. and Pfister, S. (2016). Hydropower's biogenic carbon footprint, PLoS ONE, 11, 30161947, DOI:10.1371/journal.pone.0161947.

62 Seneviratne, S.I., Nicholls, N., Easterling, D.R., Goodess, C.M., Kanae, S., Kossin, J., Luo, Y., Marengo, J., McInnes, K. and Rahimi, M. (2012). Changes in climate extremes and their impacts on the natural physical environment. In: Managing the risks of extreme events and disasters to advance climate change adaptation: a special report of Working Group I and II of the Intergovernmental Panel on Climate Change. Eds. Field, C.B., Barros, V., Stocker, T.F., Qin, D., Dokken, D.J. Cambridge (UK): Cambridge University Press. p. 109–230.

63 Sivakumar, M.V.K. and Stefanski, R. (2011). Chapter 2: Climate Change in South Asia. In: Climate Change and Food Security in South Asia. s.l.: Springer Netherlands, pp. 13–30.

64 Smit, B. and Pilifosova, O. (2003). Adaptation to climate change in the context of sustainable development and equity. Sustainable Development, 8(9).

65 Stratz, S.A., and Hossain, F. (2014). "Probable Maximum Precipitation in a Changing Climate: Implications for Dam Design." Journal of Hydrologic Engineering, 19(12). https://doi.org/10.1061/(ASCE)HE.1943-5584.0001021

66 Sutton, A.R. (2019). Evaluating design criteria for high hazard dams in a changing climate, Graduate Theses, Dissertations, and Problem Reports. 3838. https://researchrepository.wvu.edu/etd/3838

67 The Guardian. (2023). "World's Large Dams Could Lose Quarter of Capacity by 2050, Says UN." https://www.theguardian.com/environment/2023/jan/11/worlds-large-dams-could-lose-quarter-of-capacity-by-2050-says-un (Accessed March 25, 2025).

68 Toniolo, H and Schultz, J. (2005). Experiments on sediment trap efficiency in reservoirs, lakes & reservoirs, Research and Management, 10, 13–24.

69 UK Gov. (2016). "Flood Risk Assessments: Climate Change Allowances." https://www.gov.uk/guidance/flood-risk-assessments-climate-change-allowances (Accessed March 26, 2025).

70 Uranchimeg, S., Kim, J.G., Kim, J.G., Kwon, H.H., and Lee, S.O. (2018). A Bayesian quantile regression approach for nonstationary frequency analysis of annual maximum sea level in a changing climate. Journal of Coastal Research, (85): 536–540.

71 Uranchimeg, S., Kwon, H.H., Kim, B., and Kim, T.W. (2020). Changes in extreme rainfall and its implications for design rainfall using a Bayesian quantile regression approach. Hydrology and Current Research, 51(4): 699–719.

72 US Bureau of Reclamation. (2022). "Guardians of the Reservoir." https://www.usbr.gov/research/challenges/sediment-removal.html (Accessed March 25, 2025).

73 US Department of Energy. (2017). Effects of Climate Change on Federal Hydropower. The second report to congress January 2017. United States Department of Energy, Washington DC. 20585.

74 United Nations. (2013). Climate change impacts and adaptations for international transport networks. Expert group report. United Nations, New York and Geneva.

75 US Department of Energy. (2017). Effects of climate change on federal hydropower. The second report to Congress January 2017. U.S. Department of Energy, USA.

76 USACE. (2016). Guidance for Incorporating Climate Change Impacts to Inland Hydrology in Civil Works Studies, Designs, and Projects, United States Army Corps of Engineers, EBC 2016-25, 2016.

77 Vahedi fard, F., AghaKouchak, A., Ragno, E., Shahrokhabadi, S. and Mallakpour, I. (2017). Lessons from the Oroville dam. Science, 355, 1139–1140, https://doi.org/10.1126/science.aan0171.

78 Vahedifard, F., AghaKouchak, A., Ragno, E., Shahrokhabadi, S. and Mallakpour, I. (2017). Lessons from the Oroville dam. Science, 355, 1139–1140, https://doi.org/10.1126/science.aan0171.

79 Veijalainen, N., Dubrovin, T., Marttunen, M. and Vehviläinen, B. (2010). “Climate change impacts on water resources and lake regulation in the Vuoksi Watershed in Finland.” Water Res. Manage., 24(13), 3437–3459.

80 Visser, J.B., Kim, S., Wasko, C., Nathan, R., and Sharma, A. (2022). “The Impact of Climate Change on Operational Probable Maximum Precipitation Estimates.” Water Resources Research, 58(11). https://doi.org/10.1029/2022wr032247

81 Wasko, C., Westra, S., Nathan, R., Orr, H.G., Villarini, G., Herrera, R.V. and Fowler, H.J. (2021). Incorporating climate change in flood estimation guidance. Philosophical Transactions Royal Society. A. 379: 20190548. https://doi.org/10.1098/rsta.2019.0548

82 Western Dredging Association (WEDA). (2021). Reservoir Dredging: A Practical Overview. WEDA Technical Report.

83 Wild, T. B. (2014). Managing flow, sediment and hydropower in the Mekong River basin. Unpublished PhD thesis, Faculty of the Graduate School of Cornell University.

84 WIT Press. (2009). Dam-break Problems, Solutions and Case Studies. Eds. de Wrachien, D. and Mambretti, S. WIT Press, Ashurst Lodge, Ashurst, Southampton, SO40 7AA, UK. ISBN: 978-1-84564-142-9

85 Yasarer, L.M.W. and Sturm, B.S.M. (2016). Potential impacts of climate change on reservoir services and management approaches, Lake and Reservoir Management, 32: 13–26. DOI: 10.1080/10402381.2015.1107665.

86 Young, R.A., Onstad, C., Bosch, D. and Anderson W. (1989). AGNPS: a nonpoint-source pollution model for evaluating agricultural watersheds. J Soil Water Conserv. 4:168–173.

87 Yang, J., Andreasson, P., Teng, P., and Xie, Q. (2019). “The Past and Present of Discharge Capacity Modeling for Spillways—A Swedish Perspective.” Fluids, 4(1). https://doi.org/10.3390/fluids4010010

88 Yun, X., Tang, Q., Sun, S. and Wang, J. (2021). Reducing climate change induced flood at the cost of hydropower in the Lancang-Mekong River basin. Geophysical Research Letters, 48(20): https://doi.org/10.1029/2021GL094243

CHAPTER 9

Adaptions for Open Channels and Lakes

Guinevere Nalder

New Zealand. E-mail: nalder_gv@yahoo.com

Abdalla Ahmed

UNESCO CHAIR, Khartoum, New Zealand Qualifications Authority, New Zealand.
E-mail: aaahmed55.aa@gmail.com

Yangwen Jia

Dep. of Water Resources, Institute of Water Resources and Hydropower Research, China.
E-mail: jiayw@iwhr.com

Roberto Ranzi

Department of Civil, Environmental, Architectural Engineering and Mathematics,
University of Brescia, Italy. E-mail: roberto.ranzi@unibs.it

9.1 | Introduction

The effects of climate change on open channels and lakes fall into two main two main classes; changes in discharge peaks and regimes, and changes in water quality. The latest IPCC scenarios envisage the following with regard to streamflow:

9.1.1 | The IPCC AR6 scenarios for streamflow regimes

- Increases in frequency and intensity of hydrological droughts with increasing global warming in some regions (medium confidence). There will be an increasing occurrence of some extreme events unprecedented in the observational record with additional global warming, even at 1.5°C of global warming.
- It is very likely that heavy precipitation events will intensify and become more frequent in most regions with additional global warming. At the global scale, extreme daily precipitation events, with return period of 10 years, are projected to intensify by about 7% for each 1°C of global warming (high confidence).
- There is strengthened evidence, since AR5, that the global water cycle will continue to intensify as global temperatures rise (high confidence), with precipitation and surface water flows projected

to become more variable over most land regions within seasons (high confidence) and from year to year (medium confidence).

9.1.2 | Water Quality

Climate change affects water quality through two mechanisms. Variation in rainfall intensity and distribution over the year may lead to land use changes which in turn may alter the amount and type of sediment and other pollutants being washed into the open channel. A decrease in discharges would lower the dilution of pollutants available. Lesser water volumes and/or higher ambient temperatures may lead to increases in water temperature. Aquatic species are temperature sensitive to a greater and lesser degree. An increase in temperature leads to an increase in photosynthesis leading to any increased number of plants or algae blooms. In turn, decomposition of the dead plants will raise the level of anaerobic bacteria which will use up the dissolved oxygen.

Aquatic animals may experience an increase in metabolism with increasing temperature leading to an increase in demand for food and oxygen (Pankhurst and King, 2010). Bacteria also grow faster in warmer temperatures and so may render aquatic animals more sensitive to these toxins. Also increases in temperature affect fish reproduction as larvae and eggs have a much narrower temperature range. As a consequence of all these dynamics in a warmer climate most freshwater life will be severely threatened in the forthcoming decades, unless water engineerswill become aware of the threat our lifestyle poses to our water bodies (IAHR, 2021; Imberger, 2021).

9.2 | Adaption to Climate Change

Adaption to climate change can take two approaches; institutional and the engineering approaches. In general, the concern is with increase in flood hazard.

9.2.1 | Institutional

The institutional approach consists of planning and the preparation of documents such as guidelines, codes of practice. These have the advantage that they can be upgraded as further data becomes available. This approach is being used in Europe, Australia, and New Zealand as shown in the following sections.

9.2.1.1 | *Europe*

The European Flood Directive 2007/60/EC already recognised how both human activities and climate change contribute to an increase in the likelihood and adverse impacts of flood. The upgrade of the former 'Water Framework Directive' 2000/60/EC introduced the concept of considering the future changes in the risk of flooding as a result of climate change. It recommended that flood risk management plans should be reviewed and if necessary updated, every six years starting from 2018, to take into account the likely impacts of climate change on the occurrence of floods.

Some Länder in Germany, are introducing safety factors for estimating design floods. This approach received greater emphasis as a result of the severe flooding that occurred in Central Europe in summer 2021. In 2019, The Ministry of Environment and Consumer Protection in Bavaria[5]specified a 15% increase factor for the 100-year flood due to climate change. In Baden-Württemberg the factors identified by recent studies[6] differ depending on the return period and are spatially variable. For example, they range from +0% for the 1000-year floods to the +25% increase for the 100-year flood in the Upper Donau river. More often, changes in flood intensity are estimated on the basis of climate change scenarios, resulting in changes on the tails of the distribution, i.e. to the increase or decrease of extreme events (Coppola et al., 2014).

Italy has seen two approaches. In 2015 The Emilia-Romagna Regional Environmental Agency, after having assessed a + 20% increase of the design rainfall according to RCP 4.5 scenarios, recommended an increase in the design flood for the new Baganza river flood retention basin by a factor of about +30% compared to the result of a standard statistical analysis of flood peaks assuming the Two Components Extreme Values distribution. In contrast, the Eastern Alps Water District took a direct engineering approach by recommending that 0.20 m extra-freeboard should to be assigned when estimating the flood hazard mapping for the Flood Management Plans.

In Spain a recent study by the Centre for Studies and Experimentation of Public Works (CEDEX), for the Spanish Ministry of Transport, Mobility and Urban Agenda, summarized in Requena et al. (2023), showed that relative changes in quantiles of daily annual maximum precipitation accumulated along river networks and projected to 2041–2070 are expected to increase with the return period, up to +35%. However, the median and the variance of annual maxima of daily and 1 to 12 hours do not exhibit significant change in any region of Spain according to the RCP 4.5 and 8.5 scenarios for 2041–1070, while they do increase in several regions of Spain with the RCP 8.5 scenario projected to 2071–2100.

[5]https://www.stmuv.bayern.de/themen/wasserwirtschaft/foerderung/doc/infoblatt_hochwasserschutz_rueckhaltekonzepte.pdf
[6]https://www.kliwa.de/_download/Klimaaenderungsfaktoren_BW.pdf

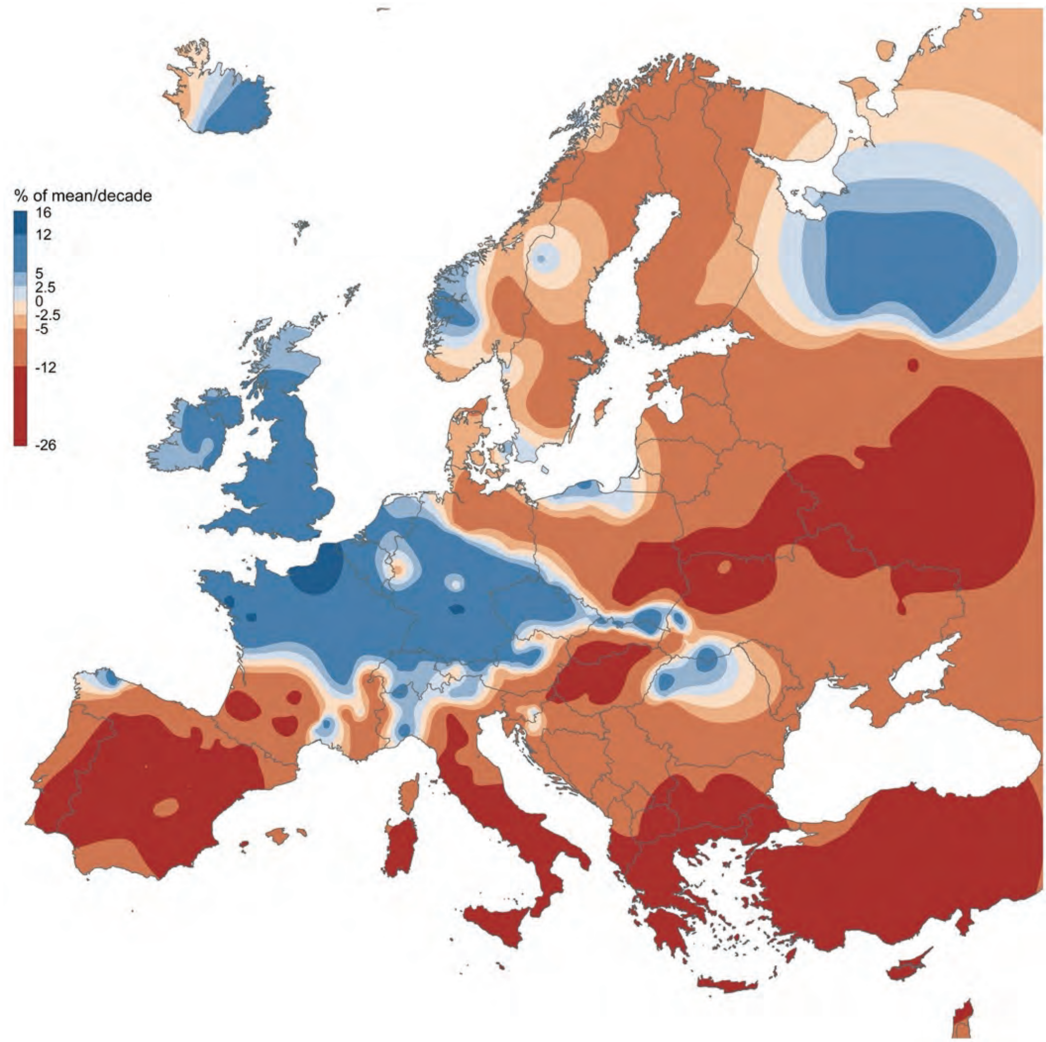


Figure 9.1 | Observed regional trends of river flood discharges in Europe (1960–2010). Adapted from Blðschl et al., 2019, courtesy of Guenter Blðschl).

9.2.1.2 | *New Zealand*

All local authorities in New Zealand are required to prepare catchment management plans for all water courses in the area they manage These usually take the form of Integrated Catchment Management Plans (ICMPs) which are cover the management of stormwater, wastewater, and water supply within the given area. As these are specific to a given area, the resulting guidelines and regulations can be tailored e.g for an urban catchment the ICMP may specify the minimum domestic floor level, while for a rural catchment, it may include maps indicated the expected encroachment of flood water on the surrounding grazing areas. A typical ICMP consists of a written report and a model developed with one of the proprietary software packages. The ICMP can be upgraded by simply running the model again, with updated parameters.

9.2.1.3 | *Australia*

The Australian Government manages adaption to climate change by incorporating climate change into the ARR-Australian Rainfall and Runoff. The most recent edition is that of 2019. This is done primarily by updating the expected rainfall and the expected interaction between rainfall and rising sea levels. As approximately 80% of Australia population lives within 50 km of the coast the rainfall - sea level interaction is particularly important. The authors (Ball et al., 2019) anticipate that climate change would have the following effects for Australia:

Change in rainfall intensity frequency duration curve (IDF) relationships. A reduction in annual rainfall but a generation of more intense rainfall events are expected. Other expected changes are:

- Change in temporal patterns of rainfall
- Change in continuous rainfall sequences
- Change in antecedent conditions and baseflow regimes
- Worsening effect of compound extremes.

These effects will require the upgrading in the design of open channels, general conveyance channels, and storage structures. ARR recommends 5% increase in rainfall depth or intensity per C^o of local warming. This allows for uncertainty in rainfall projection and regional variability in a country the size of Australia. Also in urban areas, prescribing floor level freeboard should not be used to cover the uncertainties of climate change impact of river floods. This is in contrast to the New Zealand practice.

Coastal Climate and Flooding. Section 9.5.3 of ARR points out that: anthropogenic climate change will have very little effect on the size of the relationship between extreme rainfall and storm surge, although the effects of climate change can be accounted for by changing the marginal distributions: In. the extreme rainfall intensity and the ocean level).

As part of the description of the Design Variable Method to estimate flooding, Section 9.5.5 indicates that increases in extreme rainfall, and elevated sea levels due to both increase mean sea levels and possible changes in storm surges can be expected to increase the exceedance probabilities of flooding in estuarine regions. Unfortunately modelling available to the revision committee does allow for definite statement on how the relationship between extreme rainfall and storm surge/tide can be expected to alter with climate change.

Book 6 of ARR provides a method for developing a Flood Level Table (Table 9.5–9.7) for a given location using different combinations of rainfall and storm tide in terms of AEP. ARR includes two alternative methods for adjusting a given Table. Either the

- Table can be completely updated by repeating the simulations originally carried out or
- The historical flood level table can be used but the exceedance probabilities of the extreme rainfall and storm tide can be modified to reflect future exceedance probabilities. However, it additional simulations may still be needed for low exceedance probability events.

Chapter 6 includes two worked examples. Table 9.1 is the resulting table for the Hawkesbury River at Spencer, New South Wales.

9.2.1.4 | *China*

At present the published technical standards or guidelines for river training in China do not require the consideration of the impact of future climate change. Instead planning, design, and operation of river

Table 9.1 | Flood Levels of Different Combinations of Rainfall and Storm Tide in Terms of Percentage Annual Exceedance Probability (%AEP) at Spencer on the Hawkesbury River, New South Wales (after Table 6.5.12 ARR, 2019).

	Storm Tide Events (%AEP)				
	Lower Bound	30	2	0.25	0.0025
Rain %AEP					
No rain	0.061	1.048	1.258	1.466	1.678
18.1	0.114	1.084	1.279	1.482	1.687
9.5	0.129	1.094	1.292	1.494	1.687
4.9	0.175	1.129	1.321	1.515	1.708
2	0.286	1.209	1.397	1.586	1.776
1	0.429	1.316	1.498	1.682	1.866
0.5	0.686	1.509	1.681	1.854	2.03
0.2	0.982	1.735	1.895	2.057	2.222
0.1	1.364	2.033	2.177	2.325	2.476
0.01	1.449	2.101	2.241	2.387	2.534

projects are based on historical hydrological data series which incorporate the impacts of historical climate change and human activities on river flow and flood.

Standards or guidelines related to river training in China include:

(1) The National Code for Design of River Training (GB50707-2011).
(2) The National Standard for Flood Control (GB50201-2014),
(3) The National Code for Design of Urban Flood Control Project (GBT50805-2012),
(4) The National Code for Design of Reservoir Operation (GBT50587-2010):
(5) The Professional Code for River Basin Planning (SL201-2015),
(6) The Professional Regulation for Water Conservancy Computation of Water Projects (SL104-2015),
(7) The Professional Code for Formulation of Flood Mitigation Planning (SL669-2014),
(8) The Professional Guidelines for Flood Risk Mapping (SL483-2017).

For example, in the National Code for Design of Reservoir Operation (GBT50587-2010), requires that in design for single or multiple design stages with a time span of over 2 years, the adopted basic data should be revised and supplemented if the boundary conditions of basic data are known to have changed due to climate change and human activities.

For the impacts of future climate change on design and operation of river training works and water projects, Chinese experts did a lot of researches and strongly suggested to consider the future climate change impacts during revisions of related technical standards or guidelines. Zhang and Wang (2008) argued that the design standard of water project is subject to further enhancement considering the increasing extreme events of rainstorm and drought under the background of global warming. They think that continuous drought has obvious impact on the safe operation of water structures, continuous high temperature or low temperature also lowers the safety coefficient of dam, and properly handle the relationship between climate change and water project safety is of practical meaning for sustainable utilization of water resources, coping with unfavorable climate change, and ensuring stable development of society and economy. Guo et al. (2020) recommended to update the design floods and flood control water level in water project operation period because the human activity and climate change have significantly altered the river flow and spatio-temporal distribution of flood process. They proposed non-stationary flood frequency analysis method and the regional combination method of the most likely flood based on copula function, and compared their practicability. Xie et al. (2020) thought that the inter- and intra-annual variation of water level series has made the designed lowest navigable water level in the past no longer conforms to the current situation under the impacts of climate change and human activities, and proposed a method for designing the lowest navigable water level considering the variation of water level process, which was demonstrated in estimating the lowest navigable water level at the Yunjinghong hydrological station in the Langcang River basin.

9.2.1.5 | *United States*

The US Bureau of Reclamation in its Climate Change Adaptation Strategy[7] recently issued pointed out how the decrease in snowpack and earlier springrunoff have made climate resilience an important focus area for Reclamation. Adaptation strategies as the desalination program supports desalination science, development, and demonstrations to convert unusable waters to usable water supplies through desalination. The development of hydropower projects continues to be supported.

9.2.2 | Infrastructure Approach

The engineering response is to manage the expected additional water in many cases for future floods. The options depend on the development on the river banks. Where the area is already densely developed, such as in a major city, the options are to retain the additional water within the channel or to provide some form of underground storage usually as part of a larger programme of environmental upgrade for an existing metropolitan area.

In many cities, the river banks are important recreational area and existing wall and low stopbanks frequently form a promenade for pedestrians. Raising the stopbanks would remove an important social feature, while being costly. An alternative would be a system of temporary stopbanks. There are various proprietary methods of demountable flood walls.

Where there are fewer urban constraints, it is possible to manage climate change induced flooding by allowing more physical area for the open channel. This is a process of 'naturalisation' of rivers and the approach is often referred to as allowing 'Room for the River'. Where water courses have been 'trained' by canalization, removal of the hard engineering, will allow the river to develop a natural layout. The resulting meanders can hold more water because the river naturally lengthens. However, as this is a dynamic system it is necessary to monitor the erosion. Depending on the nature of the soils, the pattern on meanders can change with time. In addition, the flood plain on each side of the channel can be altered to act as a 'sponge' to hold excess water temporarily. Alterations here could

[7]US Bureau of Reclamation 2023, Climate Change Adaption Strategy, downloaded February 2025 https://www.usbr.gov/climate/docs/2023ccas/CCAS2023Webversion.pdf

include restoration of wetlands and increasing the volume of existing detention basins by lowering their bases. This method has been used by the Dutch Government to provide extra space at locations on the Rhine, Meuse, Waal, and IJssel Rivers.

Whichever the situation, any re-engineering of open channels cannot be done in isolation; It needs to be part of a catchment wide plan.

9.3 | Climate Change Impact on Perennial and Ephemeral Streams in Africa

9.3.1 | Perennial Streams

Warming patterns in Africa are consistent with global ones and Africa is already subject to important spatial and temporal rainfall variability. Global warming, its human cause and its impact on water resources are undeniable also in this continent. Each event of repeated drought cycles in Africa kills thousands of people. Moreover, floods also occur regularly with severe impacts on people's livelihoods.

The Nile River Basin (NRB) is a typical perennial stream. The NRB represents 10% area-wise of the African continent and is located in the driest zone of Africa. At presence the NBR accommodates about 200 millions of people and about 400 million depend directly or indirectly on their livelihood and food security on the Nile Water Resources.

It is anticipated that the recently constructed Grand Ethiopian Renaissance Dam (GERD) will impact on the whole Nile System and also affect the climate of the region, since it has a very wide water surface area in a critical area. (In the year 2023, the dam's stored water volume had reached 43×10^9 m^3 of the designed 74×10^9 m^3 capacity.)

The NRB is particularly sensitive to a warmer and more variable climate because of the natural fragility of its climate conditions – arid and semi-arid regions with delicate ecosystems -, large rural population, and low resilience to climate shock on the part of many of the rural poor It has been reported that within NRB the rainy season has become shorter and more intense, and subject to erratic onset and cessation making very difficult for farmers to plan their farming calendars. Although Africa in general and NRB countries in particular produce only a fraction of the global annual greenhouse gas emissionsand their contribution to the rise of the temperature globally is negligible, the continent is highly vulnerable to the effect of the climate change.

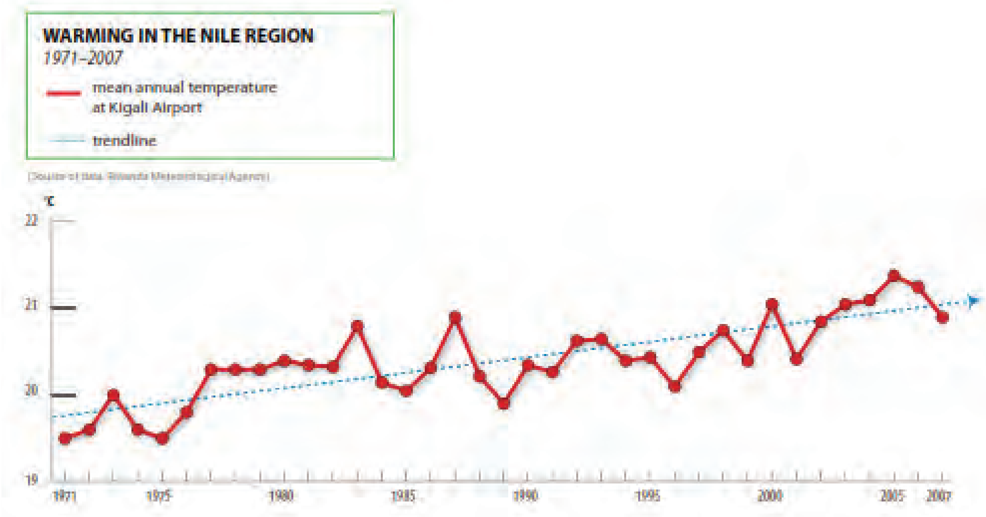


Figure 9.2 | Average Temperature Increase in the Nile River Basin (1971–2007).

Figure 9.2 shows a good example of the temperature increasing in Central of NRB Kigali Airport (1971-2007). It is clear that in the forty years the temperature increases by about 1°C.

Studying the impacts of a warming trend in climate on the NBR provides several important points. These include

(1) Higher evaporation which leads to losses from reservoirs,
(2) High evapotranspiration rates lead to rising crop water requirements and hence higher demand for irrigation water,
(3) Increase of risks of the drought,
(4) Severe rainstorms that lead to damaging floods. Furthermore, in the
(5) Strengthening of thermal stratification inEquatorial Lakes increases algal productivity and reduce oxygen dissolution, resulting if further spread of Malaria
(6) Moreover, in North Africa (Egypt Coast) sea-level rise threatensthe very productive Nile Delta of Egypt.

Although many efforts have been made to understand and predict the future climate over the NRB, however, there are no firm conclusions that can inform policy making at local or national level,

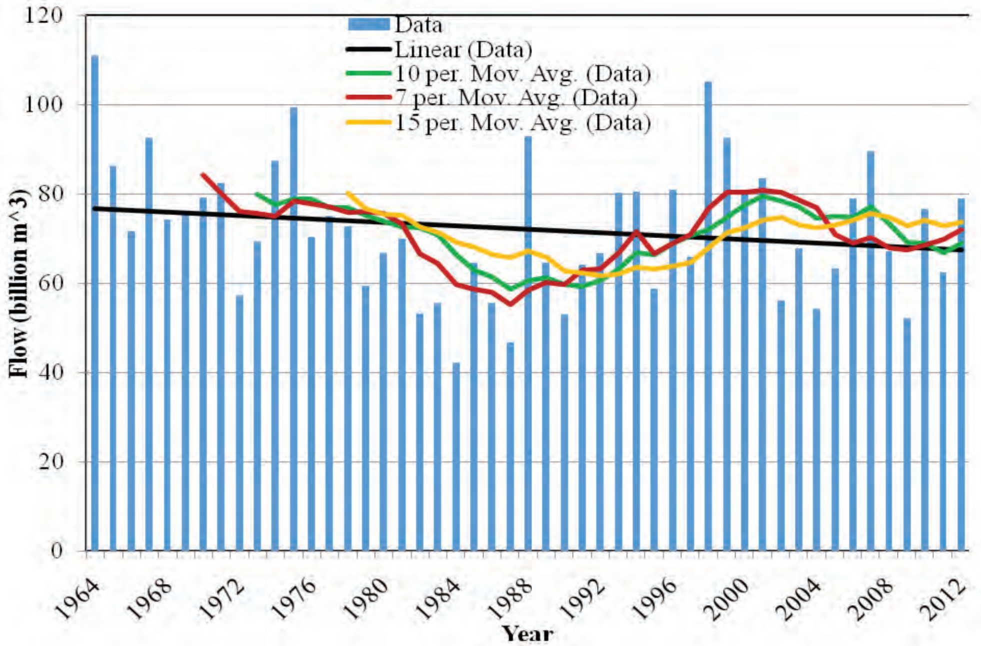


Figure 9.3 | Variation of Main Nile River flows (1964–2012).

because of the uncertainties in the results. The latter is presented and highlighted by the data collected for more than 100 years for Nile River (discharge, level, rainfall, temperature). Moreover, sediment information is used to show its impact on the reservoirs' capacities and hence their impacts on climate change combating.

Figure 9.3 shows the variation in Nile River Flow in more than 100 years. This information together with the levels and rainfall data indicate clearly the decline in the flows. The impact of the climate change on the upstream part of the NRB, (e.g. Victoria Lake) and downstream (e.g. Lake Nasser/Nubia), is proved by the streamflow variation.

In spite of the serious situation of the climate change matter in the NRB, it is clear up to this moment the response and plans of the Nile Basin countries and a climate change resilient growth among the NRB societies is well noticed.

Therefore, the structural and non-structural measures within the NRB are gradually developed to combat the climate change, in particular the implementation of practical "non-regret" measures. This might help the NRB countries people to climate change adaptation and risk reduction. Therefore, a strategic water policy should be adopted to achieve the following:

- improvement of crop productivity,
- minimization of irrigation water losses,
- improvement in water use efficiency.

9.3.2 | Ephemeral Streams

Ephemeral water courses provide several valuable and unique eco-system services such as: flood risk management, wildlife habitat sources, biodiversity, water filtration and water quality improvement, recreation and open space opportunities. They also support education and stewardship opportunities and may provide potential economic benefits.

An ephemeral watercourse experiences flow only during or immediately after heavy rainfall or snow melt, while the intermittent watercourse is one experiencing flow for a part of each year. Ephemeral streams are features that only flow as an indirect response to precipitation events and are a frequent hydrographic feature in Africa: these waters typically do not have a well-defined channel and runoff from rainfall is the primary source of the ephemeral streams.

Ephemeral streambeds are located above the water table year around (i.e. there is no water base flow contributing to ephemeral watercourse). Therefore, groundwater is not a source of water for the ephemeral stream.

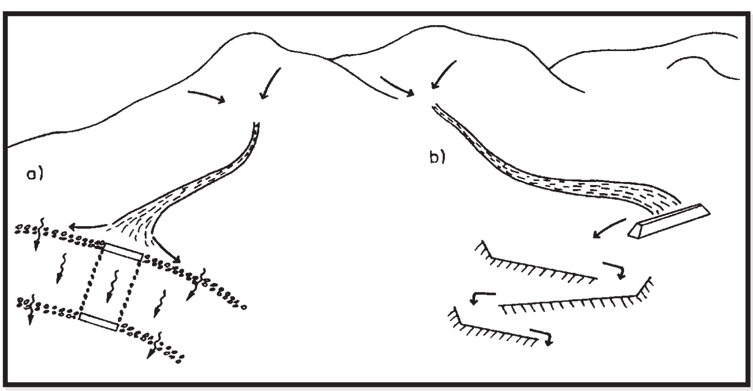


Figure 9.4 | Ephemeral Water Stream Distribution to absorb the High Flash Floods.

As climate change continues to increase temperatures and precipitation rates and tends to increase the frequency of extreme weather events, the expected flow regimes present in both perennial and temporary watercourses (ephemeral) are no longer certain. Further, as evapotranspiration increases under climate change, we may witness an increase in the amount of ephemeral and intermittent watercourses. In response, an effective watercourse management policy framework is necessary.

Although polices and process of lakes, wetlands, reservoirs and perennial watercourses (permanent rivers, streams) are relatively mature and well developed, in contrast, ephemeral and intermittent watercourses have received less attention and have generally a more ad-hoc manner in land use planning and policy.

Water harvesting techniques is essential to be used to absorb the risks of the flash floods or a sudden water storm generated by heavy rains in the upstream part of the stream. There are two useful techniques depicted in Figure 9.4, namely:

(1) Distribution system within the bed of the watercourse.
(2) Diversion of water outside the watercourse of the ephemeral stream, i.e. water spreading system.

In arid and semi-arid region there is a good chance to adopt the two above important solutions. The distribution management of ephemeral streams waters in several dry countries like in most of the Arab countries, for example, is based on an Old Islamic Water Law. It says basically that the areas upstream of the right ephemeral stream irrigate first, then those on the left. The water will be sent downstream and the same manner is applied for irrigation, and so on. In practice, this Law proved to be fair, since in most cases the water leaves those in the upstream to the downstream ones and there is no way the water to return back again upstream.

On the other hand, ephemeral streams in dry areas where the rainfall is rare might run once or twice in several years. However, it might suddenly create heavy flash destructive floods. These variations reflect the climate change impact. People usually use to settle on dry ephemeral stream watercourses believing that the flow might not run again. Unexpectedly and suddenly destructive flash floods happen to remove all the buildings and people belongings to the sea or big lakes far away from the original places. Therefore, people living in these dry areas should expect hard drought or heavy floods according to the climate change. Hence awareness and resilience are necessary to be taken into account.

9.4 | Adaption to the water quality in streams

As discussed in Section 9.1.2, the two main effects of climate change on open channels are increases in pollutants and pollutant concentration, and increases in temperature. These effects can be mitigated by a combination of land use management and soft engineering which may be included a programme of riverbank restoration.

Land use management can be influenced by official fiat: regional planning and environmental legislation. However, land owner education by public consultation, published brochures and newsletters, official websites, and local media are more likely to be effective as it removes the element of official compulsion. In addition, inducements can also be offered to encourage sediment control measures. These can include subsidies or reductions in land taxes. Sediment control will be even more necessary if climate change leads to decreases in discharge leading to a greater concentration of pollutants.

Increasing flow can be expected to lead to greater bank erosion and it may be necessary to stabilize banks initially with small structures like gabions. Alternatively, erosion can be controlled by securing natural barriers against the bank to counteract the energy of the oncoming water. These barriers can range from bundles of small branches (brash) up to whole trees. This method is popular in Scotland. A judicious choice of bankside plantings, will also help stabilize the banks. In addition, trees and large shrubs will shadow the open channel providing cooler areas for fish.

9.5 | Climate change impact on lakes

9.5.1 | Reservoirs for Hydro-Power Dams ('Hydro Lakes')

Storm surges apart, increased discharges into lakes rarely raise flood risk markedly. Long periods of drought will lower water levels, and this will require careful management of the lake resources. A major problem with changing discharges is in inflow into hydro lakes. While excess water can be discharged, drought leads to lower energy production at a time when there is higher demand for electricity for refrigeration and cooling. The operating procedures for existing dams will need to include close monitoring and management of inflows. The increased variation in inflows will need to be factored into planning for further development. For example, given the likelihood of increased lower flows, building a pair of smaller dams instead of one large one, may enable the reservoir water level to be kept at a higher level, ensuring more power generation.

9.5.2 | Water Quality

Climate change affects water quality in lakes of all sizes even ones as large as Lakes Baikal and Tanganyika. In lakes the main drivers for water quality deterioration are invasive plants and eutrophication due to stratification within the lake.

Invasive plants have been recognized as a lake water quality issue even before the emergence of climate change effects. It was usually due to the fertilizer based sediments, particularly phosphorous, being washed or air blown into the lake from the surrounding catchment. The problem will be worsened if land use changes brought about by climate change lead to increases in pollution. Again the solution lies in the careful management of land use.

Less tractable are the changes caused by the increasing temperature.Lakes exhibit a vertical temperature gradient which, under 'normal' conditions, is disrupted by seasonal vertical mixing. This may occur twice a year (dimictic) or once a year (monomictic). If this mixing does not take place, the lake become stratified with layers of decreasing oxygen concentration. The lowest layer may become completely depleted of oxygen. Rising temperatures of surface water will disrupt this process leading to a meriomictic condition where only partial vertical mixing takes place. This partial mixing will bring the oxygen deficient bottom water (monolimnion) to the surface causing fish mortality. The ideal response to climate change here would be to change the mixing from partial to complete or nearly complete. A technology suitable for large lakes is still to be found.

References

1 | Ball, J., Babister, M., Nathan, R., Weeks, W., Weinmann, E., Retallick, M. and Testoni, I. (Editors) (2019). Australian Rainfall and Runoff: A Guide to Flood Estimation, ©Commonwealth of Australia (Geoscience Australia).

2 | Blöschl, G., Hall, J., Viglione, A. et al. (2019). Changing climate both increases and decreases European river floods. Nature 573, 108–111. https://doi.org/10.1038/s41586-019-1495-6

3 | European Commission (2007). Directive 2007/60/EC of the European Parliament and of the Council, Brussels.

4 | Guo S L, Xiong L H, Xiong F, Yin J B. Theory and method of design flood in cascade reservoir operation period. Advances in Water Science, 2020, 31(5): 734–745.

5 | Imberger, j. Avoiding the impeding death of the global freshwater ecology: An opportunity to learn new engineering skills, Hydrolink, 2021 (1): 4–9.

6 | IAHR, Deep lakes, HydroLink 2021-1 https://www.iahr.org/library/hydrolink?hid=317

7 | Pankhurst NW, King HR. Temperature and salmonid reproduction: implications for aquaculture. J Fish Biol. 2010 Jan;76(1):69–85. doi:10.1111/j.1095-8649.2009.02484.x. PMID: 20738700. https://pubmed.ncbi.nlm.nih.gov/20738700/

8 | Requena, A. I., Jiménez-Alvarez, A., & García, C. (2023). Assessment of climate change impact on maximum precipitation in Spain. Hydrological Processes, 37(1), e14803. https://doi.org/10.1002/hyp.14803

9 Xie P, Wang L, Sang Y F, Chen J, Yu T. Method for designing the lowest navigable water level considering the variation of water level process. Journal of Hydraulic Engineering, 2020, 51(4): 379–390.

10 Zhang J Y, Wang G Q. Climate change and dam safety. China Water Resources, 2008, 20: 17–19, 9.

CHAPTER 10

Adaptations of Coastal Defence Systems

Inigo J. Losada
Director of Research at IH Cantabria-Institute of Environmental Hydraulics of University of Cantabria, Santander, Spain. E-mail: losadai@unican.es

Javier L. Lara
Head of Climate Risks, Adaptation and Resilience Group at IHCantabria- Institute of Environmental Hydraulics of University of Cantabria, Santander, Spain. E-mail: jav.lopez@unican.es

10.1 | Introduction

Coastal protection or coastal defence systems (CDS) refers to the strategies, measures, and actions taken to safeguard coastlines and the areas adjacent to the ocean or lakes from erosion, flooding, and other natural hazards, which can have significant environmental, economic, and social impacts in the area. Climate change is adding a new layer of concern since it poses significant challenges to coastal areas through rising sea levels, increased storm activity, erosion, and other related impacts. Mitigation and adaptation strategies are essential to protect coastal communities, economies, and ecosystems in the face of these changes. In this chapter we address some of the relevant current knowledge on how engineering is facing this new challenge especially focus on adaptation.

Coastal areas are unequivocally exposed to the threat posed by climate change. The latest climate change projections show an unfavorable trend, with accelerated sea level rises and changes in the magnitude and frequency of extreme wave events. The uniqueness of this climate threat is highlighted in the special report published by the Intergovernmental Panel on Climate Change (IPCC) in 2021 on the role of the oceans in a context of climate change, and updated in the last IPPC report (IPCC, 2021), attending to the new climate projections. Within coastal management, the role of coastal defenses, whether breakwaters or seawalls or coastal ecosystems formed by marshes, mangrove forests or coral reefs, should not be forgotten, as the first artificial element of defense against marine dynamics, having been designed or existing to meet certain requirements to ensure the economic, social, productive and environmental viability of the CDS. The combination of a changing climatic threat together with a high degree of exposure and potential highly negative consequences makes it necessary to study the temporal evolution of the hydraulic, economic, social or environmental response of the CDS, so that coastal professionals and managers can 1) anticipate with sufficient margin of action to be able to 2) plan cost-efficient adaptation measures that ensure an adequate distribution of public and private resources in a variable climatic framework.

In this framework impact assessment of climate change, associated risks and adaptation of CDS are to be mainstreamed into the existing best practices by including the effects of long-term changes in coastal local climate drivers and factoring in the additional level of uncertainty associated to climate projections, adding a new layer of complexity and uncertainty to the existing knowledge. However, all these regulations and directives are stated from a more general point of view and lack the degree of development to be implemented in a systematic way to adapt coastal zones to the new challenges posed by climate change, considering not only the impacts that climate change may generate, but also the response that the coastal system can provide in terms of its degree of resilience and adaptation to the new future conditions. The need to make a distinction in characterization of marine climate to identify the consequences arising from extreme events (related to the structural integrity and functional performance of the CDS) and from regular events (related to the usability of CDS) has created a disconnect between existing methodologies (Lucio et al, 2024). Most of the existing research and methodologies focus solely on the analysis of the consequences of extreme events (Solari et al., 2018) or regular events (Camus et al., 2019; Izaguirre et al., 2021), with very few covering the overall behavior of CDS, addressing both types of events comprehensively within a risk framework.

This chapter follows a structured approach, beginning with an introduction to the risk assessment framework. It then delves into coastal climate drivers of risk, providing insights into various components of coastal hazards and available data. Practical guidance on constructing coastal driver scenarios and recommendations is offered. The subsequent sections focus on mainstreaming climate change into conventional coastal protection systems design and adaptation, as well as discussing the adaptive capacity of coastal defense systems and decision support systems. Finally, the chapter concludes with a discussion on gaps, conclusions, and recommendations for future research.

10.2 | Risk assessment framework

The risk assessment framework is needed to evaluate CDS performance and response under the effects of various uncertain changing climatic factors and the changing economic, social or natural environment itself. Authors refer to Chapter 5 in this monograph for a more details about the implementation framework.

Several approaches for considering CC-induced risks and impacts on coastal structures (Suh et al., 2013), harbors (Camus et al., 2019, Jebbad et al., 2022) or coastal areas (Toimil et al., 2017) have been recently developed. Most authors aim to model the effects of CCs on coastal areas, regardless of the uncertainties derived through probabilistic approaches (Galiatsatou et al., 2018).

Concerning the Intergovernmental Panel on Climate Change (IPCC, 2014) risk framework, it is a foundational concept within climate science and risk assessment. At its core, the IPCC risk framework defines risk as the outcome of the interaction between three fundamental components:hazards, exposure and vulnerability (Figure 10.1).

Nicholls et al. (2021) provide a structured approach for developing sea-level scenarios under varying levels of data availability and risk assessment, emphasizing an iterative process that integrates new scientific insights while retaining valuable elements from previous assessments to enhance decision-making. Their work relies on the fact that in practice risk assessments and adaptation planning is conducted to different levels of detail requiring different levels of definition of the risk components, from

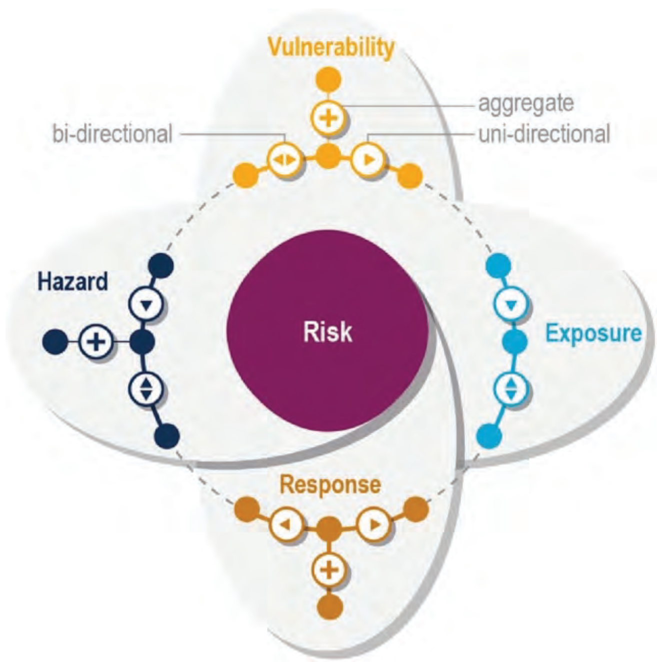


Figure 10.1 | IPCC assessment risk framework concerning multidimensional and intersectional vulnerability in the 6th Assessment Report (IPCC, 2022).

exploratory analysis to develop strategies and policies to highly detailed approaches to design adaptation solutions, as has been proposed in Chapter 5 (Tables 5.2 and 5.3). Their findings are presented in Table 10.1. Levels of assessment in the Table 10.1 are similar to Levels I, II and III in Chapter 5.

Conducting a risk analysis for a CDS, to be able to subsequently propose adaptation measures within a specific time horizon and an implementation plan, always responds to a specific need, which must be defined at the initial stage of the risk analysis. Therefore, it would be desirable to consider different key aspects from the outset, which will condition both the collection of information, the degree of granularity and the need to carry out detailed studies or not. Aspects such as identifying who are the primary and potential secondary recipients of the expected results, as well as their information needs, are very relevant. This conditions the analysis, since it will allow, if necessary, to use the results generated, with special consideration to possible technical, legal or financial requirements. In summary, the scope of the risk analysis for the CDS should be initially defined, taking into account the following: (1) the system at risk and its subsystems (sectors, agents and internal and external processes); (2) the geographical domain and its administrative framework; (3) the set of climate-related impacts that may occur on system components and subsystems (e.g. flooding, erosion, salinization, damage to protection works, coral bleaching, increased social vulnerability, etc.); (4) the climatic agents or their combination (e.g. temperature, mean sea level, waves, or total sea level; (6), inducers of such impacts and their future changes, both for their extremes (e.g. heat waves), mean values (e.g. mean annual temperature) or mean variability (e.g. frequency in intensity of El Niño) and long term (mean sea level rise); (5) the necessary level of detail and acceptable uncertainty for the risk analysis to be fit for purpose; (6) the spatial resolution of the assessment and the selection of the most appropriate analysis methodology (in general, the larger the area, the lower the spatial resolution and the greater the methodological simplification).

To better describe the specific aspects of hazard, a description of coastal climate drivers for risk analysis is followed in the next section.

10.3 | Coastal climate drivers of risk

10.3.1 | Introduction

The climate change adaptation cycle begins with a proper risk assessment. One of the main differentiating factors in coastal systems is the unique characterization of coastal hazards which do include both atmospheric and marine drivers. Beyond changes in long-term and extreme air temperature, precipitation and other relevant atmospheric variables, coastal applications are determined by the projections of marine drivers including changes in mean and extreme sea levels, coastal winds, waves, sea surface temperature and ocean acidification, among others.

Future projections of sea-level change at any coastal site comprises global-mean sea level rise (SLR) components, combined with regional and local SLR contributions. Additionally, extreme sea-level components due to astronomical tides, storm surges and wind waves must be considered to capture the full range of possibilities for risk and adaptation studies.

Unfortunately, not all the relevant marine variables are a direct outcome of Global or Regional Circulation Models (GCM, RCM) what adds a new layer of complexity and uncertainty to coastal adaptation (Toimil et al., 2021). Besides, the upgrading of existing or the design of new CDS high spatial resolution of the relevant climate variables requiring an extensive application of downscaling methods tailored for coastal applications (Lucio et al., 2024).

Nevertheless, projecting climate change-induced impacts and associated risks on coastal areas have been limited in climate change modeling. Most of previous works focus on coastal areas include changes in sea-level rise and wave heights in an uncoupled way. However, considering the combined effect of wave heights and water levels is essential for a realistic assessment of climate change impacts, particularly on coastal structures, where decreasing water depth plays a significant role. For instance, Fernández-Pérez et al. (2024b) demonstrate that, under climate projections and the compounded effects of wave action and sea level rise, the probability of failure of the outer armor layer of a rubble mound breakwater falls below the acceptable risk level. As a response, the study proposes an adaptation measure involving an adjustment in the weight of the armor units. Then, the aim must be including the latest developments related to climate change modeling at global and regional scale into a high-resolution analysis by solving transformation processes at the local scale as an essential part of the climate change-induced impact and risk assessment methodology. Such global and regional climate change projection databases are characterized by a realistic multivariate offshore wave climate modeling at hourly time-scale, including an accurate extreme value distribution (Lobeto et al., 2021).

In the following, we provide an overview of some of the most relevant climate drivers that need to be considered for CDS adaptation, based on risk analysis.

10.3.2 | Mean sea level

The mean sea-level change component includes sources of variability such as those due to ocean water thermal expansion, ice caps melt or terrestrial water storage. For coastal risks and adaptation applications the relative sea-level change, ΔRSL, for a specific location needs to be assessed, according to the following equation, Nicholls et al. (2021):

$$\Delta RSL = \Delta SL_{GMSL} + \Delta SL_{OD} + \Delta SL_{GRD} + \Delta SL_{VLM}$$

ΔRSL is the local change in mean relative sea level (the change between the ocean surface and the land /ocean floor); ΔSL_{GMSL} is the change in global-mean sea level; ΔSL_{OD} is the regional variation in mean sea level due to ocean dynamics (including the mean effect of atmospheric pressure changes); ΔSL_{GRD} is the regional variation in mean sea level resulting from the redistribution of mass between land and ocean, which leads to variations in gravitational, rotational and deformational effects and ΔSL_{VLM} is the local/regional change in sea level due to vertical land movement (uplift and subsidence).

Table 10.1 | Suggested use of climate, exposure, vulnerability and risk information for different levels of risk assessment.

SSP-RCP	BRIEF DESCRIPTION	GENERAL DESCRIPTION
SSP1-1.9	Most optimistic: 1.5°C in 2050 Very low GHG emissions: CO_2 emissions cut to net zero around 2050	Most optimistic IPCC scenario. Global CO_2 emissions are reduced to zero around 2050. Societies shift to more sustainable practices, moving from economic growth to general well-being. Extreme weather events are more frequent, but the world has dodged the worst impacts of climate change. Only one that meets the Paris Agreement target of keeping global warming to around 1.5°C above pre-industrial temperatures. Reaches 1.5°C but then declines and stabilizes at around 1.4°C by the end of the century.
SSP1-2.6	Next best: 1.8°C in 2100 Low GHG emissions: CO2 emissions cut to net zero around 2075	In the next best scenario, global CO_2 emissions are reduced dramatically, but not as rapidly, reaching zero emissions after 2050. Socioeconomic changes toward sustainability equivalent to SSP1-1.9. Temperatures stabilize at around 1.8°C above pre-industrials by the end of the century.
SSP2-4.5	Intermediate: 2.7°C in 2100 Intermediate GHG emissions: CO_2 emissions around current levels until 2050, then falling but not reaching net zero by 2100	Intermediate" scenario. CO_2 emissions hover around current levels before beginning to decline by mid-century, but do not reach zero by 2100. Socioeconomic factors follow their historical trends, with no noticeable change. Progress toward sustainability is slow, and development and income grow unevenly. In this scenario, temperatures rise 2.7°C by the end of the century
SSP3-7.0	Dangerous: 3.6°C in 2100 High GHG emissions :CO_2 emissions double by 2100	Emissions and temperatures rise steadily and CO_2 emissions roughly double from current levels by 2100. Countries become more competitive with each other, focusing on national security and securing their own food supply. By the end of the century, the average temperature will have risen by 3.6°C.
SSP5-8.5	To be avoided: 4.4°C in 2100 Very high GHG emissions: CO_2 emissions triple by 2075	It is a future to be avoided at all costs. Current levels of CO_2 emissions will roughly double by 2050. The world economy is growing rapidly, but this growth is fueled by the exploitation of fossil fuels and energy-intensive lifestyles. In 2100, the average global temperature is 4.4°C above pre-industrial values.

In general, mean sea-level projections are generated using GCMs provided by different international research institutions. The magnitude and rate of sea-level change resulting from climate change are obtained by forcing GCMs with estimates of future GHG emissions or atmospheric concentrations for different scenarios as shown in Table 10.1. But not all the components of sea level rise (SLR) are produced directly by the models, requiring the calculation using calculated offline data from other sources introducing large uncertainties. Detailed information on the calculation of SLR can be found in Special Report on the Ocean and Cryosphere in a Changing Climate (SROCC)and in the AR6 report (IPCC, 2021).

10.3.3 | Extreme sea levels

The so-called total sea level (TSL) at a given location results from the combination of the relative mean sea level, the astronomical tides, storm surges induced by changes in wind and atmospheric pressure and the contribution of waves to sea level, expressed as wave setup or runup. Therefore, changes in extreme sea levels and associated coastal impacts such as increased flooding, erosion, increased wave overtopping or damage to coastal structures will be site specific and dominated by one of the components or a combination of increasing magnitudes of several total sea level components. In general, changes in future extreme sea levels will be dominated by the relative sea level rise (RSLR). RSLR will increase the frequency of current extreme water levels and contributes to increase its magnitude. The increase in magnitude and frequency will depend on the shape of the present extreme probability distribution, the time horizon and GHG emission scenarios considered.

As per the changes in astronomical tides, rising sea levels will modify tidal wave propagation and therefore tidal range with more pronounced effects in estuaries and enclosed coastal areas. However, the tidal contribution will mostly be negligible compared to the other components of the TSL (Pickering et al. (2017) and have been ignored in earlier assessments.

However, recent advances in the modelling of global and regional storm surge climate projections (Muis et al 2016 and 2020) have allowed including the storm surge contribution into the modelling of future coastal impacts and adaptation planning. Changes in the storm surge climate can result from changes in frequency, intensity and/or tracks of extra-tropical and tropical storms and are especially relevant in coastal regions dominated by tropical storms or cyclones or in shallow water regions where the storm surge component dominates the TSL, like the North Sea or the Baltic.

10.3.4 | Waves

Even if waves contribute to the TSL as wave set-up or wave run-up, they deserve a specific section since wave height, period and direction are some of the most relevant parameters in the design of coastal protections.

The relationship between global warming and changes in wave climate was already established in Reguero et al. (2019) with several studies reporting significant wave height increasing trends in the southern hemisphere and decrease in several regions of the northern hemisphere. Subsequent studies have shown the future behavior of wind-wave extremes due to climate change (Meucci et al. 2020, Lobeto et al, 2021) or even changes to be expected in directional wave spectra under different emission scenarios (Lobeto et al., 2021). A detailed summary on the current knowledge on wave characteristics modelled projections under different scenarios can be found in Morim et al. (2020). Since AR6 report (IPCC, 2021)has been released continuous updates of global wave projections are undergoing. Still, most of the work cited refers to offshore wave conditions. Coastal adaptation of protection systems requires a detailed definition of nearshore wave conditions which is affected by the geographic location, coastal geomorphology and especially local bathymetry. This implies the need for downscaling the projected future wave climate making use of dynamic (Alvarez-Cuesta et al, 2021), statistical (Camus et al., 2017) or hybrid (Camus et al. 2019) downscaling techniques. The final decision of the downscaling technique to be chosen depends, among others ofthe spatial resolution to be achieved, the number of GMCs or RCMs used in the application, the availability and quality of local observations or the computational resources available.

10.3.5 | Compound effects

Natural climate impacts like floods, wildfires, heatwaves, and droughts may arise from interconnected physical processes occurring across various locations and timeframes (Zscheischler et al., 2018). This understanding could lead to more precise risk assessment for CDS. However, traditional risk assessment methods often concentrate on singular hazards or drivers, potentially underestimating climate-related risks unintentionally. This is because severe incidents typically result from the interaction of multiple factors with spatial or temporal correlations. In coastal areas, various elements can impact both natural and man-made systems, including coastal phenomena like storm surges and waves, as well as inland factors such as high river flows and heavy precipitation. Coastal flooding effects can exacerbate when these factors coincide or occur in close succession, within hours or days. Historically, risk assessments tended to evaluate these elements individually, mistakenly assuming their independence. Such oversight can lead to an underestimation of flood risks, particularly for coastal communities (Wahl et al., 2015; Zscheischler et al., 2020).

Regarding long-term wave climate modeling, multivariate statistical analysis has evolved over the decades to offer more realistic models and reduce uncertainty, transitioning from conditional approaches (Jonathan et al., 2010; Gouldby et al., 2014) to current copula methods (De Michele et al., 2007; Wahl et al., 2012). However, both multivariate approaches have limitations when considering other dependencies (autocorrelation and time-dependence) and different climate conditions (storm, regular, and calm wave conditions). Consequently, most wave climate studies identify primary statistical dependencies and focus on extreme (sea-storms) or central regimes (bulk of the met-ocean data).

Focusing on modeling compounding effects under climate change, risks are managed by adaptation strategies (Toimil et al., 2020), from the global and regional (Toimil et al., 2017a) to the local scale (Barnett et al., 2014). More recently, the use of the combination of climate emulators to facilitate multivariate extreme value analysis, with hybrid statistical–numerical wave propagation strategy has been effective to perform a compound modeling approach specific to coastal structure sites (Lucio et al., 2024). These advancements are designed to effectively manage multiple climate scenarios and models within the context of high uncertainty, in a climate change framework.

In summary, the focus of long-term wave climate modeling for coastal applications involves addressing extreme and regular conditions, both characterized by non-stationary multivariate events. Within coastal engineering, considerable attention has been directed towards extreme modeling. Copula-based methods, as applied in climate change studies, can utilize climate-dependent models (such as those by Camus et al. (2016) and Rueda et al. (2016), nested copulas (as seen in works by Wahl et al. (2012)), and autoregressive models (exemplified by Lira-Loarca et al., 2019) to describe non-independent climate data. When multivariate statistical methods are applied in an ocean site unaffected by sea-level influences on correlation patterns, coupling with a downscaling method becomes necessary. Consequently, climate change analysis involves probabilistic estimation of sea-level rise, playing a crucial role in wave propagation, especially as water depth decreases (Arns et al., 2017). Introducing a novel methodology, Camus et al. (2019) incorporates a time-dependent sea-level rise probability density function into the metamodel approach (originally proposed by Gouldby et al., 2014) based on the hybrid downscaling approach. This approach allows for consideration of the entire uncertainty cascade (Toimil et al, 2021; Lucio et al, 2024) from global wave data to local-scale impacts (Wilby et al., 2010), coupled with a non-deterministic temporal evolution of sea-level rise (Slangen et al., 2017), a crucial aspect in developing reliable impact-oriented frameworks with effective uncertainty management.

Table 10.2 | Examples of sources of information for coastal climate change related hazards.

Reference name	Access	Short description
NASA Sea Level Change	https://sealevel.nasa.gov	Provides observed and modelled data of sea level change together with several tools for data access, analysis and visualization
Coastal Futures (CoFu)	https://coastal-futures.org	A one stop viewer for 21st century projections of climatic impact-drivers leading to coastal impacts and risk
Copernicus Marine Service Including Coastal Services	https://marine.copernicus.eu	Providing free and open marine data and services to enable marine policy implementation, support blue growth and scientific innovation
IHData	https://ihdataprot-a.ihcantabria.com	Developed by IHCantabria provides access to wind, wave, and sea level observations and modelled data for coastal applications

10.3.6 | Data sources

There are different data sources that can be used as a starting point for coastal protection systems risk assessment or adaptation. Still, it must be said that wind, sea level and wave data are provided for offshore conditions, therefore requiring the use of downscaling techniques able to provide the necessary spatial resolution for applications.

One of the most recent compilations on the availability of observed and modelled marine climate data can be found in Elshinnawy et al. (2022). The report includes data basis corresponding to satellite information, tidal gauges, wave buoys, hindcast, reanalysis and projected wind, sea level and wave information.

Other important sources of information for coastal climate change related hazards can be found in Table 10.2.

10.3.7 | Current practice in building climate change scenarios and recommendations

To date there is no well-established practice on how to define scenarios for future coastal climate drivers. Scenarios may depend on the application, country experience and resources or decision-making level. However, several studies have compiled part of the current state of practice. Some of these results are presented here as they can be used as guidance.

Nicholls et al. (2021) provide a summary on how sea level scenarios might be developed with different levels of data availability and risk assessment. Their work relies on the fact that in practice risk assessments and adaptation planning is conducted to different levels of detail requiring different levels of definition of the risk components, from exploratory analysis to develop strategies and policies to highly detailed approaches to design adaptation solutions. Their findings are presented in Table 10.5. Levels of assessment in the Table 10.3 are similar to Levels I, II and III in Table 5.2 and 5.3, in Chapter 5.

Table 10.3 | Summary of sea-level components versus levels of assessment (Modified from Nicholls et al. 2021).

Sea-level component		Level of assessment		
		Detailed	Intermediate	Exploratory
Global sea-level change (including ice melt)	ΔSL_{GMSL}	For instance, AR6or similar source. Update with new IPCC reports when available. Include high-end scenarios (above IPCC range)		
Regional sea-levelchange	ΔSL_{OD}	Ocean dynamics (including mean effect of atmospheric pressure changes) driven deviations from individual models	Scale local deviations or similar, via pattern scaling	± 50% sensitivity 10 nálisis
	ΔSL_{GRD}	Model correction for GRD effects (IPCC)	Scale fingerprints with the projected time series	Assume no change
Vertical land movement (ΔSL_{VLM})	Due to natural causes	Intermediate level plus local observations e.g. GPS, long-term tide gauge observations or detailed geological analysis	Regional patterns of land motions from geological synthesis or GIA model estimates	Assume no change, except in river deltas where 1 or 2 mm/yr subsidence is expected
	Due to human-induced causes	Intermediate level plus analysis of subsidence potential, including driver prognosis (e.g. ground water extraction)	Synthesize changes based on geological setting, especially deltas and subsiding coastal cities	Assume no additional change to above, except in major cities located on river deltas and apply appropriate indicative subsidence values (e.g., 10mm/year as a sensitivity analysis)
Changes in wave, surge and/or tidal component to extreme sea level	ΔTSL excluding relative sea level rise	Modelling using local/ regional models or dynamical or statistical downscaling driven by climate models	Sensitivity study; e.g. no change and arbitrary increase (e.g., 10% increase of 100 year event) based on historical hindcast or observations	Assume no change

The IPCC reports provide the central part of the distribution and a range of possible estimates using process-based models. However, given the current gaps of knowledge about future levels, risk-averse practitioners often require information about plausible future conditions that lie in the tails of the SLR distribution with no robust probabilities. High-end estimates for risk assessment and adaptation planning are complementing the IPCC reports estimates and are based on expert evaluation of physical evidence and approaches currently used in policy environments to understand high end risk. For example, for global warming of +2°C in 2100 (RCP2.6/SSP1-2.6) relative to pre-industrial values high-end global SLR estimates are up to 0.9 m in 2100 and 2.5 m in 2300. Similarly, for a (RCP8.5/SSP5-8.5), estimates can reach up to 1.6 m in 2100 and up to 10.4 m in 2300 (van de Wal et al. 2022). These values largely exceed estimates developed based on climate models.

A global survey presented by Hirschfeld et al (2023) has shown that planners use widely varying sea-level rise projections for coastal adaptation. The main conclusion is that there is no global standard in the use of SLR projections. For global locations using astandard data structure, 53% are planning adaptation using a single SLR projection. The remainder areusing multiple projections, with 13% considering a low-probability high-end scenario. As expected, countries with histories of adaptation and consistent national support show greater assimilationof SLR projections into adaptation decisions. As per the magnitude used in the planning process Figure 10.2 present a comparison of SLR projections in meters for 2100, which respondents to the survey are using in their coastal plans and guidance documents.

Projections in Figure 10.1 are shown as box plotswith median values as the dark center line, the box representing the 25^{th} to 75^{th} percentiles, and the whiskers showing the full range of survey responses. Besides, projections are grouped by four projection structures (A to D), where A corresponds to practitioners using one singular estimate of SLR, B to those using a low and high estimate, C a low, intermediate and high estimate and D a low, intermediate, high and high-end estimate. The global distribution for the different categories is A (53,1%); B (14%); C (19,6%) and D (13,3%), indicating that over 50% of the respondents are using one singular estimate of SLR resulting in high uncertainty. Figure 10.1 does also include, for comparison, the IPCC Fifth Assessment Report (AR5, IPPC, 2014) and SROCC global projectionsshowing the “likely” ranges between the 17^{th} and 83^{rd} percentile.

The lack of specific guidance or recommendations and the range of possible combinations when building scenarios of coastal climate drivers to feed risk assessment processes or adaptation planning results in a high diversity of studies and approaches. However, it has beento highlight that one of the main goals in risk-averse practitioners or decision-makers is trying to map and reduce uncertainty as much as possible (Toimil et al, 2021; Lucio et al, 2024). The framework is designed to facilitate

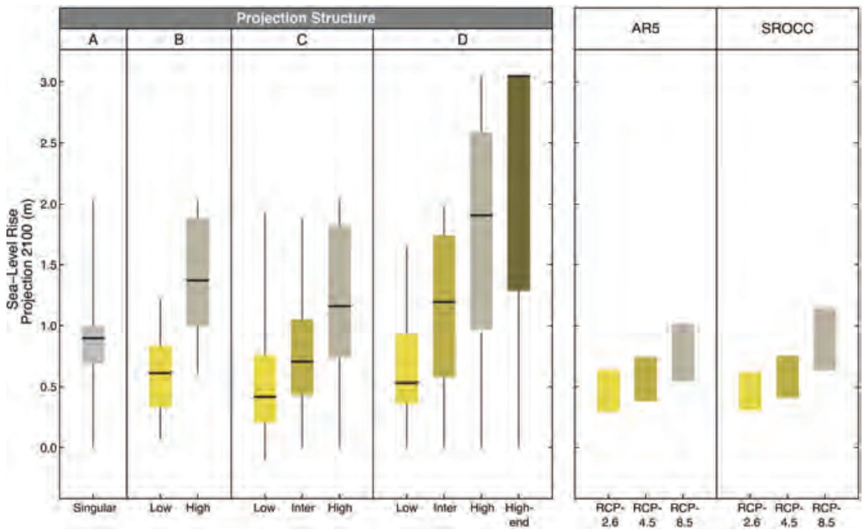


Figure 10.2 | Comparison of sea-level rise projections in planning and available science. (Source: Hirschfeld et al. (2023)).

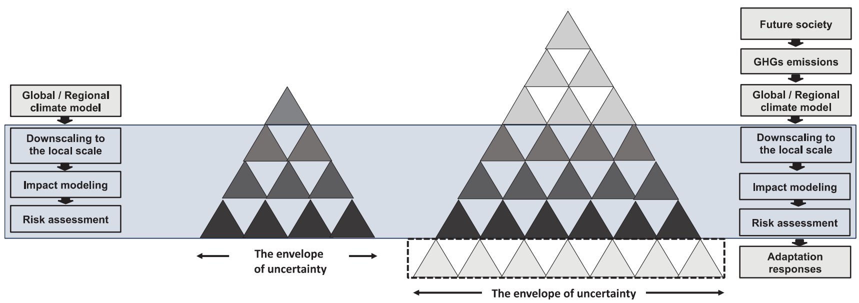


Figure 10.3 | Reference framework for the development of a methodology for assessing climate- related impacts and risks. Source: based on Lucio et al, (2024).

decision-making amidst substantial uncertainty. In this context, special emphasis should be placed on the cascade of uncertainty (depicted in Figure 10.3, elaborated based in Lucio et al., 2024), highlighting the importance of propagating uncertainties from global or regional-scale climate modeling to the assessment of climate-induced impacts and associated risks (Wilby et al., 2010). Consequently, managing uncertainty becomes dominant, even when analyzing the current climate scenario, as shown on the left side of Figure 10.3. However, it becomes particularly crucial when evaluating climate change-induced impacts and risks, as depicted on the right side of Figure 10.3. Climate change analysis introduces uncertainties related to projecting the future climate system. The process begins with defining a future society, which is based on the development of various scenarios involving different degrees of socio-economic development, population growth, land use patterns, and energy sources. These scenarios result in distinct greenhouse gas concentration trajectories that dictate the future interaction between policymaking and the climate system. By considering different representative concentration pathways, the third step involves modeling the ocean-atmosphere system at both global and regional scales. While this step is replicable under current climate conditions as it models the relationships between wind fields and the ocean surface, coastal areas represent highly localized interventions, necessitating the downscaling of global and regional databases to obtain high-resolution climate data tailored to site-specific conditions. These data are utilized to model interaction processes between climate dynamics and coastal infrastructure to assess expected impacts and risks or to plan adaptation responses, as explain in following sections.

10.4 | Mainstreaming climate change into conventional coastal defense systems design and adaptation

In section 10.3, we have provided an overview of current practice in coastal driver scenario building and recommendations for climate impact assessment and risk analysis as a preliminary step to complete the CDS adaptation process. We then propose an approach to integrate climate change impacts into conventional coastal protection and adaptation design. The main proposition is the fact that the current approach to the design of coastal structures can be integrated into the IPCC risk framework and is shown in Figure 10.4 (Fernandez et al., 2024a). The extrapolation of this framework of analysis to natural or hybrid systems is straightforward and involves the particularization in the definition of the elements of exposure and vulnerability specific to them.

According to the IPCC framework, a predefined Acceptable Level (AL) of impact or risk should be established when setting adaptation objectives, as stated in section 10.2. In this case, the AL can be defined as the minimum coastal protection system that will be considered operational, complying with the requirements of the use and survival of the different elements comprising the infrastructure. For example, following Fernández et al. (2024), the Limit State method can be used to characterize the performance of port infrastructures through Ultimate Limit States (ULS), Serviceability Limit States (SLS), and Operational Limit States (OLS). To determine the acceptable impact levels for each evaluated limit state, technical requirements of the infrastructures to be analyzed can be determined using current standards, which typically define a maximum allowed value for each impact based on the type of infrastructure and the expected socio-economic service. These limits are integrated into the characterization of the probability of infrastructure failure, both globally and for each of its components, as well as its functionality. Technical standards such as ROM in Spain, or design recommendations, such as those provided by PIANC for different infrastructures, link the economic consequences of infrastructure failure and loss of functionality to extreme events, and social and environmental aspects to operation during the occurrence of average climatic events can be used. Another important aspect is determining the lifespan of the infrastructures that make up the Coastal Defense Systems (CDS), which is determined based on the type of infrastructure. This aspect varies depending on local regulations but is a key factor in characterizing and planning changes in the infrastructures within a framework of unsteady climate conditions and high uncertainty.

The next step corresponds to hazard assessment (blue box in Figure 10.4), where met-ocean variables (correspondingto sea waves, wind and sea level and other atmospheric variables that could be involvedas wind or precipitation) are obtained at coastal structure of coastal protection systems

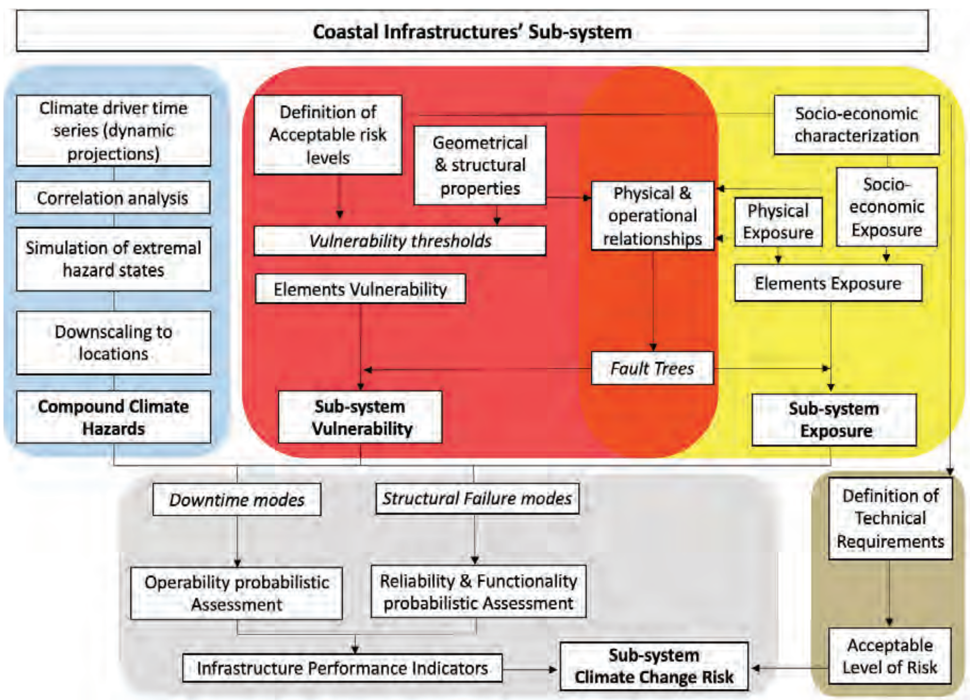


Figure 10.4 | Workflow for climate change derived compound risk for coastal infrastructures subsystems (based on Fernandez et al., 2024a).

atlocal scale according to section 10.2. This is a necessary preliminary step to assess how these climatic factors and their expected medium- and long-term variations induced by climate change may alter the socioeconomic environment in which they are integrated. Thus, the characteristics of the CDS will determine the number and type of impacts to be assessed, as well as the extent to which a given degree of impact is acceptable. Thus, a coastal defense characterized by a detached breakwater that protects a beach will require information on waves and sea level, in all its components, as mentioned in section 10.3, for the characterization of coastal flooding and the functionality and structural integrity of the infrastructures. However, a coastal area, with a dune system protecting an estuary with fluvial input, will require, in addition to the above, information on precipitation and ecological status of the dune system, for impact assessment. It is important to note that it may be necessary to evaluate the occurrence of composite climate events to assess impacts, including for marine and atmospheric drivers. This requires downscaling of the variables involved with the same degree of spatial and temporal resolution for the climate projections used.In addition, critical impacts that are assessed for critical coastal infrastructure may not be viewed as crucial when evaluating infrastructure that hosts tourist areas, for example, and their resulting consequences should not be treated in the same way. Thus, impact assessment criteria should not be limited to technical factors, but should also consider the social, cultural, economic, administrative and environmental implications of the disruptions and failures of the assessed infrastructures.

The second component of risk, exposure (yellow box in Figure 10.4), is defined by evaluating subelements of the CDS and considering their interactions and physical and operational relationships. It can be viewed as complex system comprising various interconnected subsystems. For instance, in the case of a beach with a dune system protecting an estuary, the beach itself constitutes a subsystem composed of submerged and emerged beach profiles, including the dune system and any associated constructions or infrastructure. The estuary, along with its inlet and internal natural and anthropogenic elements, represents another subsystem. Understanding their interrelation is essential for comprehending the overall functionality of the coastal zone, necessitating both individual and simultaneous evaluation of impacts. Marine climate hazards affect these sub-elements heterogeneously, with different sources of impact, potentially leading to additional impacts on various subsystems. Exposure is thus defined by a comprehensive classification of all components of the CDS, both natural and anthropogenic, identifying those susceptible to climatic impacts and incorporating those located at sea and on land. The impact analysis can be conducted for each sub-element individually, considering single or compound effects of climatic factors, and subsequently aggregated to assess the consequences for the entire system.

The third component, vulnerability (red box in Figure 10.4), is expressed in terms of vulnerability functions for the exposed elements, based on technical, environmental, and socio-economic requirements. Vulnerability depends on factors such as limit state definitions, geometric properties, and materials used in the protection system.

Combining hazards, exposure, and vulnerability for a given set of impacts enables the aggregation of their consequences for different subsystems to compute the total consequence for the global system. Firstly, the combination of exposure and vulnerability allows for a probabilistic approach, where failure trees of subsystems can be defined if a level III of approach is defined (Table 10.1). This approach incorporates the uncertainty of design variables, including climate forcing, design formula coefficients, and structural geometry and material parameters, for both new and existing structures. Characterizing disruptive mechanisms representing the interaction of analyzed elements and climate hazards through vulnerability curves allows impacts to be identified when parameters exceed vulnerability thresholds defined by the Acceptable Level (AL). If a level I approach is followed, hazard is defined based on expert judgement, or pre-defined thresholds based on historical information or existing guidelines. Risk is expressed in terms of consequences with a qualitative risk scale (i.e.:. low to high) or colour code based on experts' criteria.Note that the framework shown in Figure 10.4 applies regardless of the degree of definition in the characterization of the different risk components.

Quantifying disruptive mechanisms for present and future climate scenarios detects situations where AL are not met. This can be achieved by defining impact indicators aligned with AL, by probabilistically quantifying the probabilities of exceeding AL, considering composite events for both climate drivers and impacts or by experts' criteria. Only the first method enables uncertainty limitation and optimization of adaptation measures, including their intensity and temporal implementation. The process should be iterative, allowing for the evaluation of different measures and selection of the most suitable one through cost-benefit analysis. Additionally, implementation barriers related to administrative, social, cultural, and environmental factors should be considered.

10.5 | Adaptive capacity of coastal defense systems

The preceding section has introduced a methodological framework, based on the IPCC risk framework, for evaluating the performance of CDS by defining the Acceptable Level (AL) of impact or risk, regardless of the level of approximation. This methodology delineates instances when these Als are exceeded, both currently and in the future, along with their frequency. Consequently, it addresses two fundamental questions: (1) when adaptation of a CDS necessary is, and (2) to what extent, considering

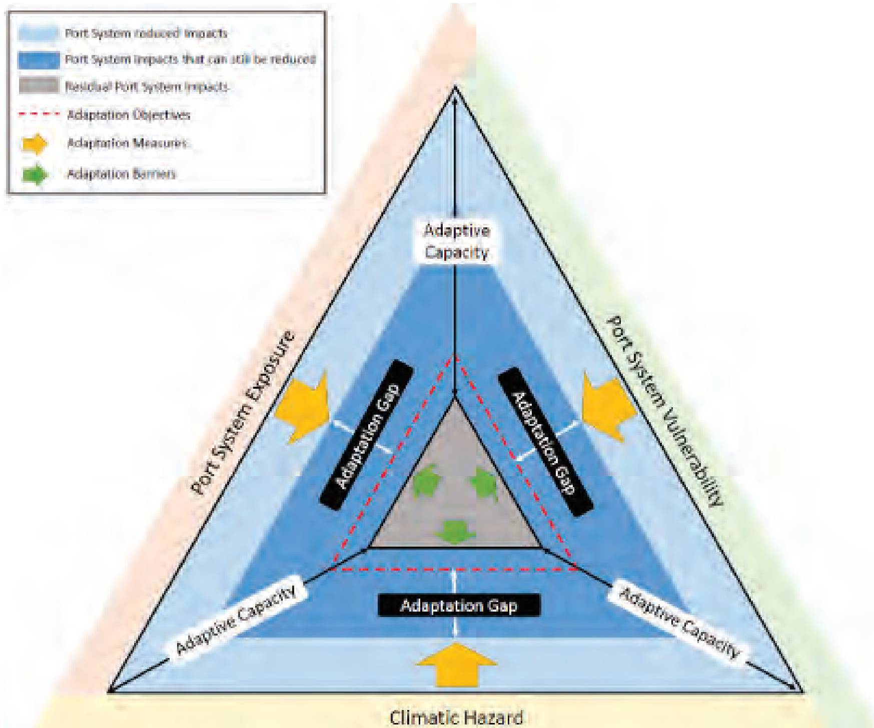


Figure 10.5 | Adaptation Space for port infrastructures. (Based on Fernandez et al., 2024a).

a probabilistic multi-hazard compound impact assessment framework or a simplified approach based on expert criteria that encompasses economic, social, environmental, and administrative factors.

However, the acceptability and physical and economic feasibility of adaptation measures, as well as the potential residual consequences and specific area conditions, may not be readily applicable. Hence, a coherent and robust assessment of an adaptation plan necessitates determining the adaptation space. Given the unique characteristics of coastal areas, this requires analyzing a multidimensional space, considering the multi-risk and multi-exposure nature of the various elements, services, and infrastructures they encompass (Shavazipour et al., 2021).

The proposed methodological framework is based on the IPCC (2022), which follows the definition of an adaptation space as the solution space (Haasnoot et al., 2020) where efforts to reduce climate change-induced impacts are to be defined. This space is defined as the interaction of three different elements: (1) Adaptation Objectives, (2) Adaptive Capacity, and (3) Adaptation Gap.

Adaptation objectives are defined as the minimum conditions required for acceptable performance of the evaluated element or system, previously referred to as AL in the preceding section. Adaptive capacity of a system is defined as its ability to adjust, be adjusted, or respond to potential impacts. In the context of CDS, it can be identified as the level of risk reduction achievable through the implementation of a series of adaptation measures. These measures must be feasible and acceptable, meaning they are technically and economically viable and socially and environmentally acceptable. The assessment of Adaptive Capacity is carried out by identifying the main barriers to adaptation within the system, which may include social acceptance, economic viability, administrative feasibility, and lastly, environmental barriers. Finally, the adaptation gap is defined as the difference between the adaptation implemented and the Adaptation Objectives. In the context of CDS, the adaptation gap corresponds to the impacts that have not yet been reduced through adaptation but may be diminished by future feasible adaptation measures within the adaptive capacity of the system.

Figure 10.5 illustrates the relationships among the elements, where the adaptation space is delineated by bold and thick lines, encompassing both the impacts that have already been addressed and those that need to be reduced. The considered adaptation measures play their role within the adaptation space, reducing climate change-induced impacts. However, they cannot surpass the Adaptive Capacity of the system due to their interaction with adaptation barriers. Characterizing the adaptation space allows for the coherent preparation and assessment of a set of adaptation measures with achievable impact reduction goals, considering the elements and characteristics of the system that can affect the effectiveness of these measures or prevent their implementation. Nonetheless, prior to characterizing the adaptation space, it is essential to identify the impacts to which adaptation is required.

Additionally, the dynamic interaction between assessed infrastructure and its environment drives the dynamic nature of adaptation limits and needs, with technical requirements, codes, infrastructure uses, location, and stakeholders' perceptions potentially changing throughout the infrastructure's lifespan. Coupled with the uncertainty of climate change variability (and its impact on evaluated coastal and port infrastructures, this highlights the importance of incorporating flexibility into infrastructure adaptation planning. While the concept of flexibility has been extensively theorized (Haasnoot et al., 2013) and applied in urban (Rosenzweig et al., 2014) and riverine management plans (Bloemen et al., 2018), its application in coastal areas is less common in the literature.

Hence, there's a need for flexible adaptation frameworks for CDS based on quantified compound climate risk assessments to seamlessly integrate proposed adaptation measures for a changing climate into flexible port management planning. Within this framework, the proposed method shown here for adaptation based on risk assessment enables the combination of defined adaptation options in a flexible manner. It evaluates not only the effectiveness of measures in reducing climate change impacts but also how options can be followed by further measures if necessary, quantified by the flexibility proxy. Moreover, the introduced flexibility allows for adaptation schemes considering the concatenation of optimized actions. These flexible adaptation plans are characterized by quantifying their solution space, where multiple predefined options exist, but the selection of implemented measures may depend on stakeholder preferences or future hazard variable progress. This reduces social and climate change-derived uncertainties and their impacts on adaptation planning. Several examples will be discussed in following sections.

10.6 | Decision making approaches

The flexible adaptation framework outlined in preceding sections aims to facilitate the development of an adaptive plan capable of navigating conditions characterized by deep uncertainties stemming from climate change scenarios and the socioeconomic evolution of coastal areas. It enables decision-makers to keep options open and avoid rigidly adhering to a single predefined path when shaping the adaptation plan. This tool offers valuable guidance to decision-makers by presenting various adaptation options that can be considered while introducing flexibility into the adaptation planning process.

One of the most significant and attractive aspects of this method is its capacity to rationalize investment expenditure in coastal adaptation, thereby preventing decision-makers from committing to solutions that may not be optimal for addressing long-term problems. By refraining from selecting a specific adaptation measure prematurely, the method mitigates the risk of maladaptation due to the high uncertainty and dynamic nature of climatic, environmental, social, and economic conditions in the future. Decision-makers can develop a strategy that adapts to changing circumstances over time and adjust it as different risk components (hazard, exposure, and vulnerability) evolve. The approach acknowledges that while immediate decisions may not always be feasible, they can be planned, prioritized, and prepared for. The transition from one pathway to another occurs when a tipping point is reached. The concept of a tipping point, widely discussed in climate change research literature, refers to the point at which a system change, initiated by an external forcing, no longer requires the external forcing to sustain the new pattern of change (Kwadijk, 2010). In adaptation, a tipping point is reached when the magnitude of climate impact or risk is such that the CDS can no longer achieve its objectives, necessitating new actions or implementations to attain them. To successfully implement these new measures, a lead time is essential, anticipating the moment when the tipping point is reached to ensure that the adaptation measure is fully operational when needed. The lead time depends on various factors, including technical aspects required for design and implementation, as well as administrative and legal considerations. Additionally, the implementation of an active monitoring plan is essential to identify when the system is nearing a tipping point and accurately quantify the lead time required.

One of the early applications of the methodology occurred during the design and construction of London's flood defenses, with a focus on the Thames Barrier, as outlined by Bloemen et al. (2018). This extensive project spanned 30 years, from the decision to build to its operational phase. The project's uniqueness necessitated consideration of the impacts of climate change. A decision pathway was established, projecting outcomes until the year 2100, accounting for various climate change scenarios and sea-level rise projections, along with alternative adaptation options.Rather than being time-bound, the decision pathway was based on future points at which investment would be necessary, contingent upon the progression of climate change and sea-level rise. This approach ensured the functionality of the system while reducing uncertainty regarding potentially inefficient designs and rationalizing public investments. Importantly, this method allows for the integration of new scientific and technological advancements as they become available (Reeder et al., 2011). For instance, the decision pathway permits short-term measures, such as enhancing existing defenses, without ruling out the possibility of constructing a new barrier. However, the initiation of the latter is deferred until future conditions meet specified thresholds and it becomes evident that more cost-effective options have been exhausted. Clear timelines for these actions have been established to facilitate effective implementation, and the transition from one pathway to another, involving different courses of action, is considered as part of the initial planning process.

More specifically for coastal structures, the methodological framework introduced by van Gent (2019) provides a flexible and dynamic alternative to the static methods promoted by Burchard et al. (2014). Van Gent (2019) examines adaptation options aimed at mitigating wave overtopping on a rubble-mound breakwater by incorporating various elements into the structure. The effectiveness of each adaptation is evaluated in terms of its capacity to reduce wave overtopping under evolving mean sea level conditions over time (Figure 10.7).

A common aspect between the work of Bloemen et al. (2018)and van Gent (2019) is that they focus their entire framework for future adaptation on a single climate driver, which is mean sea-level rise. More recently, Lucio et al. (2024) expands this framework by considering not only climate projections of mean sea-level rise but also projections of other marine and atmospheric climate drivers, such as waves or wind, and their combined effect and impact, for the design of adaptation measures for coastal and port structures. Likewise, it combines different limit stated linked to the hydraulic response of the coastal structures in the analysis. This proposal, like the previous ones, define action

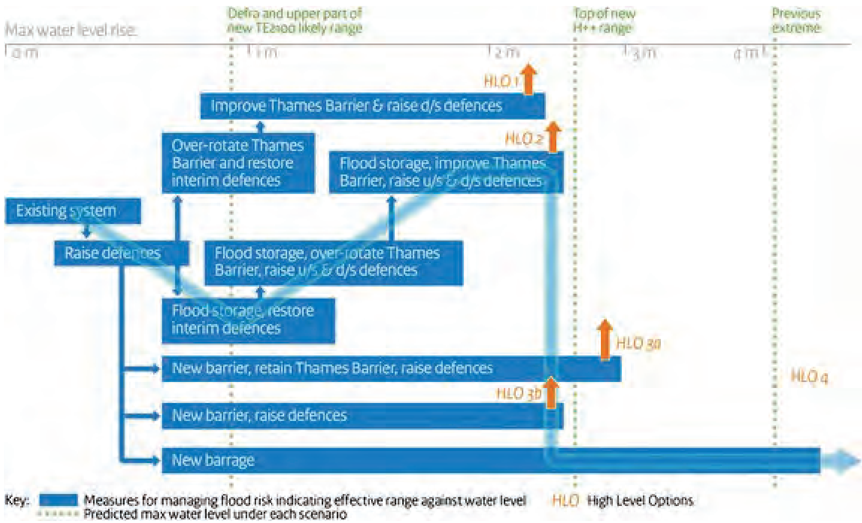


Figure 10.6 | Adaptation pathway map for the Thames Estuary (Environment Agency UK 2012a) (Source: Bloemen et al., 2018).

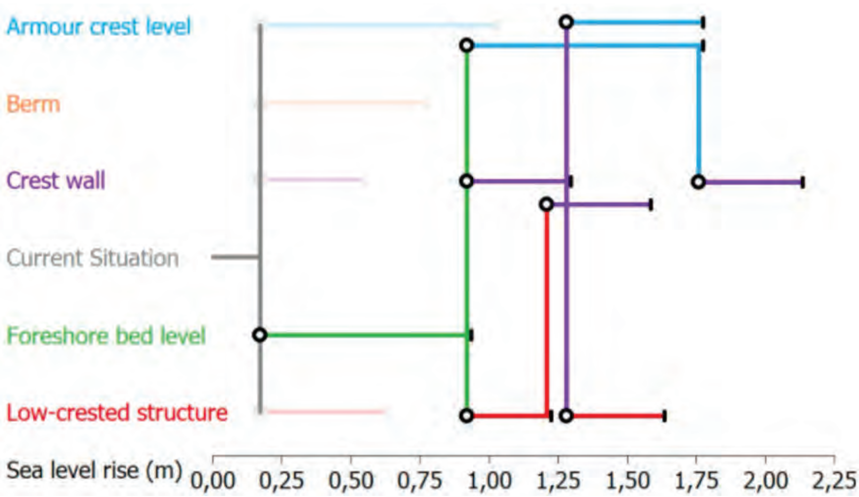


Figure 10.7 | Adaptation pathway map for a rubble-mound breakwater(Source: van Gent et al., 2023).

points based on exceeding a threshold of climatic variables to switch pathways and options for an alternative measure. Fernandez et al. (2024a) further expands this framework to the analysis of the

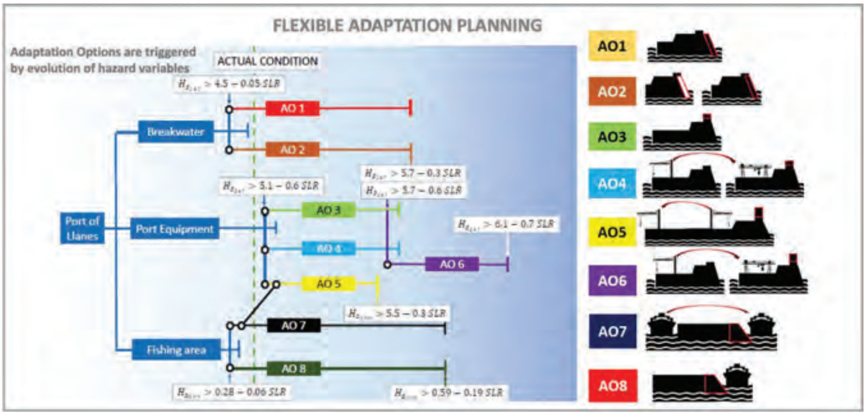


Figure 10.8 | Proposed flexible adaptation planning for Port of Llanes (Spain).

entire port, considering different drivers and their impact on various subsystems, developing proposals for flexible adaptation plans. In this analysis, pathways are defined based on risk, and a series of impact and risk indicators are established, based on an increase in risk and a reduction in the functionality and structural safety of port elements. Exceeding the risk increase indicators triggers a change in the adaptation pathway. Figure 10.8 shows an example of the adaptation plan for the port of Llanes (Spain), in which different adaptation options are highlighted based on climatic driver variations and the induced risk.

10.7 | Gaps, conclusions and recommendations

CDS serve as crucial defenses to protect vital infrastructure from threats posed by climate hazards in coastal areas. In light of climate change, it is imperative to strengthen adaptation planning with the latest science drawn from climate change modeling, impact assessments and risk analyses. Moreover, it's essential not only to translate the implications of future climate policies into actionable strategies tailored to the performance of CDS at the local level but also to systematically track and address uncertainties throughout the planning process. Addressing these challenges necessitates the implementation of an uncertainty cascade at different granularity, requiring methodologies that encompass a range of plausible climate change scenarios stemming from various climate policies, the utilization of multiple climate models to project future conditions, the application of high-fidelity downscaling strategies to tailor projections to specific coastal infrastructure sites, and the use of high-resolution impact and risk assessment tools commonly employed in the design process.

In addition, the latest IPCC Assessment Report (IPCC, 2022) emphasizes the urgent need to integrate CDS (manmade and natural) adaptation to climate change (CC) into national plans, a matter already addressed by various institutions. Although some countries are already implementing special plans and policies, much work remains to be done. Furthermore, it advocates considering adaptation within risk assessments not as a mere immediate action, but as a process of continuous interaction between a changing climate, the elements requiring adaptation, and the affected environment, communities and policy makers. This highlights the importance of avoiding blindfolded low-risk measures that could inadvertently block future actions needed due to unforeseen side effects and uncertain impacts of climate change, known as maladaptation. Further research could explore how certain measures might lead to lock-in situations or unforeseen collateral effects. In addition, the dynamic nature of the boundaries and adaptation needs is driven by the interaction between the CDS and its environment, influenced by technical requirements, codes, uses of different component elements (infrastructure, or ecosystems), location and stakeholder perceptions, which may vary over the lifetime of the infrastructure or ecosystems. This variability, coupled with the uncertainty of climate change variability and its impact on the CDS, underscores the need to incorporate flexibility into adaptation planning.

The degree of granularity required is a function of the purpose of the analysis and the needs required for the implementation of the adaptation. There is a need to develop flexible adaptation frameworks for CDS, based on quantified assessments of compound climate risks when possible, in order to consistently integrate proposed adaptation measures for a changing climate into flexible coastal management planning. The combination of adaptation options defined in a flexible framework, assessing not only the effectiveness of the measures in reducing climate changeimpacts, but also how the options can be followed by other measures if needed, quantified by the flexibility proxy. Furthermore, the flexibility introduced allows for adaptation schemes that consider the concatenation of optimized actions, where different adaptation options are proposed in different timeframes, leaving room for potential improvement of the planned measures.

Although in this chapter we have presented some necessary ideas within the adaptation design process, there is still much work to be done in the future. We have shown examples of different methodologies, which with different degrees of approximation can lead to risk assessments, and which respond to concrete questions, which must be defined from the beginning of the adaptation process, and which must be carried out in accordance with the environmental, economic and social conditions in each specific case.

References

1 Álvarez-Cuesta, M., Toimil, A., Losada, I.J., 2021: Modelling long-term shoreline evolution in highly anthropizedcoastal areas. Part 2: Assessing the response to climate change. Coastal Engineering 168, 103861.

2 Arns, A., Dangendorf, S., Jensen, J., Talke, S., Bender, J., Pattiaratchi, C., 2017. Sea-level rise induced amplification of coastal protection design heights. Scientific Reports 7, 40171.

3 Barnett, J., Graham, S., Mortreux, C., Fincher, R., Waters, E., Hurlimann, A., 2014. A local coastal adaptation pathway. Nature Climate Change 4, 1103–1108.

4 Bloemen, P., Reeder, T., Zevenbergen, C., Rijke, J., & Kingsborough, A. (2018). Lessons learned from applying adaptation pathways in flood risk management and challenges for the further development of this approach. Mitigation and Adaptation Strategies for Global Change, 23(7), 1083–1108.

5 Burcharth, H. F. (1992). "Introduction of partial coefficients in the design of rubble mound breakwaters," in Coastal structures and breakwaters (London, England: Thomas Telford), 543–566.

6 Burcharth, H. F. (1993). "Reliability evaluation and probabilistic design of coastal structures," in International seminar on hydro-technical engineering for future development of ports and harbors (Un'yushō Kō wanGijutsuKenkyū jo).

7 Burcharth, H. F., Andersen, T. L., and Lara, J. L. (2014). Upgrade of coastal defence structures against increased loadings caused by climate change: A first methodological approach. Coast. Eng. 87, 112–121. doi: 10.1016/j.coastaleng.2013.12.006

8 van Gent, M.R.A. and D.Y.Y. Teng (2023): Climate adaptation of coastal structures: Application of adaptation pathways for rubble mound breakwaters, Proc. PIANC-COPEDEC X, Manila.

9 Reeder, T., & Ranger, N. (2011). How do you adapt in an uncertain world? Lessons from the Thames Estuary 2100 project. World Resources Report 2010–2011: Decision Making in a Changing Climate, 101–117.

10 Camus, P., Losada, I.J., Izaguirre, C., Espejo, A., Menendez, M., Pérez, J, 2017: Statistical wave climate projections for coastal impactassessments. Earth's Future 5, 918–933.

11 Camus, P., Rueda, A., Meíndez, F., Losada, I.J., 2016. An atmospheric-to-marine synoptic classification for statistical downscaling marine climate. Ocean Dynamics 66, 1589–1601.

12 Camus, P., Tomás, A., Díaz-Hernández, G., Rodriguez, B., Izaguirre, C., Losada, I.J., 2019: Probabilistic assessment of port operation downtimes under climate change. Coastal Engineering, 147, 12–24.

13 Coastal Engineering Manual (CEM) (2002), U.S. Army Corps of Engineers, Engineer Manual 1110-2-1100, U.S. Army Corps of Engineers, Washington, D.C. (6 volumes).

14 De Michele, C., Salvadori, G., Passoni, G., Vezzoli, R., 2007. A multivariate model of sea storms using copulas. Coastal Engineering 54, 734–751.

15 Elshinnawy, A.I., Menendez, M., Losada, I.J., Melet, A., Le Cozannet, G. et al., 2022: Deliverable 3.1. Report on the state of the art: Climate databases, review and evaluation. Coclico Research and Innovation Action. 129 pages. https://coclicoservices.eu/wp-content/uploads/2022/12/WP3_D3.1.Report-on-the-state-of-the-art.pdf

16 Fernandez, A., Losada, I.J., Lara, J.L. (2024a) A framework for climate change adaptation of port infrastructures. Coastal Engineering Coastal Engineering. 191, 104538.

17 Fernandez-Perez, A., Lara, J.L, Lucio, D., Losada, I.J. (2024b) Compound climate change risk analysis for port infrastructures. Coastal Engineering, 2024, 193, 104560

18 Galiatsatou, P., Makris, C., Prinos, P., 2018. Optimized reliability based upgrading of rubble mound breakwaters in a changing climate. J. Mar. Sci. Eng. 6 (3).

19 Gouldby, B., Meíndez, F., Guanche, Y., Rueda, A., Miínguez, R., 2014. A methodology for deriving extreme nearshore sea conditions for structural design and flood risk analysis. Coastal Engineering 88, 15–26.

20 Haasnoot, M., J.H. Kwakkel, W.E. Walker, and J. ter Maat, 2013: Dynamic adaptive policy pathways: a method for crafting robust decisions for a deeply uncertain world. Global Environment Change, 23(2), 485–498.

21 Haasnoot, M., Kwakkel, J. H., Walker, W. E., & ter Maat, J. (2020). Dynamic adaptive policy pathways: A method for crafting robust decisions for a deeply uncertain world. Global Environmental Change, 60, 102033.

22 Hill, K., Hirschfeld, D., Lindquist, C., Cook, F., & Warner, S. (2023). Rising coastal groundwater as a result of sea-level rise will influence contaminated coastal sites and underground infrastructure. Earth's Future, 11, e2023EF003825.

23 Hirschfeld, D., Behar, D., Nicholls, R.J., Cahill, N., James, T., Horton, B.J. et al., 2023: Global survey shows planners use widely varying sea-level rise projections for coastal adaptation. Communications Earth & Environment 4:102.

24 Intergovernmental Panel on Climate Change (IPCC). (2019). Special Report on the Ocean and Cryosphere in a Changing Climate. H.-O. Pörtner, D.C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, M. Nicolai, A. Okem, J. Petzold, B. Rama, N. Weyer (Eds.). IPCC. https://www.ipcc.ch/srocc/

25 IPCC, (2014) Climate change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Report of the Intergovernmental Panel on Climate Change, Geneva, Switzerland, 151 pp.

26 IPCC (2019) Special Report on the Ocean and Cryosphere in a Changing Climate. Report of the Intergovernmental Panel on Climate Change, Cambridge, UK and New York, NY, USA, 755 pp.

27 IPCC (2021) Summary for Policymakers. En: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Masson-Delmotte et al. (Eds.). Cambridge University Press. In Press.

28 IPCC (2022). Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)]. Cambridge University Press.23. Cambridge University Press, Cambridge, UK.

29 IPCC (2023) Climate change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Report of the Intergovernmental Panel on Climate Change, Cambridge, UK and New York, NY, USA, 84 pp.

30 Izaguirre, C., Losada, I.J., Camus, P., Vigh, J., Stenek, V., 2021. Climate change risk to global port operations. Nature Climate Change 11, 14–20.

31 Jebbad, R., Sierra, J. P., Mösso, C., Mestres, M., and Sánchez-Arcilla, A.: Assessment of harbour inoperability and adaptation cost due to sea level rise. Application to the port of Tangier-Med (Morocco), Appl. Geogr., 138, 102623,

32 Jonathan, P., Flynn, J., Ewans, K., 2010. Joint modelling of wave spectral parameters for extreme sea states. Ocean Engineering 37, 1070–1080.

33 Konidari, P., & Mavrakis, D. (2006). Multi-criteria evaluation of climate policy interactions. Energy Policy, 34(17), 2683-2694.

34 Kwadijk, J.C., Haasnoot, M., Mulder, J.P., Hoogvliet, M.M., Jeuken, A.B., van der Krogt, R.A., van Oostrom, N.G., Schelfhout, H.A., van Velzen, E.H., van Waveren, H., de Wit, M.J., 2010. Using adaptation tipping points to prepare for climate change and sea level rise: A case study in the Netherlands. Wiley Interdisciplinary Reviews: Climate Change 1, 729–740. doi:10.1002/ wcc.64.

35 Lawrence, J., & Haasnoot, M. (2017). Facing the future: Building a robust strategy for climate change adaptation in the Netherlands. Water, 9(9), 672.

36 Lira Loarca, A., Cobos, M., Besio, G., Baquerizo Azofra, A., 2021. Projected wave climate temporal variability due to climate change. Stochastic Environmental Research and Risk Assessment 35, 1–17.

37 Lobeto, H., Menendez, M., Losada, I.J, Hemer, M., 2022: The effect of climate change on wind-wave directional spectra. Global and Planetary Change 213, 103820.

38 Lobeto, H., Menendez, M., Losada, I.J., 2021: Future behavior of wind-wave extremes due to climate change. Scientific Reports 11:7869.

39 Lucio, D., Lara, J.L.., Tomas, A., Losada, I.J. (2024) Projecting compound wave and sea-level events at a coastal structure site under climate change. Coastal Engineering, 185, art. no. 104380.

40 Meucci, A., Young, I. R., Hemer, M., Kirezci, E. & Ranasinghe, R. Projected 21st century changes in extreme wind-wave events. Sci. Adv. 6, eaaz7295 (2020).

41 Meucci, A., Young, I.R., Hemer, M., Kirezci, E., Ranasinghe, R., 2020: Projected 21st century changes in extreme wind-wave events. Science Advances, 6 (24) DOI: 10.1126/sciadv.aaz7295.

42 Morim, J., Hemer, M., Cartwright, N., Strauss, D., and Andutta, F. (2018). On the concordance of 21st century wind-wave climate projections. Global planetary Change 167, 160–171. doi: 10.1016/j.gloplacha.2018.05.005

43 Morim, J., Trenham, C., Hemer, M., Wang, X.L., Mori, N., Casas-Prat, M. et al, 2020: A global ensemble of ocean wave climate projections from CMIP5-driven models. Scientific Data, 7: 105. https://www.nature.com/articles/s41597-020-0446-2.

44 Muis S, Apecechea MI, Dullaart J, de Lima Rego J, Madsen KS, Su J, et al, 2020: A high-resolution global dataset of extreme sea levels, tides, and storm surges, including future projections. Frontiers in Marine Science, 7 (263) https://doi.org/10.3389/fmars.2020.00263.

45 Muis S, Verlaan M, Winsemius HC, Aerts JCJH, Ward PJ, 2016: A global reanalysis of storm surges and extreme sea levels. Nature Communications, 7:11969 https://doi.org/10.1038/ncomms11969.

46 Muis, S., Güneralp, B., Jongman, B., Aerts, J. C., & Ward, P. J. (2020). Flood risk and adaptation strategies under climate change and urban expansion: A probabilistic analysis using global data. Science of the Total Environment, 710, 136156.

47 Muis, S., Verlaan, M., Winsemius, H. C., Aerts, J. C., & Ward, P. J. (2016). A global reanalysis of storm surges and extreme sea levels. Nature Communications, 7(1), 1–9.

48 Nicholls R.J., Hanson, S.E., Lowe, J.A., Slangen, A.B.A., Wahl, T., Hinkel, J., Long, A.J., 2021: Intergrating new sea-level scenarios into coastal risk and adaptation assessments: An ongoing process. Wiley Interdisciplinary Reviews: Climate Change 12 (3) e706. DOI: 10.1002/wcc.706

49 Nicholls RJ, Verlaan M, et al., 2017: The impact of future sea-level rise on the global tides. Continental Shelf Research, 142: 50–68 https://doi.org/10.1016/j.csr.2017.02.004.

50 PIANC, 2016. Report No 196-2016. Criteria for the selection of breakwater types and their re- lated optimum safety levels. The World Association for Waterborne Transport Infrastructure.

51 Pickering, M. D., Wells, N. C., Horsburgh, K. J., Green, J. A. M., & Souza, A. J. (2017). The impact of future sea-level rise on the global tides. Continental Shelf Research, 142, 50–68.

52 Reguero, B.G., Losada, I.J., Mendez, F.J. (2019). A recent increase in global wave power as consequence of oceanic warming. Nature Communications. 10:205.doi: 10.1038/s41467-018-08066-0

53 ROM 1.0-09 (2010). Recommendations for the project design and construction of breakwaters (Part 1: Calculation and Project Factors. Climate Agents). Spain: Puertos del Estado.

54 ROM0.0-01, 2001. Spanish Recommendations for Maritime Structures. General procedure and requirements design of harbor and maritime structures. Part I. Puertos del Estado, Spanish Ministry of Public Works and Transport, 220 pp.

55 ROM1.0-09, 2009. Spanish Recommendations for the Project Design and Construction of Break- waters. Part I: Calculation and Project Factors. Climate Agents. Puertos del Estado, Spanish Ministry of Public Works and Transport, 532 pp.

56 ROM1.1-18, 2018. Spanish Recommendations for Maritime Works: Recommendations for Break- water Construction Projects. Puertos del Estado, Spanish Ministry of Public Works and Transport, 222 pp.

57 ROM3.1-99, 1999. Spanish Recommendations for Maritime Port Configuration Design: Ap- proach channel and Harbour basin. Puertos del Estado, Spanish Ministry of Public Works and Transport, 435 pp

58 Rosenzweig, C., & Solecki, W. (2014). Climate change adaptation in New York City: Building a risk management response. Annals of the New York Academy of Sciences, 1336(1), 298–308.

59 Rosenzweig, C., & Solecki, W. (2014). Hurricane Sandy and adaptation pathways in NewYork: Lessons from a first-responder city. Global Environmental Change, 28, 395–408.

60 Rueda, A., Camus, P., Tomaís, A., Vitousek, S., Meíndez, F., 2016. A multivariate extreme wave and storm surge climate emulator based on weather patterns. Ocean Modelling 104, 242–251.

61 Shavazipour, B., Kwakkel, J. H., & Miettinen, K. (2021). Multi-scenario multi-objective robust optimization under deep uncertainty: A posteriori approach. Environ.Model. Softw., 144, 105134.

62 Slangen, A., Adloff, F., Jevrejeva, S., Leclercq, P., Marzeion, B., Wada, Y., Winkelmann, R., 2017. A review of recent updates of sea-level projections at global and regional scales. Surveys in Geophysics 38, 395–416.

63 Solari, S., Losada, M.A. (2012) Unified distribution models for met-ocean variables: Applicationto series of significant wave height. Coastal Engineering 68, 67–77.

64 Solari, S., Alonso, R., Teixeira, L. (2018) Analysis of Coastal Vulnerability along the Uruguayan coasts. Journal of Coastal Research, 2018, 85, pp. 1536–1540.

65 Stagnitti M, Lara JL, Musumeci RE and Foti E (2022) Assessment of the variation of failure probability of upgraded rubble-mound breakwaters due to climate change.Front. Mar. Sci. 9:986993.doi: 10.3389/fmars.2022.986993

66 Suh, K.-D., Kim, S.-W., Kim, S., Cheon, S., 2013. Effects of climate change on stability of caisson breakwaters in different water depths. Ocean Eng. 71, 103–112.

67 Toimil, A., Losada, I.J., Camus, P., Diíaz-Simal, P., 2017a. Managing coastal erosion under climate change at the regional scale. Coastal Engineering 128, 106 – 122.

68 Toimil, A., Losada, I.J., Diíaz-Simal, P., Izaguirre, C., Camus, P., 2017b. Multi-sectoral, high- resolution assessment of climate change consequences of coastal flooding. Climatic Change 145, 3.

69 Toimil, A., Losada, I.J., Nicholls, R., Dalrymple, R., Stive, M., 2020. Addressing the challenges of climate change risks and adaptation in coastal areas: A review. Coastal Engineering 156.

70 van de Wal, R. S. W., Nicholls, R. J., Behar, D., McInnes, K., Stammer, D., Lowe, J. A., et al. (2022). A high-end estimate of sea level rise for practitioners. Earth's Future, 10, e2022EF002751. https://doi.org/10.1029/2022EF002751

71 van de Wal, R. S. W., Nicholls, R. J., Behar, D., McInnes, K., Stammer, D., Lowe, J. A., et al. (2022). A high-end estimate of sea level rise for practitioners. Earth's Future, 10, e2022EF002751.

72 Wahl, T., Jain, S., Bender, J., Meyers, S., Luther, M., 2015. Increasing risk of compound flooding from storm surge and rainfall for major US cities. Nature Climate Change 5, 1093–1097.

73 Wilby, R.L., Dessai, S., 2010. Robust adaptation to climate change. Weather 65, 180–185.

74 Zscheischler, J., Martius, O., Westra, S., 2020. A typology of compound weather and climate events. Nature Reviews Earth and Environment 1, 333–347.

75 Zscheischler, J., Westra, S., Van Den Hurk, B., Seneviratne, S., Ward, P., Pitman, A., Aghak- ouchak, A., Bresch, D., Leonard, M., Wahl, T., Zhang, X., 2018. Future climate risk from compound events. Nature Climate Change 8, 469–477.

This IAHR Water Monograph brings together a wealth of knowledge and guidance for practitioners, planners and decision-makers. It offers a comprehensive view of how climate change affects all aspects of water engineering — from flood control and sanitation to hydropower, urban drainage and coastal defence. The chapters address crucial issues such as non-stationarity in hydrological design, hydroclimatic variability, nature-based solutions, and the limitations of current modelling approaches.

It clearly shows the growing need for robust adaptation strategies grounded in sound risk assessment and long-term monitoring."

Jaak Monbaliu

ABOUT THE AUTHORS

Roberto Ranzi (Editor)
Department of Civil, Environmental, Architectural Engineering and Mathematics, University of Brescia, Italy.

Abdalla Ahmed
Unesco Chair, Khartoum, Sudan.

Bregje Van Wesenbeeck
Deltares, The Netherlands and Delft University of Technology, Faculty of Civil Engineering and Geosciences, The Netherlands.

Deg-Hyo Bae
Department of Civil and Environmental Engineering, Sejong University, South Korea.

Giorgi Filippo
International Centre for Theoretical Physics, Trieste, Italy.

Giovanna Grossi
Department of Civil, Environmental, Architectural Engineering and Mathematics, University of Brescia, Italy.

Guinevere Nalder
New Zealand.

Hyun-Han Kwon
Department of Civil and Environmental Engineering, Sejong University, South Korea.

Iñigo J. Losada
Director of Research at IH Cantabria IHCantabria- Institute of Environmental Hydraulics of University of Cantabria, Santander, Spain.

Javier L. Lara
Head of Climate Risks, Adaptation and Resilience Group at IHCantabria- Institute of Environmental Hydraulics of University of Cantabria, Santander, Spain.

Kenichiro Kobayashi
Graduate School of Science and Engineering, Saitama University, Japan.

Ramesh Teegavarapu
Department of Civil, Environmental and Geomatics Engineering, Florida Atlantic University, Boca Raton, USA.

Talita Silva
Department of Hydraulic Engineering and Water Resources, Universidade Federal de Minas Gerais, Brazil.

Van-Thanh-Van Nguyen
Department of Civil Engineering, McGill University, Canada.

Yangwen Jia
Department of Water Resources, China Institute of Water Resources and Hydropower Research (IWHR), China.

ISBN 978-90-835589-3-6
9 789083 558936

IAHR Global Secretariat
iahr@iahr.org

Madrid Office
Paseo Bajo Virgen del Puerto, 3
28005 Madrid, SPAIN
T +34 91 335 7908
F +34 91 335 7935

Beijing Office
A-1 Fuxing Road, Haidian District
100038 Beijing, CHINA
T +86 10 6878 1128
F +86 10 6878 1890

IAHR.org