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Adaptation of coastal flood protection systems

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Adaptation des systèmes de protection contre les inondations côtières

Apports conceptuels et recherche de développements méthodologiques dans les contextes du changement climatique et de l'aménagement des territoires

Thèse

présentée pour l'obtention du grade de

DOCTEUR DE L'UNIVERSITÉ GUSTAVE EIFFEL

par

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Adaptation of coastal flood protection systems

Conceptual contributions and research of methodological developments in the context of climate change and land planning



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Specialty: Urban Engineering

« Pour moi, l'optimisme, c'est une méthodologie, pas un état d'âme. »

Paul B. Preciado

« Les barrages de la mère dans la plaine, c'était le grand malheur et la grande rigolade à la fois, ça dépendait des jours. C'était la grande rigolade du grand malheur. C'était terrible et c'était marrant. Ça dépendait de quel côté on se plaçait, du côté de la mer qui les avait fichus en l'air, ces barrages, d'un seul coup d'un seul, du côté des crabes qui en avaient fait des passoires, ou au contraire, du côté de ceux qui avaient mis six mois à les construire dans l'oubli total des méfaits pourtant certains de la mer et des crabes. Ce qui était étonnant c'était qu'ils avaient été deux cents à oublier ça en se mettant au travail. »

Marguerite Duras, *Un barrage contre le Pacifique*, 1950

Short summary

Coastlines are subject to multiple developments related to land use planning and the effects of climate change, developments likely to generate a strong increase in the risk of coastal flooding. This PhD on published works focuses on systems to protect against this hazard, and presents:

- a bibliographical analysis on the concepts, methods and strategies for adapting protection systems through strengthening their resilience. This analysis is based on the essential assumption that a coastal flood protection system is a social-ecological system;
- in relation to the state of the art and with the aim of completing it, a summary presentation of the research that led to:
 - the revision of the concept of a coastal flood protection system;
 - the establishment of a methodological framework to strengthen the resilience of protection systems.

Résumé court

Les littoraux sont sujets à de multiples évolutions liées à l'aménagement des territoires et aux effets du changement climatique, évolutions susceptibles de générer un fort accroissement des risques d'inondation côtière. Cette thèse sur travaux traitant des systèmes de protection contre cet aléa comporte :

- *une analyse bibliographique sur les concepts, les méthodes et les stratégies destinés à l'adaptation des systèmes de protection par le renforcement de leur résilience. Cette analyse repose sur l'hypothèse essentielle qu'un système de protection contre les inondations côtières est un système socio-écologique ;*
- *en relation avec l'état de l'art et dans l'objectif de le compléter, une présentation synthétique des recherches qui ont conduit à :*
 - *réviser le concept de système de protection contre les inondations côtières ;*
 - *établir un cadre méthodologique de nature à renforcer la résilience des systèmes de protection.*

In-depth abstract

Coasts are subject to multiple changes: climate change, demographic growth, poor land management, the unsustainable use of natural resources, declining ecosystems, etc. These changes, which are often increasingly rapid, generate an increase in hazards, as well as the emergence of new risks, by combination or cascade effects. By the end of the 21st century, habitability will be compromised on many coastlines, some of which are densely populated: 600 million people live in deltas and urban islands. Coastal flooding caused by marine flooding or insufficient drainage of continental waters to the sea is generally the main hazard. The multiple changes and the increase of this hazard over a few decades raises the question of how to adapt the levee systems deployed over a millennium. In order to reduce the risk of disaster, progressive or more radical changes will have to be considered, not in response to extreme events, but as part of a planned approach.

A bibliographical analysis on this topic shows that the adaptation of protection systems through the development of their resilience has been considered with significantly different approaches according to disciplines: the levee system specialists apply the concept of resilience to the protection system with the main objective of maintaining its performance in the short and medium term, while planning specialists apply the concept of resilience to the territory with the objective of its sustainable development, but without a fair appreciation of the performance of the protection system and the risks associated with its use. This misalignment between disciplines almost systematically sabotages relevant forms of adaptation: the utilization of two conceptual approaches – social ecological resilience and technical resilience – applied to two distinct systems, the territory and its protection system, results in a form of partitioning in the risk analysis methods and in the formulation of adaptation strategies employed in both areas. It is therefore necessary to seek conceptual and methodological developments to coordinate over the long term the adaptation of territories and their protection systems.

The literature review has helped to make conceptual progress by reconsidering a coastal flood protection system as a social-ecological system: a complex adaptive system that integrates components of the natural environment, the built environment, and the social and institutional environment. The management principles for strengthening its resilience were thus clarified. However, the state of the art is deficient when it comes to evaluating the performance of systems or defining adaptation or transformation strategies, taking into account the specificity of sites and their developments. In response to these shortcomings, research conducted after Storm Xynthia hit the French Atlantic coastline in 2010, led to:

- the revision of the concept of a coastal flood protection system, specifying the links between the protection structures and the other structural elements of the territory, including both the stakes to be protected and the infrastructure or natural features;
- the establishment of a methodological framework to strengthen the resilience of protection systems, supporting decision-making at the stages of the diagnosis, the definition of adaptation strategies, and the crisis management, while offering operational tools for the development of supply chains for strategic material resources (in particular armourstone).

Key words : coastal flooding, protection system, resilience, adaptation, transformation, climate change, coastal territories, concept, methodology, social-ecological system, complex adaptive system, adaptive co-management, sustainable resource management.

Résumé substantiel

Les littoraux sont sujets à de multiples évolutions : changement climatique, croissance démographique, gestion inappropriée des sols, utilisations non durables des ressources naturelles, écosystèmes en déclin, etc. Ces évolutions, souvent de plus en plus rapides, génèrent un accroissement des risques, ainsi que l'émergence de nouveaux risques, par combinaison ou effet de cascade. Avant la fin du XXI^e siècle, l'habitabilité sera compromise sur de nombreux littoraux, dont certains sont densément peuplés : 600 millions de personnes vivent dans les deltas et les îles urbaines. Les inondations côtières provoquées par les submersions marines ou par un drainage insuffisant des eaux continentales vers la mer constituent en général le principal aléa. Les multiples évolutions et la recrudescence de cet aléa sur quelques décennies posent la question de l'adaptation de systèmes d'endiguement déployés sur un millénaire. Pour réduire les risques de catastrophe, des transformations progressives ou plus radicales devront être envisagées, non pas en réaction aux événements extrêmes, mais de façon anticipée, dans le cadre d'une démarche planifiée.

Une analyse bibliographique sur ce sujet montre que l'adaptation des systèmes de protection par le développement de leur résilience a été envisagée avec des approches sensiblement différentes selon les disciplines : les spécialistes des systèmes d'endiguement appliquent le concept de résilience au système de protection avec pour principal objectif le maintien à court et moyen terme de ses performances, tandis que les spécialistes de l'aménagement appliquent le concept de résilience au territoire avec pour objectif son développement durable, mais sans une juste appréciation des performances du système de protection et des risques associés à son utilisation. Ce déphasage entre les disciplines condamne presque systématiquement des formes pertinentes d'adaptation : la cohabitation de deux approches conceptuelles – résilience socio-écologique et résilience technique – appliquées à deux systèmes distincts, respectivement le territoire et son système de protection, aboutit à une forme de cloisonnement dans les méthodes d'analyse de risque et de définition des stratégies d'adaptation employées dans les deux domaines. Il convient donc de rechercher des développements conceptuels et méthodologiques pour coordonner sur le long terme l'adaptation des territoires et de leurs systèmes de protection.

L'analyse bibliographique a contribué à progresser sur le plan conceptuel en reconsidérant un système de protection contre les inondations côtières comme un système socio-écologique, système adaptatif complexe, intégrant des composantes de l'environnement naturel, de l'environnement construit, et de l'environnement social et institutionnel. Les principes de gestion destinés au renforcement de sa résilience ont ainsi pu être précisés. Cependant, l'état de l'art présente des insuffisances dès lors qu'il s'agit d'évaluer la performance des systèmes ou de définir des stratégies d'adaptation ou de transformation, en tenant compte de la spécificité des sites et de leurs évolutions. En réponse à ces insuffisances, les travaux de recherche, menés après la tempête Xynthia qui a frappé le littoral atlantique français en 2010, ont conduit à :

- réviser le concept de système de protection contre les inondations côtières, en précisant les liens entre les ouvrages de protection et les autres éléments structurants du territoire, dont les enjeux à protéger, les infrastructures et les formations naturelles ;*
- établir un cadre méthodologique de nature à renforcer la résilience des systèmes de protection, en étayant la prise de décision aux stades du diagnostic, de la définition des stratégies d'adaptation et de la gestion de crise, tout en proposant des outils opérationnels pour le développement des filières d'approvisionnement en ressources stratégiques de matériaux (en particulier les enrochements).*

Mots-clés : *inondations côtières, système de protection, résilience, adaptation, transformation, changement climatique, territoires littoraux, concept, méthodologie, système socio-écologique, système adaptatif complexe, cogestion adaptative, gestion durable des ressources.*

Retrospective and contextualization

The work presented in this paper was carried out at the Cerema, in collaboration with the Urban Planning Laboratory of Gustave Eiffel University and the Saint-Venant Hydraulics Laboratory. The work was initiated following the storm Xynthia by an empirical approach conducted over the period 2010-2018. However, this work quickly revealed the need for new conceptual contributions concerning coastal flood protection systems. The research has led to the publication of methodological manuals and scientific articles.

Since 2019, the review was broadened to the issue of the resilience of protection systems in the evolving context of coasts (such as demographic changes, local anthropogenic disturbances of the environment, and the multiple effects of climate change on these environments), and the adaptive co-management of these systems and the resources used.

At the end of 2020, Gustave Eiffel University validated the principle of formalizing the research work in a doctoral thesis. The manuscript was written between April and November 2021. In order to ground the work in the scientific literature, the first part of the manuscript is mainly devoted to a bibliographic analysis.

As coastal flood protection is one of the main challenges of climate change adaptation, the publications of the Intergovernmental Panel on Climate Change¹ (IPCC) have been consulted regularly during the writing of the manuscript and a concordance was sought on the terms defining the main concepts and on the basic knowledge agreed upon in the scientific community.

Similarly, the Sendai Framework (UNISDR², 2015) has been used as a reference for the general disaster risk reduction objectives that can be attributed to coastal flood protection systems, and general guidance for a more integrative approach to risks (natural and anthropogenic).

Finally, since coastal sites strongly affected by subsidence have certain similarities with the situations that the coastlines will experience when faced with rising sea levels, particular attention has been given to the study of the resilience of the Indonesian coastline to natural hazards (Cerema, 2019a). This study, which is the result of a scientific and technical collaboration between the Cerema and Diponegoro University of Semarang (Indonesia) over the period 2013 to 2018, also has the advantage of analyzing a very contrasting situation in comparison with most European territories, with regard to demographic dynamics and the level of economic development.

1 The IPCC provides regular assessments of the scientific basis of climate change, its impacts, future risks, and options for adaptation and mitigation.

2 The United Nations Office for Disaster Risk Reduction (UNDRR, formerly UNISDR) works to significantly reduce disaster loss.

Acknowledgements

This thesis could only be undertaken thanks to the joint ambition of Cerema and Gustave Eiffel University to collectively progress a major contemporary theme: the adaptation of coastal territories to high population growth and the effects of climate change. Therefore, I must express my deep gratitude to the leaders of these two institutions, in particular to Pascal Berteaud, Director General of Cerema, and to Laurent Gautron, Director of the Department of Doctoral Studies at the University, for entrusting me to carry out this project.

I give also my warmest thanks for my thesis supervision, guided by two voices that have become familiar to me over time: Youssef Diab, a specialist in sustainable development and urban engineering, and Marissa Yates, a specialist in hydrodynamic and morphodynamic processes in coastal areas. While their two specialties generally concern quite distinct territories, dry land for one, and the ocean and its shores for the other, dealing with the problem of protection against coastal flooding required a synergetic dialogue between both. I owe it to Youssef and Marissa for creating and maintaining conditions conducive to the emergence and sharing of ideas. Even more than their insights into their respective fields, I appreciated the spirit in which they invited me and encouraged me to progress: giving me a great freedom in the proposal of content – a freedom necessary for research work -, and evaluating my results with rigorous critical analysis – rigor required for the scientific approach -. This state of mind was lifesaving: at first, I thought that producing a state-of-the-art work on a subject that I thought I already knew quite well could only have been a penum! Instead, it seemed to me that every day was usefully spent reorganizing and completing my knowledge, as well as developing new ideas.

The completion of the project was also facilitated by the supervision and guidance by the Department of Risks, Waters and Seas, and by the Department of Innovation and International Research. Within the context of having strong demands on the multiple challenges that research regarding ecological transition provoked, the recognition of my initiative as a priority and the consequent allocation of necessary means, especially working time, were important contributions to the smooth running of the project. Equally important was the involvement of two colleagues and friends in the finalization of the manuscript: Séverine Hallot, for the production of a large number of graphic elements, and Ashley Grosche, for the precise proofreading of the manuscript in its English edition. Everyone knows how much the completion of a work corresponds to a period when reinforcements can be particularly appreciated. The production of this manuscript found the support of these living forces at the right time, which made it possible to finish quickly.

To conclude these acknowledgements, I must stress the context and the duration of this project. Indeed, although the final phase of writing and preparation for the defense took 18 months, it is ultimately the culmination of the previous ten years' worth of work that formed the basis of this thesis. During this long-term work, belonging to a team mobilized by coastal risks, the encouragement and help of all kinds brought by my entourage, both by colleagues and by my family and friend circle, have meant more to my personal motivation than one could ever imagine. The problem of coastal flooding is so great that no one can hope by their own efforts to respond effectively to it. So, it was the feeling of participating in a collective effort that was my main motivation. The result is all the happier for me, because this thesis, more than just a work to be placed neatly on the shelf, is a learning experience that I am happy to share with all those I meet regularly.

Acronyms

CAS : Complex Adaptive System

CRDP : Climate-Resilient Development Pathway

ES : Ecosystem Service

ESL : Extreme Sea Level

GIA : Glacial-Isostatic Adjustment

GMSL : Global Mean Sea Level

IPCC : Intergovernmental Panel on Climate Change

RCP : Representative Concentration Pathways

RSL : Relative Sea Level

SES : Social-Ecological System

SPRC : « Source-Pathway-Receptor-Consequence » conceptual model

SSP : Shared Socio-economic Pathway

USD : United States Dollar

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General introduction

In order to reduce the risk of coastal flooding (marine flooding, but also other types of flooding resulting from insufficient drainage of continental waters towards the sea) to an acceptable level, levee systems have been deployed where the natural configuration of the site did not provide satisfactory protection. Land was also developed on the sea, especially in deltas, initially for agricultural purposes. In a millennium, considerable areas of land have been poldered around the world, with an ever-growing population whose activities have diversified, cities and metropolises occupying at an increasing rate places initially devoted to primary production activities. Throughout history, man has thus modified his environment, while also adapting to it. This co-evolution process has led to acceptable risk control situations at certain sites and at certain times. However, in recent decades, the insufficiently controlled urbanization of coastlines, as well as other forms of development (such as deforestation and soil sealing) and intervention on rivers and wetlands (dams and drainage) led to a significant increase in the risk and the stakes exposed. In addition, in environments where the degree of complexity increases with the degree of artificialization, new natural or industrial hazards emerge by combination or domino effect. As climate change exacerbates the phenomena against which protection is sought and further weakens protection systems, the principles that we have relied on for a millennium for development cannot be maintained indefinitely. The 21st century will mark a turning point in the history of low-lying coastlines.

The question of adapting coastal flood protection systems is therefore raised. This is a challenging question, because the adaptability of these systems cannot be established over indefinite periods because of multiple uncertainties in the evolution of hazards, as well as in the evolution of territories.

The treatment of this problem requires working at both the conceptual and methodological levels by:

- reframing coastal flood protection systems within the context of more comprehensive systems (including technical, ecological, social, and economic components), and recognizing that through the concepts of resilience and adaptation, the interactions between these systems occurs at various spatio-temporal scales. The various types of activities, planning objectives, and types of risk must be considered;
- defining guidelines for the adaptation of protection systems, taking into account not only the hazards against which they provide protection, but also changes and disturbances, slow or rapid, localized or diffuse, to which they are exposed, and more generally, all the constraints arising from the natural or built environment, at the level of the territory or at higher levels (such as the region or the planet).

A bibliographical study has been undertaken to address these two objectives. This study, presented in the first part, confirmed the need to have better benchmarks for the definition and characterization of protection systems, the forms of which can vary depending on the sites considered. The research carried out on this topic over the period 2010-2018, following the Storm Xynthia that affected the French Atlantic coastline, contributes to addressing this issue.

In the second part of the thesis are copies of scientific papers documenting this work.

PART 1 – PRESENTATION OF MY RESEARCH

INTRODUCTION

In this first part of this thesis, the bibliographic analysis and research work are presented in five main chapters:

- chapter 1 describes the fundamentals of coastal flood protection: firstly, the phenomena that cause coastal floods and the natural and human factors that favor them, and then, as a counterpoint, the approaches traditionally adopted to protect against these risks;
- chapter 2 reconsiders protection systems as a social-ecological system, in order to integrate the theme of protection against coastal flooding into more global land use planning schemes by strengthening their resilience. Methods for understanding risk and defining adaptation strategies are reviewed for two types of areas: protection systems and urban territories. The links between these methods, which may be systemic or analytical, are studied;
- chapter 3 seeks to recognize relevant adaptation strategies for the territories and their protection systems. In particular, analyses are proposed to support decision-making about adaptation, transformation, or forced abandonment of protection systems. These analyses cover both the protection systems and the territorial and regional levels at which the topics of resource management and modes of governance must be addressed;
- chapter 4 is based on the definition of the resilience of a system, and determines, using a systematic approach, the conditions that methodological developments should meet to contribute to the strengthening of the resilience of systems. This analysis, based on the conceptual framework set out in Chapter 2 and the critical analysis of adaptation strategies in Chapter 3, responds to the need to rethink the concept of coastal flood protection systems and having new operational methodologies and tools to support the integration of protection systems:
 - in natural ecosystems;
 - in urban areas;
 - in policies for the sustainable management of natural resources (such as water, sediments, armourstone and wood);
- chapter 5, as a response to the problem, presents the results of research carried out over the period 2010-2018, namely the conceptual contributions to the definition and characterization of coastal flood protection systems; and using these new conceptual bases, methodological frameworks relating to:
 - the diagnosis of protection systems following an episode of marine submersion;
 - the definition of adaptation strategies based on economic assessment;
 - the development of emergency response preparedness for protection structures;
 - the development of strategic material resource supply chains (especially armourstone).

The figure 1 shows the organization of the first part.

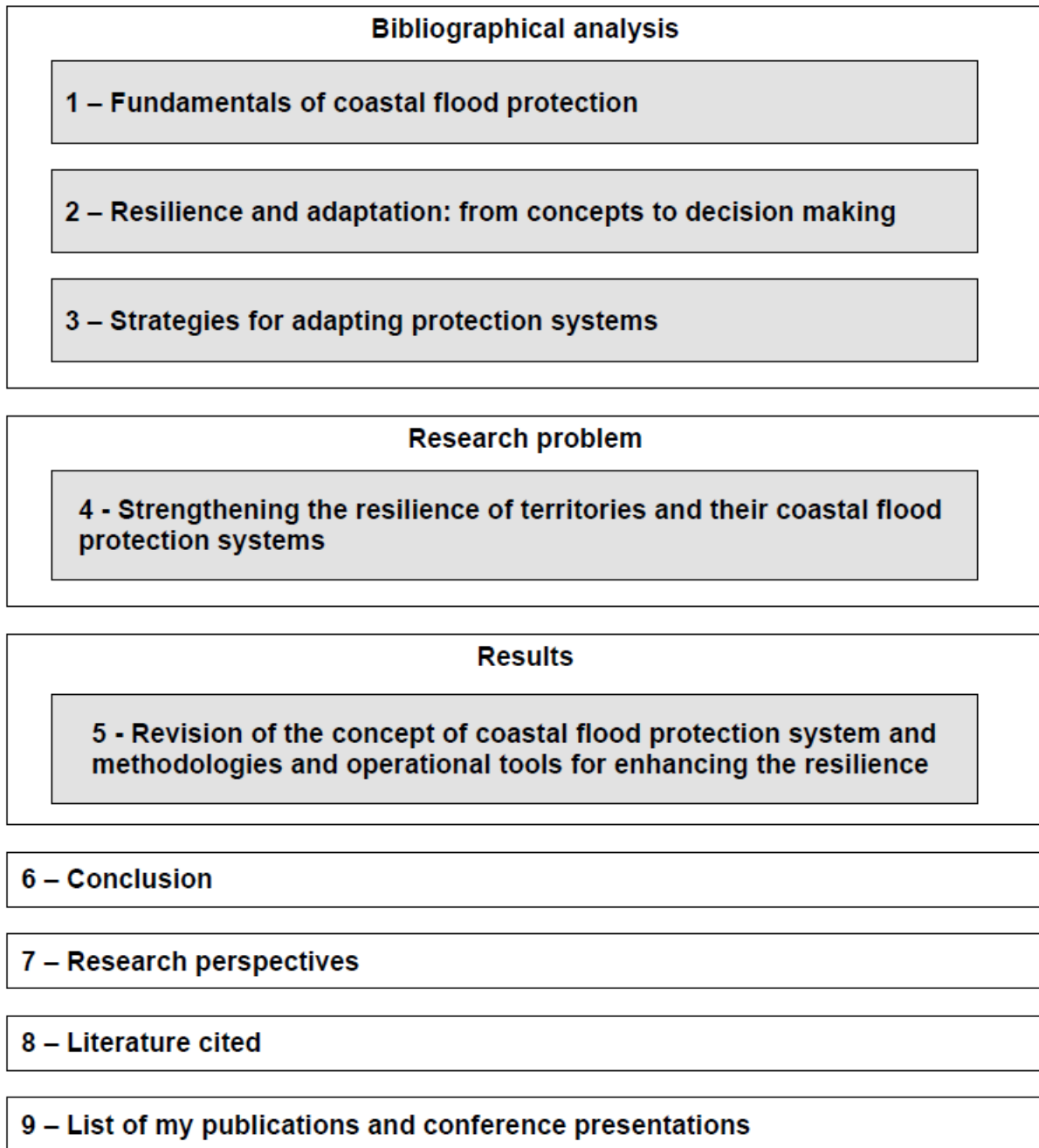


Figure 1: Organization of the first part of the thesis.

1 FUNDAMENTALS OF COASTAL FLOOD PROTECTION

This chapter aims to weigh essential knowledge of coastal flooding events against the most commonly used risk prevention strategies.

Although coastal flooding can also be the result of intense rainfall, river overflows, or increases in the water table, the first focus will be on marine submersion. Marine submersions are generated by physical phenomena (in particular, storms, cyclones, tsunamis) occurring on large scales and have been documented in the history of humanity as the origin of many major disasters, with arguably the deadliest events having been caused by phenomena of geophysical origin (Flather, 2001). In addition to the victims affected and the damage directly caused by flooding, these disasters also lead to health disorders, psychological trauma, economic losses, and even social, political and philosophical upheavals... One particular event holds a special place in the history of the Western world: by striking on the morning of All Saints Day the year 1755 in Lisbon, the capital of a deeply Catholic country, the earthquake and associated tsunami had a profound impact on philosophers in Europe during the period of Enlightenment. This disaster can be considered a founding event in crisis management and risk prevention. Following this event, the city of Lisbon adopted a risk management strategy based on a scientific, non-religious and non-superstitious approach (Delatour et al., 2017). In the 21st century, despite advances in scientific knowledge, prediction and warning, there are alarming signs of increased risk of disasters worldwide: in recent decades, high population growth at the coast resulted in both an increase in exposure to hazards and a destabilization of the natural environments that constitute the first form of protection. Climate change also has multiple effects that exacerbate the risks.

1.1 Marine submersion – Physical markers and phenomena

Marine flooding can be caused by storms and other spinning weather events (known as cyclones, hurricanes, or typhoons depending on the region of the globe in which they occur), which may be referred to as the generic term « meteo-oceanic event » (Mazas, 2017), or by earthquakes or other underwater terrain movements causing tsunamis. The mechanisms at work are significantly different depending on the origin of the phenomena, but they ultimately result in changes in the sea level. In both cases reference will be made to Extreme Sea Level (ESL), defined as:

« A temporary increase, at a particular locality, in the height of the sea due to extreme meteorological conditions (low atmospheric pressure and/or strong winds) or a tsunami. The surge (due to the weather or the tsunami) is defined as being the excess above the level expected from the tidal variation alone at that time and place (IPCC, 2019) ».

In anticipation of the extreme events giving rise to submersion, some essential points of reference will be given on long-term changes in sea level. These changes are likely to significantly alter the risk of coastal flooding.

1.1.1 Sea level changes – Physical markers

Sea level changes, both globally and locally, vary according to seasonal, annual, or longer time scales. These variations may be caused, according to the IPCC (2019), by:

- changes in the mass of water in the ocean (*e. g.*, due to melting of glaciers and ice sheets);
- changes in ocean water density (*e. g.*, water volume expansion under warmer conditions);
- changes in the shape of the ocean basins and changes in the Earth's gravitational and rotational fields; and
- local subsidence or uplift of the land.

These processes are represented schematically in the figure 2.

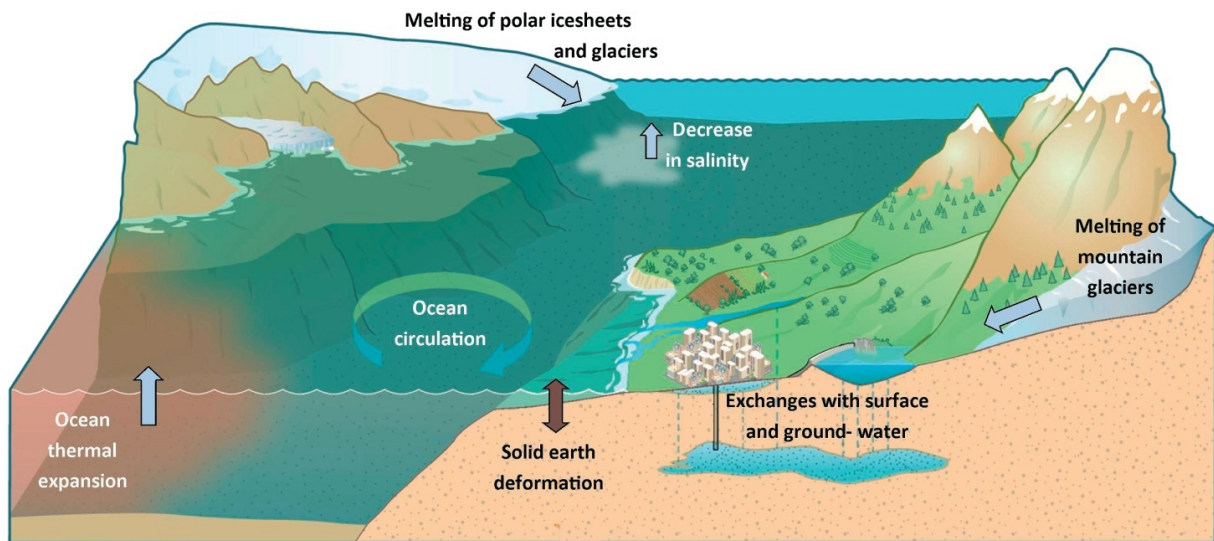


Figure 2: Schematic showing the main factors causing sea level changes (Cazenave and Le Cozannet, 2013).

Among the causes of sea level change identified by the IPCC (2019), a distinction is made between variations in the mass or volume of the oceans and vertical movements of the Earth's surface in relation to the surface of the sea. In the first case, a sea level change is defined as « eustatic »; and in the second case, it is defined as « relative » (Rovere et al., 2016).

Changes in Global Mean Sea Level (GMSL)

The global mean sea level (GMSL) can be defined as an average of the eustatic sea level at a global scale³.

Eustatic sea level changes are driven by different processes that cause changes in the volume or mass of the world ocean (Rovere et al., 2016). GMSL changes are therefore independent from local factors such as ground movement that exist:

- in areas subject to post-glacial rebound, *i. e.* the viscoelastic response of the Earth's crust and mantle to the last deglaciation, also called glacial isostatic adjustment (GIA). This process gives rise to vertical land movement, *e. g.*, crustal uplift in high latitudes of the Northern Hemisphere (Whitehouse, 2018; Tamisiea and Mitrovica, 2011);
- in active tectonic and volcanic regions; or
- in areas subject to strong ground subsidence due to natural causes (*e. g.*, sediment loading in river deltas) or human activities (groundwater and oil/gas extraction) (Cazenave and Le Cozannet, 2013).

Neither the eustatic level of the sea nor its global average, the GMSL, correspond to a physical level of the sea with reference to a point on the earth's surface (Rovere et al., 2016). Since the early 1990s, sea level is routinely measured with quasi-global coverage by high-precision altimeter satellites that function with a revisit time of days or weeks (called « orbital cycle »). Compared to tide gauges that provide sea level relative to the ground, satellite altimetry measures « absolute » sea level variations in a geocentric reference frame. Observations show that GMSL is rising and that the rate of rise displays strong regional variations (Cazenave and Le Cozannet, 2013).

³ <https://sealevel.colorado.edu/presentation/what-definition-global-mean-sea-level-gmsl-and-its-rate>

Changes in Relative Sea Level (RSL)

The IPCC (2019) proposed Relative Sea Level (RSL) to be defined as the following:

« Sea level measured by a tide gauge with respect to the land upon which it is situated ».

Beyond this definition, it is necessary to specify clearly why the variations of the RSL are important and especially to know the past variations of this parameter and the mechanisms that determine these variations, in order to assess its future changes.

The reconstruction of GMSL at different time scales is mostly of interest for the study of ice melting or warming of water masses, whereas RSL changes are more appropriate to investigate regional and local processes (Rovere et al. 2016).

During the period of 1993–2012, satellite altimetry revealed that sea level is not rising uniformly. In some regions like the western Pacific, rates of sea level rise were about three times faster than the global mean rate. In other regions, rates were slower than the global mean (e. g., the eastern tropical Pacific) (Cazenave and Le Cozantet, 2013).

These non-uniform variations in RSL are explained by phenomena both at regional or supra-regional scales (greater than 100 km) and at local scales. They will be presented separately.

At regional or supra-regional scales, there are primarily two reasons for variations in RSL:

- the first reason lies in the behavior of water in the oceans. Observed spatial patterns in sea level trends have mainly resulted from changes in the density structure of the oceans associated with temperature and salinity variations, called « steric effects » (Bindoff et al., 2007). Except in the Arctic region, the largest contribution comes from ocean temperature variations (Cazenave and Le Cozantet, 2013).
- the second reason is the interaction between water and the Earth's crust. According to the eustatic level global approach, the world's ocean basins are similar to a giant « bathtub », with fixed borders represented by continents with sharp and steep boundaries. However, ice- and water-load variations trigger solid Earth deformations, including gravitational and rotational perturbations. This gives rise to currents that cause spatial variability in sea level (Kopp et al., 2015).

As a result, although it might seem counterintuitive, it is possible that the combination of several processes in one area may result in a relative sea level fall even under conditions of GMSL rise. For example, this appears in the RSL projections provided by James et al. (2014) when comparing the period of 1986-2005 to the 21st century. Projected RSL for the year 2100 varies by approximately 1 m of RSL fall where land is rising quickly at the Hudson Bay, compared to the approximately 0.70 m of RSL rise at the Beaufort coast where the land is subsiding.

These regional sea level changes are broad-scale but their regional « fingerprint » is different for each melting source (*i. e.*, for the last glaciation ice sheets, Greenland, Antarctica, and glaciers). An increase by several percent of the GMSL rise is expected far from the melting sources while significant sea level reduction may occur around the melting bodies (Tamisiea and Mitrovica, 2011).

At the local scale, vertical land motions such as uplift or subsidence of the ground due to GIA, tectonic and volcanic activity, sediment loading, groundwater pumping, and oil and gas extraction can produce sea level variations relative to the seafloor (Cazenave and Le Cozantet, 2013). These phenomena will be studied in more detail in the presentation of factors aggravating the risk of coastal flooding.

For coastal management purposes, what is of interest is the « total » RSL change, *i. e.*, the sum of the regional or supra-regional scale (greater than 100 km) components and local components. The figure 3 shows the evolution of this parameter during the 20th century.

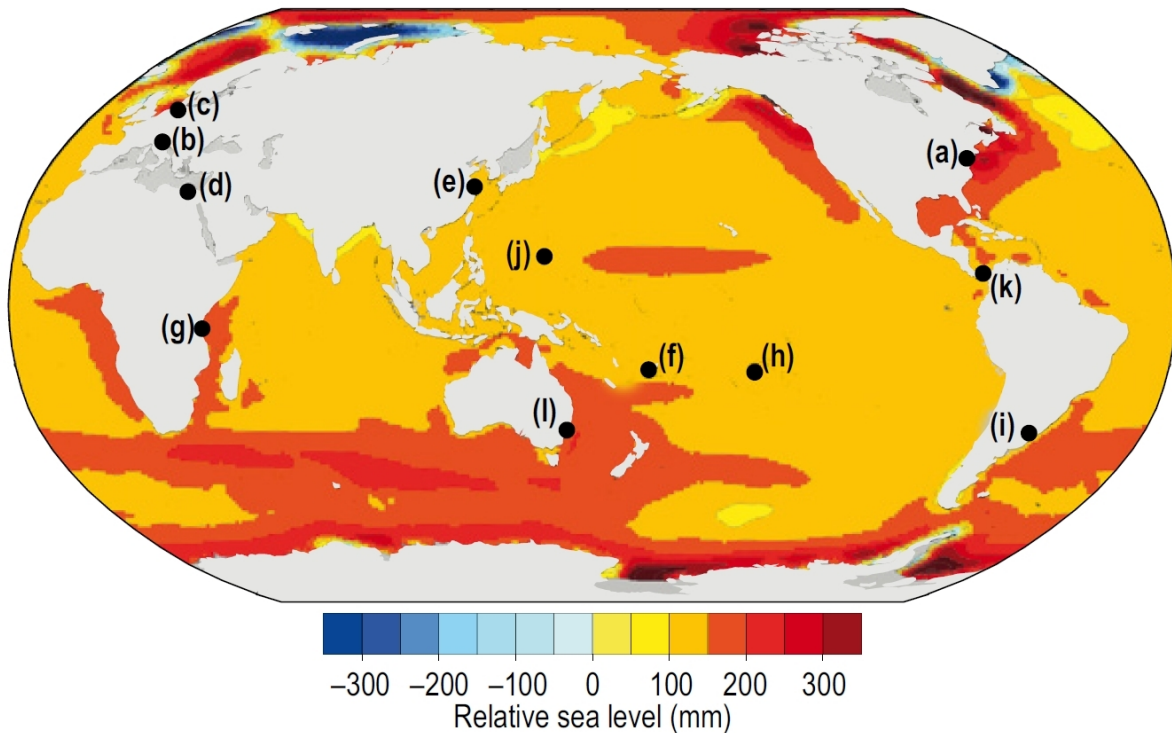


Figure 3: 20th century simulated regional sea level changes by coupled climate models. Credit: IPCC (2019), updated from Meyssignac et al. (2017b).

By the end of the 21st century, almost all coastlines worldwide will be affected by sea level rise. Moreover, in some regions, the combination of all effects will cause significant amplification of the global mean rise. For example, climate models project that due to steric effects, sea level rise will be higher than the global average along the eastern coast of the USA by 2100. This is particularly concerning as this region is already subject to RSL rise because of GIA effects (Cazenave and Le Cozantet, 2013).

1.1.2 Meteo-oceanic submersions

Meteo-oceanic submersions are mainly associated with tropical cyclones, but they can also be caused by deep atmospheric depressions at mid-latitudes. At low-lying coasts, the most significant damages are usually associated with storm surges and the subsequent flooding rather than direct wind effects, particularly if the storm surge coincides with high tides (Bertin, 2012). The impacts of waves and currents that can develop on typically emerged lands are two phenomena likely to endanger humans and plant and animal life, and to cause heavy material damage.

In Europe, the additional water levels due to storm surges typically remain, unless exceptional events occur, less than 3 m. Hurricanes very commonly generate surges exceeding this value on the coast. For example, in the case of Hurricane Katrina that struck Louisiana (USA) in 2005, Alabama's coast experienced surges ranging from as high as 3.05 m in the east to 4.57 m in the west, while surges in eastern Louisiana ranged from 3.05 m to 5.79 m (Graumann, 2006). The storm surge exceeded 8 m in several locations along the Mississippi coastline (Dietrich et al., 2010). As the increase in water levels favors the propagation and spread of waves along the coast (CIRIA et al., 2007), this parameter is influential not only for submersion heights, but also for the power of waves reaching the coast.

In addition, cyclones and other storm events can be accompanied by very heavy rainfall on land combined with the spread of water from the sea. Cyclone Idai that devastated the Beira region of Mozambique in March, 2019 is an example of this type of event with the combined effects of multiple occurring phenomena (Emerton et al., 2020).

Some of the most emblematic disasters in recent decades are:

- the Bhola cyclone, which impacted the coasts of Bangladesh and India in 1970, with winds exceeding 200 km/h and a storm surge of 5 to 6 m. This event resulted in the disappearance of more than 300 000 people (Das, 1972); In 1991, the region was again devastated by a cyclone that killed more than 135,000 people (India Meteorological Department, 1992);
- the tropical cyclone Nargis, which flooded the low-lying Irrawady Delta (Burma) in 2008 and killed over 130 000 people (Wolf, 2009);
- Hurricane Katrina, which impacted the U.S. Gulf Coast in 2005. This hurricane is the third deadliest in the history of the United States (with 1 500 deaths) and the costliest (81 billion USD in damages) (Blake, 2007). Figure 4 illustrates the power of these phenomena and their destructive effects on a house.



Figure 4: Before/after images of a house in the path of Hurricane Katrina. Credit: Kimberly King, The COMET Program.

The Netherlands was also heavily affected by a storm that occurred in 1953 (with more than 1 800 victims). This event led to the implementation of the Delta plan for protection against marine flooding (Gueben-Venière, 2015).

While some countries were less affected during the 20th century, events such as the Storm Xynthia that struck France in 2010 are a reminder of the need for risk assessment and defining appropriate preventive measures.

In order to assess better the measures to be implemented to protect against these phenomena, it is necessary to specify their origin and characteristics.

Meteo-oceanic submersions are caused by storm surge: an abnormal rise in water, beyond the expected astronomical tide, generated by atmospheric forcing, specifically by the drag of the wind on the sea surface and by variations in the surface atmospheric pressure associated with storms. Storm surge is mainly produced by water being pushed toward the shore by the force of the winds. The impact of the low pressure associated with the storm on surge is minimal in comparison to the water

being forced toward the shore by the wind. Storm surges last for periods ranging from a few hours to 2 or 3 days (Flather, 2001).

The figure 5 provides a schematic representation of a hurricane approaching the coast.

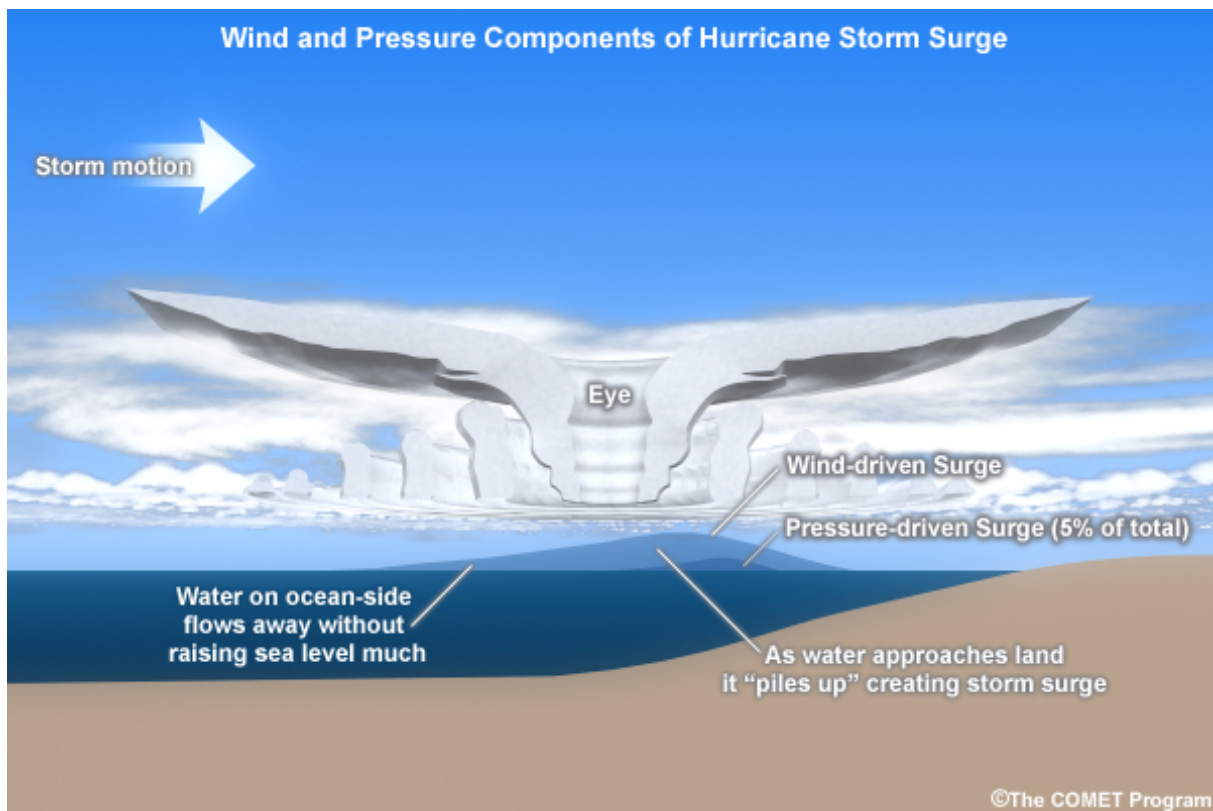


Figure 5: Wind and pressure components of hurricane storm surge. Credit: The COMET Program, UCAR and NOAA⁴.

The use of numerical models for the prediction of storm surges accompanying tropical cyclones is a well-established technique that forms the basis of operational prediction systems (Daniel et al., 2007).

The main causes of high water levels are winds and the response to an atmospheric depression. At least three other distinct processes associated with the passage of a storm, which can alter the water level, are recognized (Harris, 1963) :

- the earth's rotation ;
- waves ;
- rainfall.

The influence of these processes varies depending on the location: far from the coast (in deep water), close to the coast (in shallow waters) or at the coastline.

Far from the coast, the surge is mainly controlled by atmospheric pressure effects. This is called the inverted barometer effect, and it represents the hydrostatic response of the ocean. Close to the coast, dynamic effects become more pronounced: the local bathymetry, shallow water depth, and coastline configuration amplify the surge height which may reach several meters (Daniel et al., 2007).

⁴ <https://scied.ucar.edu/learning-zone/storms/what-causes-storm-surge>

A wave that comes from the ocean displaces a certain volume of water. When it enters a bay or an area where the seabed rises, the volume within that area remains the same, resulting in the displacement of water in the form of storm surge and waves. The steeper the slope of the continental shelf, the less the storm surge will enter the land, resulting instead in the creation of higher waves. Conversely, a gently sloping continental shelf allows the sea to propagate farther inland but with weaker waves (CIRIA et al., 2007).

In shallow waters, the wind effect can significantly dominate the effect of the low-pressure surge. This is the reason why low-lying coasts bordered by extensive continental shelves and exposed to the regular passing of hurricanes and storms are particularly vulnerable to storm surges and coastal flooding. The Bay of Bengal and the Gulf of Mexico are two notable zone with these characteristics (Bertin, 2012).

At the coastline, waves also contribute to elevated sea levels through two phenomena:

- wave set-up : superelevation of the water surface attributable to onshore mass transport of the water by wave action alone (CIRIA et al., 2013);
- run-up : the height reached by a wave on a beach or a coastal structure, relative to the static water level, measured vertically (the run-up generates overtopping which, unlike overflowing, occurs intermittently).

Figure 6 represents the contributions to « static » and « instantaneous » water levels of these phenomena on the shoreline.

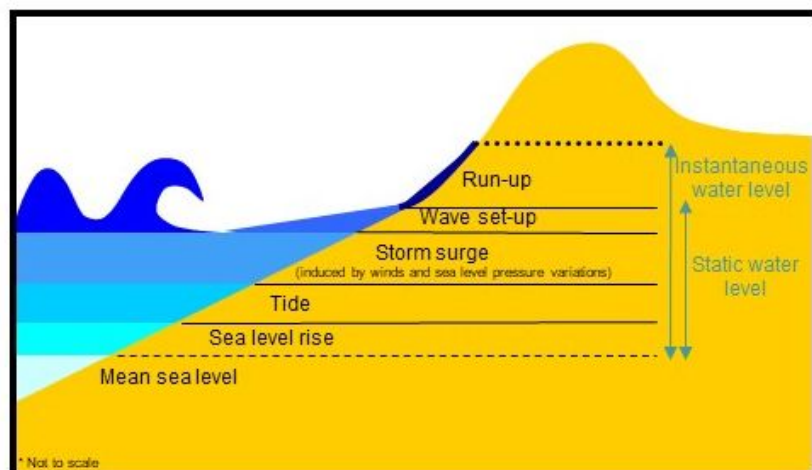


Figure 6: Schematic diagram of the different contributions to the total sea level. Credit : M. Yates.

The maximum potential storm surge for a particular location depends on a number of different factors. Storm surge is a very complex phenomenon because it is sensitive to the slightest changes in storm intensity, forward speed, size (radius of maximum winds), angle of approach to the coast, central pressure, and shape and characteristics of coastal features such as bays and estuaries⁵.

The effect of intense rain should also not be overlooked: hurricanes may produce as much as 300 mm of rainfall in 24 hours over large areas. Cumulative precipitation over the duration of a hurricane can exceed 500 mm (Emanuel, 2017). The fluvial flood resulting from this rainfall can increase the water level near the head of many tidal estuaries. In some bayous and swamps, even though very near the sea, several days may be required to drain the excessive rain produced by a hurricane (Harris, 1963).

5 <https://www.nhc.noaa.gov/surge/>

To understand the effect of these meteo-oceanic events on coastlines, they must be considered in conjunction with the astronomical tide. It is therefore necessary to distinguish between large tidal range (macrotidal) and small tidal range (microtidal) coasts:

- on macrotidal coastlines, the most unfavorable case corresponds to the conjunction of the surge (related to atmospheric pressure, wind and breaking waves) with a spring tide. In all cases, the peak of the event typically has a maximum duration of about three hours, but overflowing and overtopping generally occur over a shorter duration, around the high tide. Since these phenomena can span a considerable spatial extent, the inflows can be very important, as shown in Figure 7, which displays a photograph taken in the aftermath of the storm Xynthia on the coast of Charente-Maritime, France;



Figure 7: Port-des-Barques, Charente-Maritime, France, taken February 28, 2010, submerged by storm Xynthia. Credit: B. Landreau, Cerema.

- on microtidal coasts, (e. g., the Mediterranean), the water rise is mainly generated by the surge. This involves a submersion event that can extend over several days depending on the duration and characteristics of the storm. Marine submersions in Camargue (France), in 1982 and 1997 were among the most significant events to take place on the coastline. Although the water levels were relatively low, less than 1 m, the submersions having affected urban areas for several days, the damage was significant (Heurtefeux et al., 2007).

1.1.3 Tsunamis

Tsunamis are a series of extremely long waves caused by earthquakes, landslides, volcanic eruptions, and more rarely, by meteorites and nuclear tests (Margaritondo, 2005).

The most emblematic modern disaster was a tsunami which occurred in the Indian Ocean on December 26, 2004. It mainly struck the northern part of the island Sumatra in Indonesia, the coasts of Sri Lanka, the south of India, and the west of Thailand. This tsunami claimed more than 200,000 lives, most of which were in Aceh, a northern province in Sumatra (Cerema, 2019a). Figure 8 shows how devastating this type of event can be.



Figure 8: Aceh, Sumatra, Indonesia (Jan. 4, 2005). A lone mosque stands among the damage of a coastal village near Aceh, Sumatra, Indonesia. Credit: U.S. Navy photo by Photographer's Mate 3rd Class Jacob J. Kirk.

Situated on the Asian Ring of Fire, Japan is subject to more tsunamis than almost any other country in the world. In March 2011, one of the largest ever recorded earthquakes unleashed one of the most damaging series of tsunamis (ranking second over the last several hundred years, with the first being the Indian Ocean Tsunami of 2004). Fifty-one minutes after the first earthquake, the first wave (15 meters high), reached the Fukushima Daiichi nuclear power plant, which resulted in the second worst nuclear disaster after Chernobyl (Schreurs, 2021).

As for the submersions engendered by meteo-oceanic events, it is necessary to understand the origins of the phenomenon and its characteristics to better protect against it.

Not all earthquakes trigger a tsunami. To generate a tsunami, the fault where the earthquake occurs must be under or nearby the ocean, and create a vertical motion (up to several meters) of ocean floor over a large area (up to 100 000 km²). Shallow earthquakes (less than 70 km deep) along subduction zones are responsible for most destructive tsunamis. The amplitude of the horizontal and vertical motion of the ocean bottom, the area of the fault, the simultaneous appearance of a subsurface sediment collapse due to the earthquake, and the efficiency with which energy is transferred from the Earth's layer to the ocean's bottom are all factors that contribute to the tsunami formation mechanism (Intergovernmental Oceanographic Commission, 2012).

On the high seas, as shown in Figure 9, very long waves radiate outward in all directions, traveling through the entire water column, from the ocean floor to the surface (Archana, 2021). Their speed can exceed 800 km/h (220 m/s). However, at the surface maximum wave heights on the order of only a few tens of centimeters are visible. For this reason, in the deep ocean, tsunamis are often unnoticed⁶. Tsunami waves are also distinguished from ordinary oceanic waves by their large crest-to-crest wavelength, which often exceeds 100 km in the deep ocean, and by their period, which ranges from 10 minutes to one hour (Intergovernmental Oceanographic Commission, 2012). As these waves propagate very rapidly and travel over the entire water column (an average of 4 000 m in the open ocean), they carry considerable energy.

⁶ The origin of the Japanese term « tsunami », which literally means « port wave » is explained by the behavior of the phenomenon: Fishermen, having not perceived anything abnormal in the offshore, returned to find their port city ravaged.

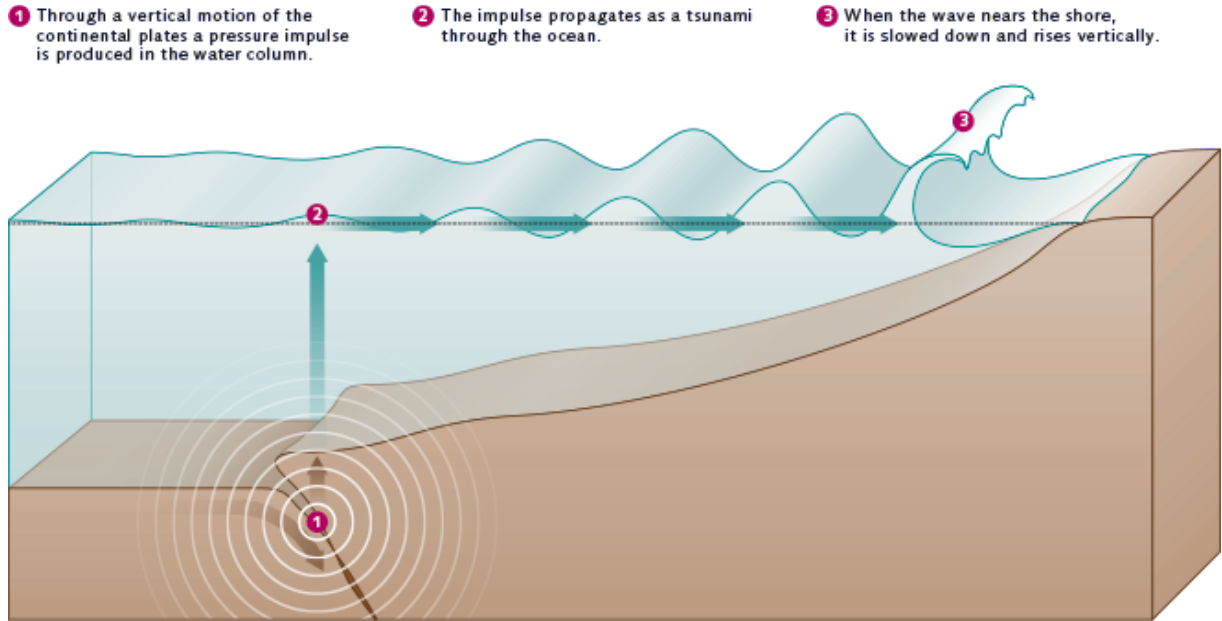


Figure 9: Tsunamis often originate from a shift downward or upward of continental plates in the ocean crust during an earthquake. Credit : Maribus.

Once the tsunami reaches shallow water near the coast, the wave transforms and becomes dangerous: its wavelength decreases and the amplitude increases significantly, causing the sea to rise dramatically (Archana, 2021).

The arrival of the wave at the coast is marked by a retreat of the sea, followed by a sudden rise in the level of the water, and finally by a rapid retreat (see Figure 10). Due to the very long wavelength, the elevated water level is maintained over periods from 5 to 30 minutes, potentially penetrating land over a long distance. The different phases of the tsunami are much longer than the period of wind-generated waves (5–20 s). This can cause tragic mistakes in judging the tsunami's behavior when it reaches a beach: an initial harmless « drawdown » (a sudden drop of the water height at the shore) can attract people to the beach. After a relatively long time, this is followed by a devastating large wave that cannot be outrun (Margaritondo, 2005).

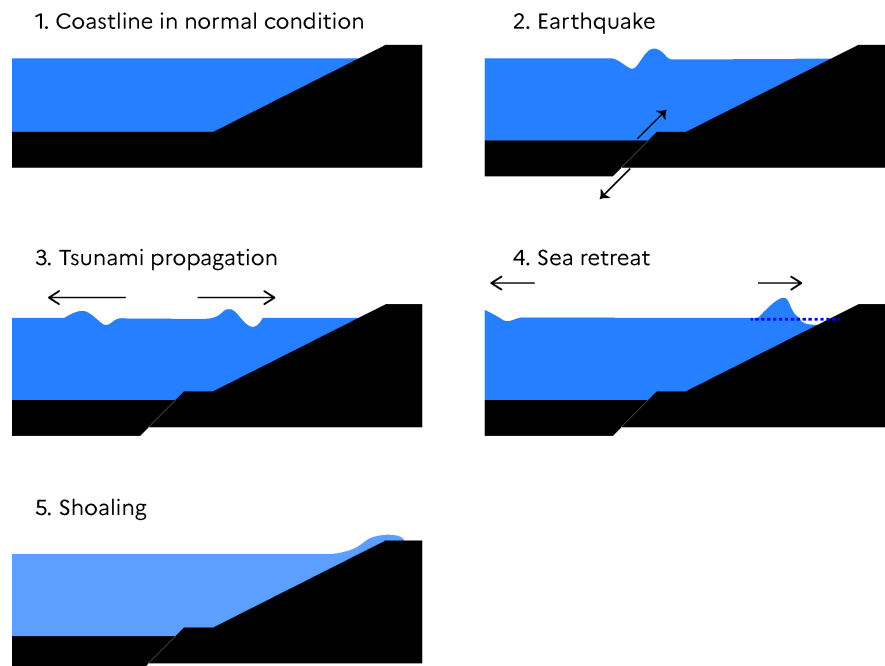


Figure 10: Formation, propagation, and surge of a tsunami in 5 steps. Credit: Cerema, after Lachaume.

Numerical modeling, which is necessary for the understanding and representation of weather-marine phenomena, is also a powerful tool for understanding the behavior of tsunamis, predicting their impacts on coastal zones and developing warning systems (Sugawara, 2021).

The Intergovernmental Oceanographic Commission (IOC) is coordinating the implementation of the Global Tsunami Warning and Mitigation System, building on its experience in the Pacific Ocean to implement warning systems for the Indian Ocean, the Caribbean, the Atlantic, and the Mediterranean (IOC, 2012).

1.2 Developments leading to increased risk

In the current day and age, the coast is a space which is both particularly exposed to natural phenomena and yet remains attractive to people. It is also subject to the spread of urbanization in the context of increasing international trade and globalization. These changes may lead to situations of local concern in terms of fitness for habitation and exposure to natural disasters (Cerema, 2019a).

Climate change effects, in particular the GMSL rise, is on most coastlines causing increases in coastal risks (not only does this include the risk of coastal flooding, but also the risks of erosion, shoreline retreat, and dune migration). However, attributing impacts to sea level rise remains difficult in most regions, since impacts are also exacerbated by human-induced non-climatic drivers, such as land use change, land subsidence (caused by groundwater and/or hydrocarbon extraction), and coastal habitat degradation (IPCC, 2019). Human factors unrelated to climate will therefore be addressed first, considering that these are often exacerbated by the effects of climate change.

1.2.1 Demographic changes and urbanization of coastal areas

The rush to coastal areas

More or less non-damaging co-evolutions have been constructed over time between human settlements and coastal areas. Today, however, global population growth and rapid urbanization processes are producing imbalances that are putting coastal territories under stress (Cerema, 2019a). An unwanted side effect of rapid urbanization is the increased susceptibility to flooding, as the result of the concentration of people and assets in flood-prone areas – many urbanized areas are located along major water bodies (Zevenbergen et al., 2008). Furthermore, this urban pressure causes an artificialization of the coastline to the detriment of natural environments (Cerema, 2019a).

In addition to urbanization, other processes come into play such as rural exodus, the development of international maritime trade, and the development of tourism. To understand these long-term developments, the research community uses scenarios known as the Shared Socioeconomic Pathways (SSPs). SSPs are based on narratives that describe plausible future changes in demographics, human development, economy, institutions, technology, and the environment. Broadly speaking, SSPs describe potential futures that diverge on axes of increasing challenges to adaptation and mitigation, where each quadrant (high/low challenges to adaptation and mitigation) is represented by an SSP, along with a fifth pathway describing moderate challenges to both (see Figure 11). SSPs range from very optimistic, where governments are able to develop sustainable futures that facilitate adaptation to climate change while largely mitigating its impacts, to very pessimistic, where governments must confront the effects of increasingly severe climate events while lacking the political will or resources to invest in adaptation or mitigation measures (O'Neill et al., 2014; O'Neill et al., 2017; Sellers and Ebi, 2018).

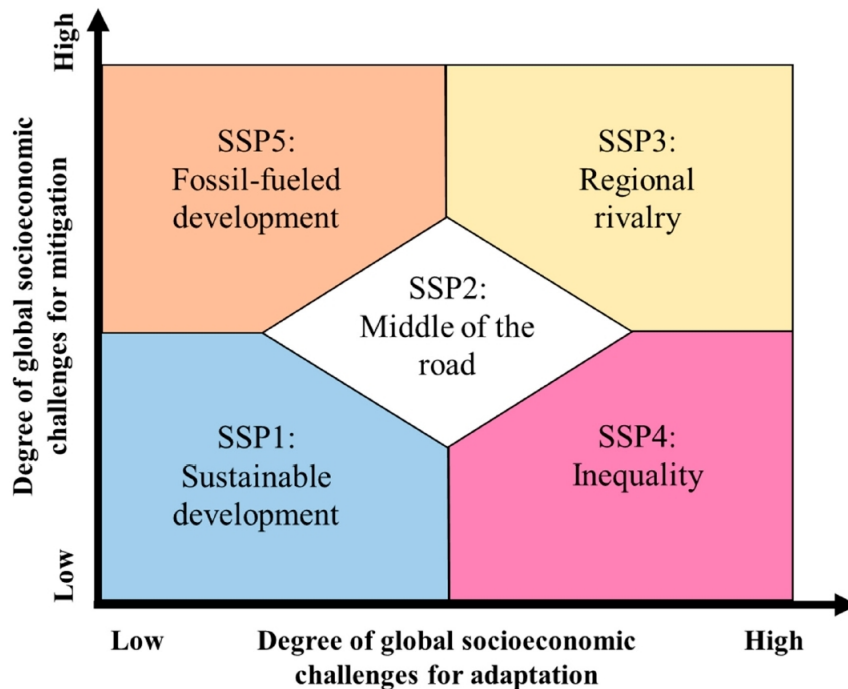


Figure 11: SSP adaptation and mitigation axes. Credit: Sellers and Ebi (2018), adapted with permission from O'Neill et al. (2017).

The low elevation coastal zone (classified as having land less than 10 m above sea level) is where people and infrastructure are most exposed to coastal hazards, and is currently home to around 11 % of the global population (around 680 million people). By the year 2050, the population in this zone is projected to grow to more than one billion under all SSPs (Merkens et al., 2016). These projections account for differences in coastal and inland population developments, as well as in urban and rural areas.

Forecast of the exposed stakes evolution

Global coastal flood risk is expected to increase in the future as a result of increasing exposure, due to growth in population, wealth, and economic activities in flood-prone areas (Tiggeloven et al., 2020). Even without taking climate change into account, the extent of urban areas exposed to floods (and droughts) is predicted to at least double by 2030. The emerging coastal metropolitan regions in Africa and Asia are predicted to be larger than those in the developed countries and will have larger areas exposed to flooding (Güneralp et al., 2015).

Neumann et al. (2015) investigated how coastal populations will be affected by coastal hazards at global and regional scales by the years 2030 and 2060. Starting from baseline population estimates for the year 2000, the authors assessed future population change and trends in exposure to 100-year coastal floods based on four different sea-level and socioeconomic scenarios. They show that the number of people living in low-elevation coastal zones, as well as the number of people exposed to flooding from a 1-in-100 year storm surge event, is the highest in Asia. China, India, Bangladesh, Indonesia and Vietnam are estimated to have the highest total coastal population exposure in the baseline year and this ranking is expected to remain largely unchanged in the future. However, Africa is expected to experience the highest rates of population growth and urbanization in the coastal zone, particularly in Egypt and sub-Saharan countries in western and eastern Africa.

In particular, deltas attract many people and show rapid economic development because of the fertile soils, easy access to markets *via* waterways and sea ports, and ease of construction on a relatively flat surface (Klijn et al., 2015). This explains the above-average development rate of deltas, coastal fringes, and river floodplains (Jongman et al. 2012), and it is also the main explanation of increasing economic losses as a result of floods (FLOODsite, 2009).

The case study of Semarang, Indonesia, emblematic of cities with high population growth

To fully comprehend the phenomenon of urbanization of coastal areas, the case study of Semarang (Indonesia, north coast of Java) is appropriate. In 2016⁷, Semarang, which had a population of 1,730,000 inhabitants, experienced strong population growth. This resulted in urban sprawl on a large scale. In 1999, only 15% of the municipality's territory was urbanized compared to 44 % 15 years later, in 2014. Following the same trajectory, the entire 374 km² of the territory could be impacted by urbanization in 2030⁸, despite public policies to protect natural areas. Urbanization results in many environmental changes within a territory, such as deforestation, and creating patches of bare ground in certain places, making them more susceptible to erosion and landslides (Cerema, 2019a).

1.2.2 Ground and sediment movements

Previous research on the evolution of the RSL shows that the risk of coastal flooding can be influenced by ground movements of multiple origins: tectonic activity, subsidence of natural or human origin... These vertical ground displacements are often aggravated by sediment displacements on the Earth's surface. These sediment displacements are the result of hydraulic or wind actions and are also subject to the influence of biological or anthropogenic factors. The topographical changes lead to an increase in risk when they result in a reduction of reliefs that were an obstacle to the spread of water, or when they position vulnerable stakes at topographical levels where their exposure to hazard is greater.

Dans cette section, les mouvements verticaux du sol et le déplacement des sédiments seront abordés séparément. In this section, ground and sediment movements will be addressed separately. It should be kept in mind, however, that these two phenomena can be combined in some territories. For example, subsidence may cause the drowning and subsequent loss of land through increased coastal erosion, which is aggravated by sediment depletion resulting from trapping behind dams and the regulation of rivers (Syvitski et al., 2009).

Vertical ground movements

Ground movement can be of natural (geological) or of anthropogenic origin.

Among the natural phenomena, vertical ground movement triggered by tectonic activity can be considered separately and, except where it generates tsunamis, occupy a minor place in the scientific literature on flood risk. For these ground movements to have an impact on the risk of coastal flooding, they should satisfy the following conditions:

- location on the coast;
- lowering of the ground from an « emerging in all circumstances » to an « episodically submerged » level.

This type of situation exists. For example, Ballu et al. (2011) compared in the Torres Islands (Vanuatu) the role of absolute sea-level rise and vertical tectonic motions in coastal flooding and concluded that vertical ground motions are the predominant factor in the apparent sea-level rise.

However, an increase in the risk of coastal flooding due to ground movement of tectonic origin is rare, particularly since volcanism is more likely to lead to ground lifting than to ground lowering, and the risks associated with tectonic activities may have a deterrent effect on the exposure of stakes to natural hazards in general.

Apart from tectonic activities, vertical ground movements are subsidence phenomena which may be of geological or anthropogenic origin.

⁷ On the basis of the calculation of the BPS 2016, Badan Pusat Statistik kota Semarang - <https://semarangkota.bps.go.id>
⁸ Source: Diponegoro University (UNDIP).

In a schematic way, subsidence of geological origin can be considered to occur at regional or supra-regional scales and involves the Earth's crust, which is why the phenomena take place over very long periods and with great inertia. Conversely, anthropogenic subsidence manifests itself mainly at local scales and involves in the upper layers of the ground, consisting mainly of sediments. For this reason, the reactions of the ground surface to the actions it undergoes are much faster.

This formal distinction, however, remains schematic, since it is clear that geology is, in this field, significantly influenced by anthropogenic activities in a time rightly described as the Anthropocene. This is what emerges from the analysis of the causes and mechanisms of subsidence.

In geology, according to the *Encyclopædia Universalis* (Brunet, 2021), subsidence is defined as :

« the sinking of the surface of the Earth's crust under the effect of an additional charge either above the crust (water, sediments, volcano, ice cap, mountain range, lithospheric plate, etc.), either inside it (phase change by metamorphism) or below it (heavy mantle material) ».

These geological processes occur over large areas and are normally relatively slow: from 0.01 mm/year to 1 mm/year. However, many Arctic coastlines are located in areas with a rapid GIA (James et al., 2014) and, for this reason, have low sensitivity to RSL rise.

For anthropogenic subsidence, phenomena can also be caused by load changes that can arise from growth or shrinkage of a large ice mass (especially due to the effects of climate change), from the weight of new sediment added to a delta (particularly resulting from a disturbance of sedimentary transit in rivers), and from the weight of coastal water added or subtracted with RSL fluctuations (an additional effect of climate change). However, the most damaging subsidence phenomena result mainly from the extraction of water and hydrocarbons in deltas (Tessler et al., 2018). For this reason, the IPCC (2019) provides the following definition of local anthropogenic subsidence phenomena :

« Downward motion of the land surface induced by anthropogenic drivers (e. g., loading, extraction of hydrocarbons and/or groundwater, drainage, mining activities) causing sediment compaction or subsidence/deformation of the sedimentary sequence, or oxidation of organic material, thereby leading to relative sea level rise ».

Anthropogenic subsidence occurs on smaller surfaces than geological subsidence. Conversely, the speed of the phenomenon can be much higher, since subsidence rates of the order of 1 to 10 cm/year are commonly measured. Currently, the observed subsidence rates in coastal megacities are exceeding the sea level rate by a factor of ten (Erkens et al., 2015; Sarah et al., 2018). During the 20th century, the coasts of Tokyo, Shanghai, and Bangkok collapsed by several meters as a result of water extraction and soil loading by building and infrastructure construction (Nicholls et al., 2008) and subsidence is expected to continue to affect coastal flood risk in the future (Dixon et al., 2006).

Figure 12 shows the evolution of the cumulative subsidence rate over the 20th and early 21st century in six coastal spaces, in comparison with the elevation of the GMSL. Some cities are currently seeing an acceleration of subsidence as a result of economic growth, which is accompanied by an increase in the extraction of water and hydrocarbons, and in the loading of soils by the development of urbanized areas. Tokyo stands out as an example where subsidence has stopped after successful mitigation measures were implemented: it has been acknowledged that a shift to using surface water instead of groundwater is necessary. However, water storage through the construction of dams and treating the polluted surface water is much more technically complex and expensive (in the short term) than extracting groundwater (Erkens et al., 2015).

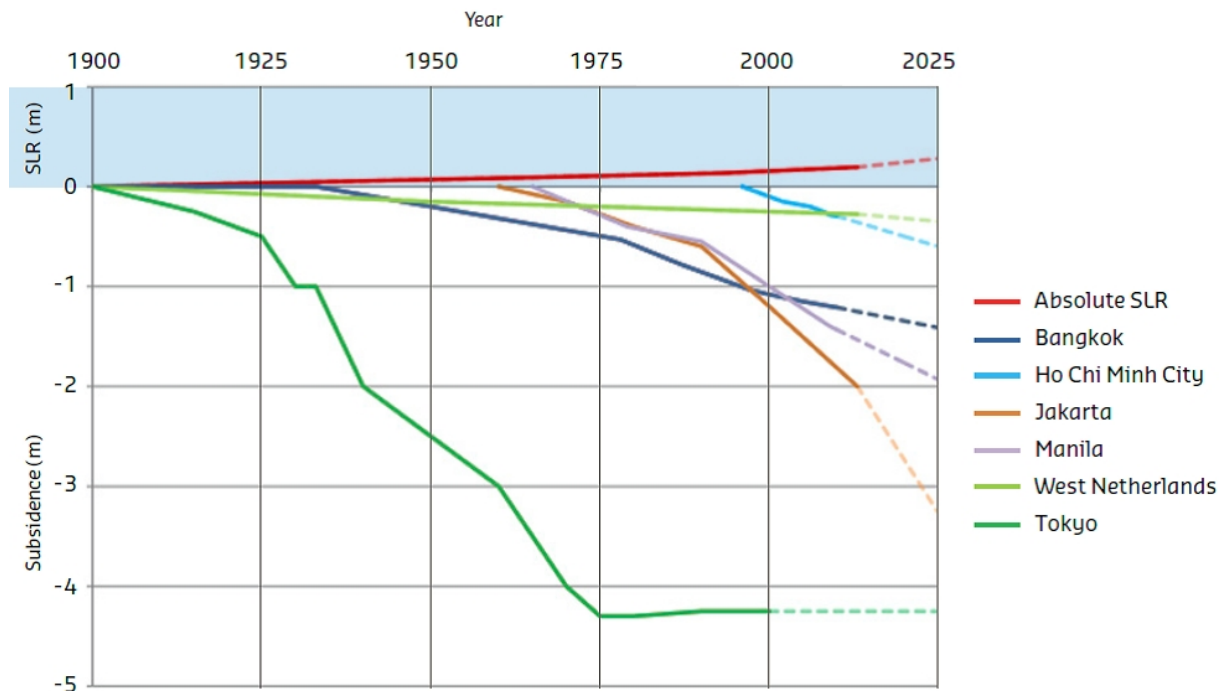


Figure 12: Subsidence history (cumulative) in coastal cities around the world (Erkens et al., 2015).

In figure 12, GMSL rise is depicted as the reference. Subsidence can differ considerably within a city area, depending on groundwater levels and subsurface characteristics. Values provided in the figure can be seen as averages for the local subsidence hotspots.

Land subsidence increases flood vulnerability (frequency, inundation, depth, and duration of floods). In addition, differential land movement causes significant economic losses in the form of structural damage and high maintenance costs for infrastructure. The total damage worldwide is estimated to be billions of dollars annually (Erkens et al., 2015).

River deltas are coastal features developed from the accumulation of sediment near the mouths of rivers (Syvitski, 2008). They are seaward prograding land areas that have accumulated for approximately 6 000 years, when GMSL stabilized within a few meters of the present level (Amorosi and Miller, 2001). More than half a billion people live in these areas and are thus exposed to the risks of coastal flooding, wetland loss, shoreline retreat, and loss of infrastructure (Syvitski, 2008).

For example, Bangkok's urbanization is intensifying, while the city is located on the Chao Praya river delta below sea level. In some sectors, land is sinking by 5 cm per year leading to fears in the medium term for the immersion of part of the city. Bangkok was very badly impacted by the 2011 floods as the flow of water coming from the north had difficulty draining towards the sea, even though the economic and financial centre was spared by the protective dikes that were erected for kilometers (Cerema, 2019a).

Delta plains are nearly flat: 0,005 m/m for steeper, mountainous river deltas, to 0,00001 m/m for the larger deltaic systems (Syvitski and Saito, 2007). A delta's low gradient is both attractive and dangerous to human utilization. In the event of subsidence or RSL rise, this type of space has little possibility of adaptation.

Disturbance of sediment fluxes in rivers

The increased risk is also caused by disturbance of sediment fluxes in rivers and along coasts. Deltas are the areas most affected by this phenomenon. Tessler et al. (2015) presented a systematic global-scale assessment of the changing risk profiles of coastal deltas. Figure 13 shows the location of the deltas studied. The sites were selected based on several other world-wide comparative studies on a

one-hundred year time scale, ensuring a certain representativeness of the most critical situations in the world.



Figure 13: Locations of the 48 deltas studied by Tessler et al. (2015).

The evolution of risk, as it emerges from this study, is shown in figure 14. Both axes indicate a change over time using 100-year projections for the two risk components:

- increases in exposure (red) are taken as proportional to the current rate of change ; and
- increases in vulnerability (orange) are based on the difference between current and future estimates.

Several delta systems (e. g., the Mississippi, Rhine, and Yangtze) are at risk both from RSL rise, leading to increased exposure to flooding, and from reduced effectiveness of risk reduction strategies that may not be sustainable on the century scale.

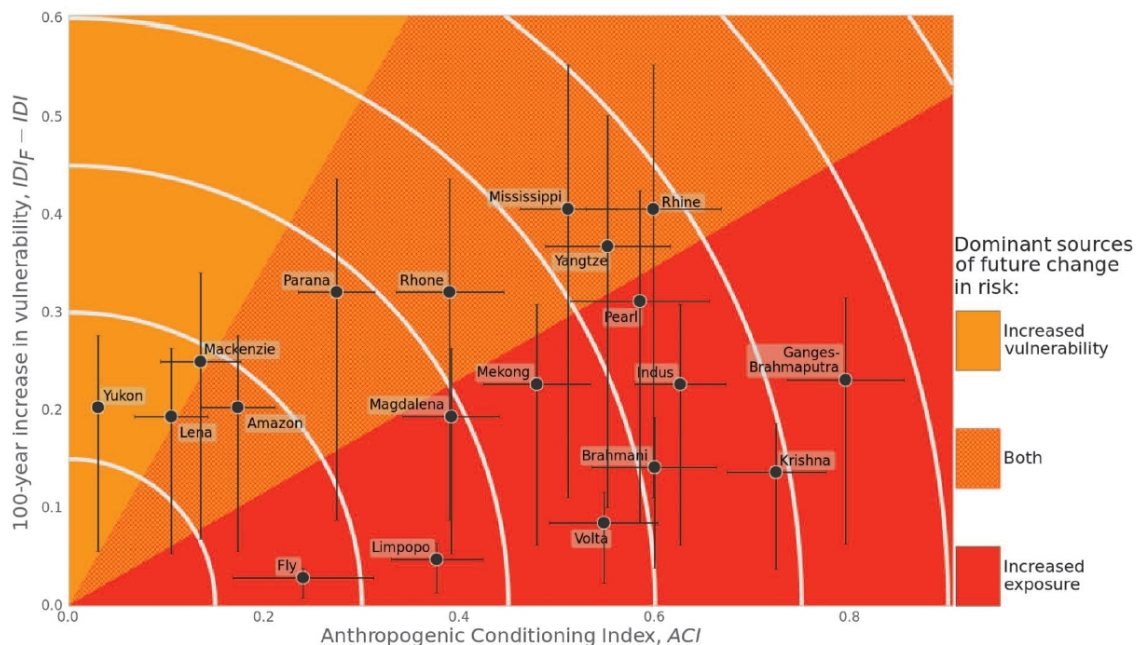


Figure 14: Estimated future changes in exposure and vulnerability for selected deltas (Tessler et al., 2015).

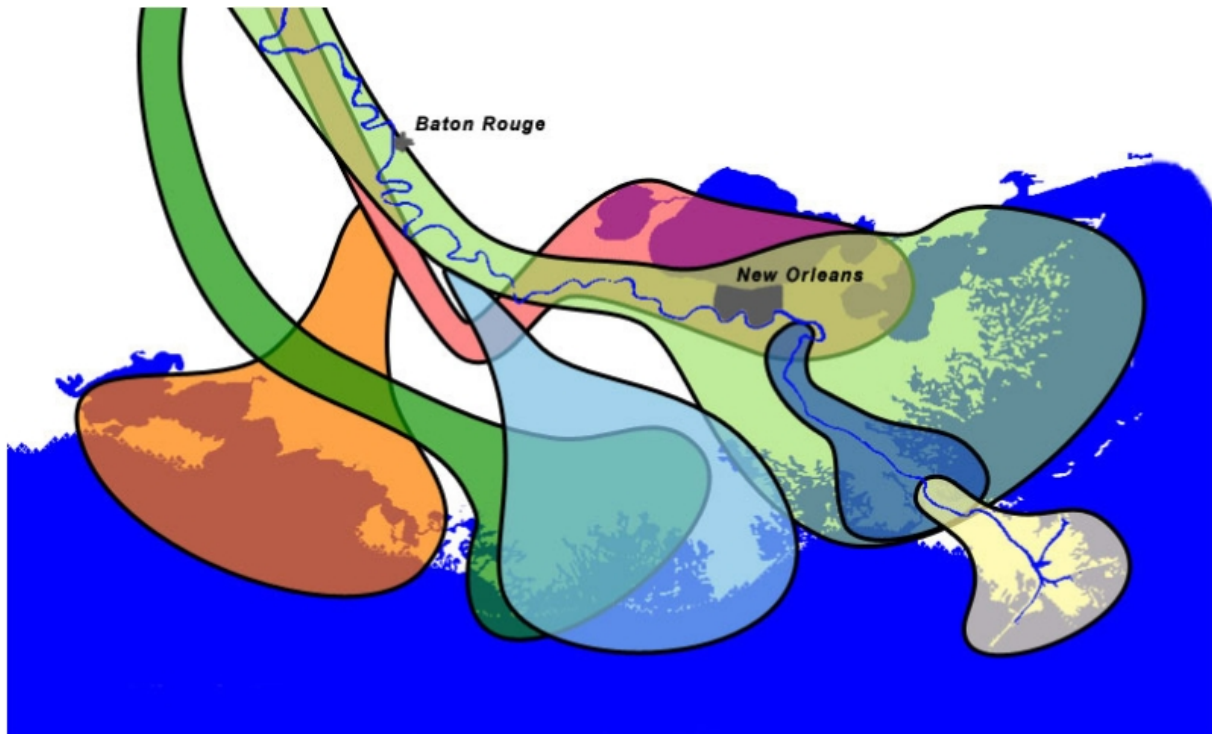
The sediment supply reaching the coast is a critical factor for delta sustainability (Tessler et al., 2018). Dam construction, land use changes, and sand mining can result in a significant decrease in this supply (Ouillon, 2018). The reduction rates of sediment inputs from the studies are considerable. For example:

- Ha et al. (2018) estimated the decline in sediment supply to the Mekong Delta to be around 75% between the 1970s and the period 2009–2016. Sediment supply to the sea started to be significantly affected during the 2000s by various anthropogenic activities such as dams, sand mining, reforestation, and soil conservation ;
- in the Red River, the construction of the Hoa Binh Dam in the 1980s led to a 65% drop in sediment supply to the sea (Vinh et al., 2014).

Most conventional engineering strategies that are commonly employed to reduce flood risk (including levees, sea walls, and dams) disrupt a delta's natural mechanisms for building land, either by holding the sediments upstream (in the case of dams), or by accelerating the flows and thus preventing sediment deposition (in the case of levees and sea walls). Delta sediments naturally compact over time, requiring new sediment fluxes from the upstream river network and deposition on the delta surface to maintain land elevation (Syvitski et al., 2007). The lack of sediment deposition is revealed during floods or storms, as erosion phenomena are not compensated by an accumulation of sediments that would have occurred in an unperturbed delta system.

Therefore, conventional engineering approaches reduce the long-term resilience of deltas (Tessler et al., 2015; Welch et al., 2017). Deltas that fall short in sediment deposition may not be able to maintain their elevation relative to sea level, which could lead to an increase in salinization, erosion, and flood hazards (Dunn et al., 2018). Systems particularly prone to flood risk due to anthropogenic activities include North America's Mississippi River Delta, Europe's Rhine River Delta, and deltas in eastern Asia (Renaud et al., 2013; Day et al., 2016). This diagnosis is fully consistent with the study by Tessler et al. (2015) previously mentioned.

The human control of routing river discharge across delta plains contributes in particular to the sinking of world deltas (Syvitski, 2008). For example, in the Mississippi Delta, the little remaining sediment also disappears into the gulf (Klijn et al., 2015) as the main discharge is channelized via the birdfoot, this term designating the shape of the artificialized delta seen from the sky. Figure 15 shows both the considerable natural fluctuations that the Mississippi Delta has experienced over the past millennia and how the flow is currently channelled into this delta. This channelization leads to an advance of the delta into the Gulf of Mexico.



	Salé-Cypremort	4600 years BP		Lafourche	1000-300 years BP
	Cocodrie	4600-3500 years BP		Plaquemine	750-500 years BP
	Teche	3500-2800 years BP		Balize	550 years
	St. Bernard	2800-1000 years BP			



Figure 15: At the top, the seven deltaic lobes of the Mississippi River. The distance between Baton Rouge and New Orleans is more than 100 km. The Balize Delta is the current « bird's foot » delta. Credit: Wikimedia Commons. Right: satellite image of the « bird's foot ». Credit : NASA.

It should be noted that, conversely, an increase in the contribution of sediment can also cause flooding, but by overflow of streams. For example, in the case of a city like Semarang (Indonesia), deforestation and urbanization aggravate soil erosion, causing an accumulation of sediment in the canals to the detriment of their hydraulic function. Dredging operations, difficult to put into action, gradually lose their effectiveness. This results in making inland flooding worse during intense rain events (Cerema, 2019a).

Coastal erosion

Coastal erosion often increases the risk of marine submersion by weakening natural formations, in particular dunes and beaches, which provide protection.

At the global scale, 24% of the world's sandy beaches are eroding at rates exceeding 0.5 m per year, while 28% are accreting for the period 1984–2016 (Luijendijk et al., 2018).

Figure 16 represents the main areas of erosion and accretion in the world.

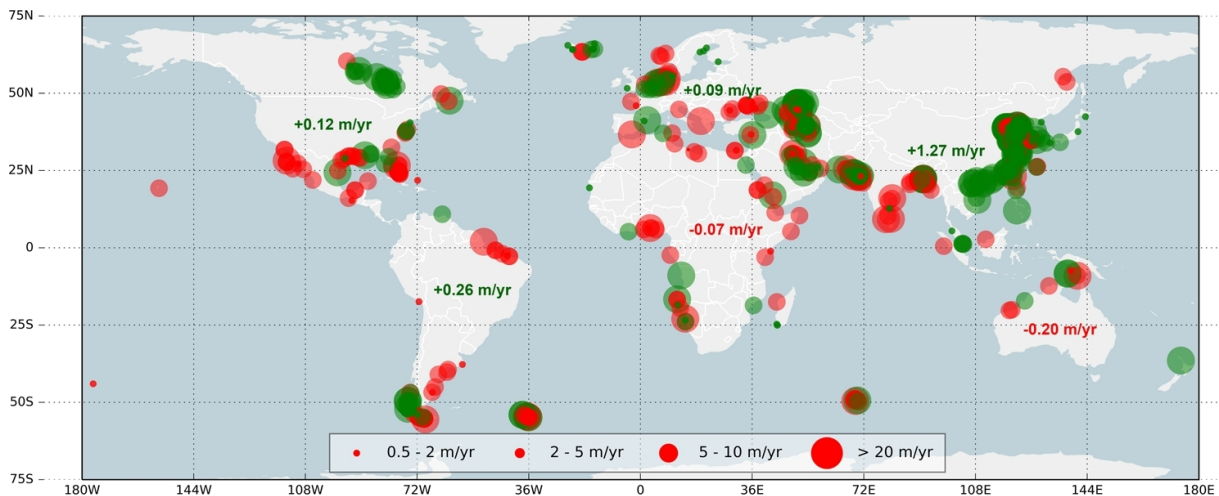


Figure 16: Global hotspots of beach erosion and accretion; the red circles indicate erosion and green circles indicate accretion for the four relevant shoreline dynamic rate classifications indicated in the legend (Luijendijk et al., 2018).

In France, almost 20% of the coastline is affected by erosion (Cerema, 2019b). Figure 17 shows the retreat of the shore of a particularly concerning site north of the mouth of the Gironde. In this figure, the recent coastline is traced in blue, the old coastline in green, with the profiles drawn every 200 m in white and the columns proportional to the calculated rates of change. The calculated value is displayed at the bottom of the column.

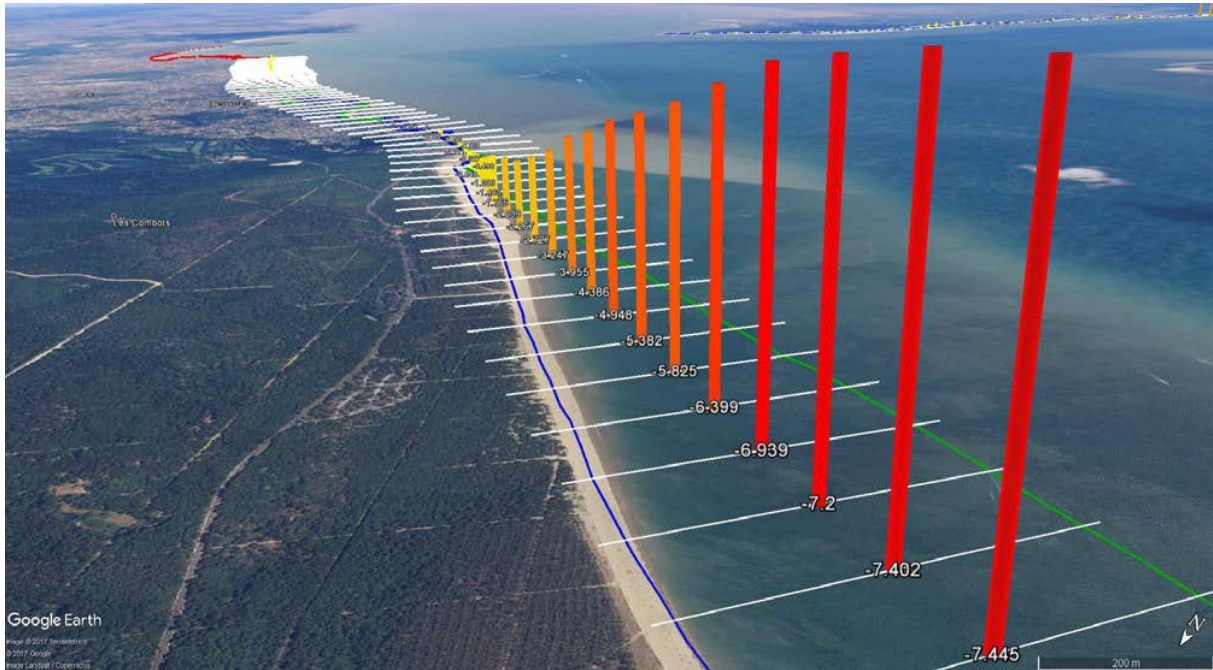


Figure 17: Representation of the coastline erosion at north of the mouth of the Gironde, France (Cerema, 2019b). Background: Google Earth.

Observing the coastlines of West Africa, Ndour et al. (2018) shows that adaptation strategies developed at regional, national, and local levels often produce more setbacks than solutions. The various installations and infrastructure (dams, major seaports and groins) have often been constructed without any appropriate planning and knowledge on the physical dynamics driving the coastal system. Consequently, in numerous coastal areas in Senegal and Benin, this intensive occupation, which also commonly involves the uncontrolled exploitation of coastal resources contributes to the erosion phenomena.

1.2.3 Wetland degradation and coastal compression

The degradation of coastal habitats generally results in multiple impacts on coastal wetlands. Moreover, the combined effects of coastal erosion and the pressure exerted by urbanization on these territories has led to « coastal squeeze ».

Degradation of wetlands

Wetlands are defined as areas flooded, either temporarily or permanently. Coastal wetlands, such as mangroves, salt marshes, and coral reefs, act as protection barriers against meteo-oceanic events, and tsunamis. Inland wetlands, such as rivers, floodplains, and lakes function like sponges, absorbing and storing excess precipitation and buffering against flash floods (Ramsar, 2016).

Wetlands encompass a great diversity of landscapes. Figure 18, with images taken from the RAMSAR⁹ photo gallery, shows examples from all continents of various types of coastal wetlands. These examples represent only a fraction of the diversity of wetlands on the planet.

⁹ 9 Photos extracted from the site <http://www.ramsar.org>.



Figure 18: Examples of coastal wetlands (representing a small fraction of the global diversity).

Figure 18 shows from top to bottom and left to right:

- the Tana River Delta, Kenya (credit: WIKIPEDIA by SGT R.A. WARD) ;
- Gippsland Lakes, Australia (credit: Official site for Melbourne, Victoria, Australia) ;
- the Suncheon Estuary, Republic of Korea (credit: Suncheon City municipality government) ;
- the Kota Kinabalu Mangrove, Malaysia (credit: CONANP Mexico) ;
- the Rocas Atoll at the Biological Reserve of Rocas, Brazil (credit: Ministry of Environment of Brazil) ;
- beaches and dunes of the Wadden Sea, Germany (credit: Linking Tourism and Conservation).

Nearly 50% of the pre-industrial, natural extent of global coastal wetlands have been lost since the 19th century. World wetland loss and degradation has accelerated since the 1990s, caused by both anthropogenic and natural factors, such as land reclamation, aquaculture, urbanization, harbor and navigation channel construction, decreased sediment input from the catchments, RSL rise, and erosion (Li et al., 2018). The over-exploitation and pollution of water resources are two more major threats. In particular, using large quantities of water and nitrogen-based fertilizers, agricultural irrigation greatly reduces the flow of watercourses and leads to local eutrophication (biofouling of water that create dead zones due to the lack of oxygen). For example, in the Camargue (France) and the Hula Valley (Israel), these changes have already had profound effects on wetlands (Mediterranean Wetlands Observatory, 2014).

The Briefing Note n°7 to the Ramsar Convention on Wetlands of International Importance warns of certain situations of particular concern, for example near the Yellow Sea, over approximately 4 000 kilometers of coastline (approximately 65% of intertidal wetlands), have been lost over the past 50 years due to industrialization, intensive urbanization, and agricultural development (Murray et al., 2014). In other sectors, wetland losses are primarily related to forestry, *e. g.*, on U.S. coastal watersheds (Dahl and Stedman, 2013).

It is important to note that the reduction of inland and coastal wetlands is generally part of the overall development of territories where urban areas extend over areas dedicated to agriculture. Then agriculture, in turn, moves over natural areas, including wetlands, to meet the population's growing primary production needs (Gardner et al., 2015). Kummur et al. (2016) also observed that croplands are spreading from highly populated coastal zones to inland zones. In the context of globalization, if the phenomenon of exploitation of natural spaces does not occur within the territory in question, it is exported to other regions.

Coastal wetlands provide protection against storm surges, and sediment accumulation for land accretion. They also provide other important services, such as direct resources of food and bio-materials, habitats for wildlife, carbon sequestration, water purification, tourism resorts, and other functionalities. That's why it is a critical time to stop the depletion of these vulnerable ecosystems and make efforts to restore the coastal wetlands (Li et al., 2018).

Wetlands also suffer from the effects of climate change. For example, in the case of mangroves, if the non-climatic causes mentioned above (which are the strongest contributors) are excluded, large-scale mortality episodes since the 1960s are generally due to low-frequency and high-intensity weather events, such as tropical cyclones, and extreme weather events such as droughts and heat waves (Sippo et al., 2018).

Projected sea level rise is another potential factor threatening the vulnerable coastal wetlands (Nicholls and Cazenave, 2010). It is still controversial because wetlands can migrate landward if no seawall or steep relief exists behind the wetlands, but this is often not the case, due to the « coastal squeeze » phenomenon, presented below.

Coastal squeeze

Doody (2013) characterized coastal squeeze as coastal habitats being pushed landward through the effects of SLR and other coastal processes (such as increased storminess), combined with the presence of static, natural, or artificial barriers effectively blocking this migration, thereby squeezing habitats into an ever narrowing space (see figure 19).

Shoreline erosion leads to coastal squeeze if the eroding coastline approaches fixed and hard built or natural structures (Pontee, 2013; Wong et al., 2014), a process to which SLR also contributes (Doody, 2013; Pontee, 2013).

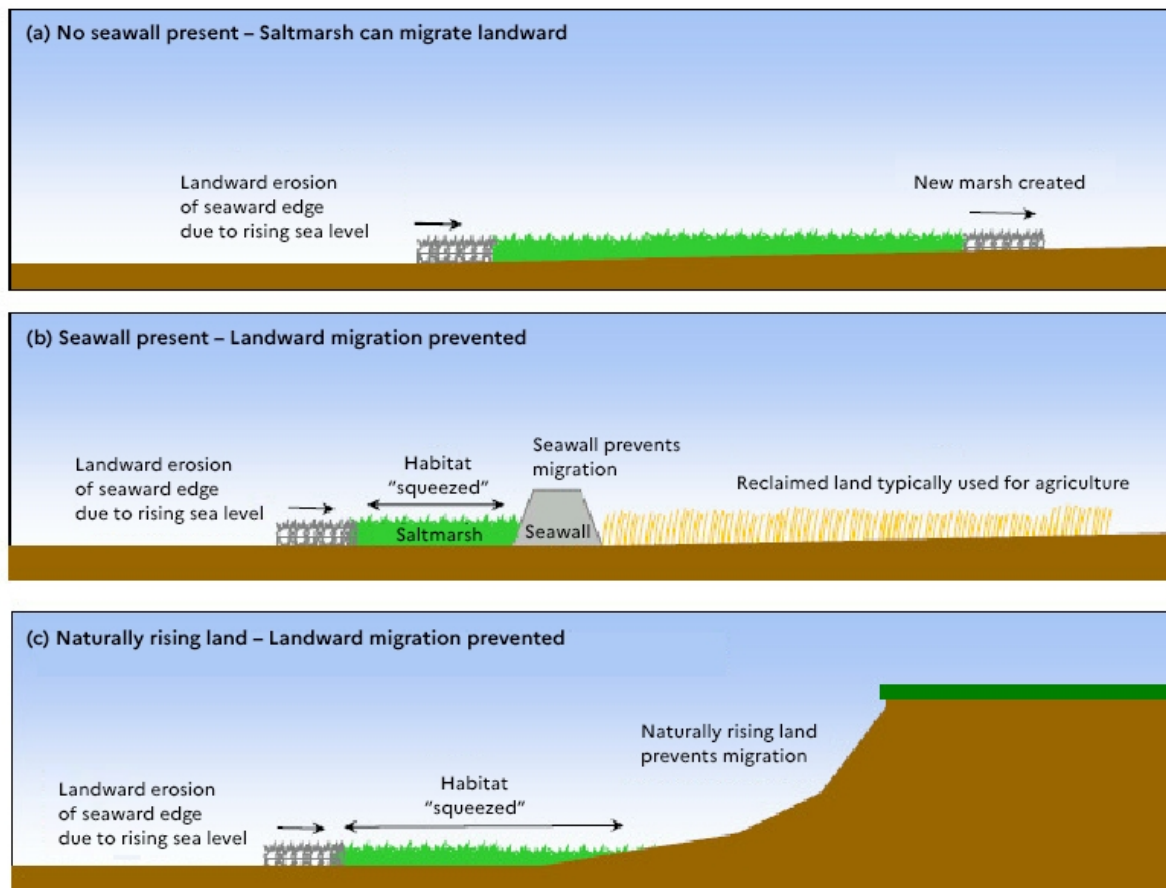


Figure 19: A simplified illustration of coastal squeeze as defined by Doody (2013).

The illustration 19 shows three cases:

- (a) Unrestricted landward migration of the saltmarsh habitat in low lying areas, which maintain coastal habitat extent – sometimes referred to as « natural transgression » or « rollover » ;
- (b) Landward migration of the saltmarsh is prevented by a sea wall which results in a reduction in the width of the saltmarsh – the most common definition of coastal squeeze ;

- (c) Landward migration of the saltmarsh is prevented by rising land, which results in a reduction in the width of saltmarsh – occasionally referred to as « natural coastal squeeze » by some authors.

Coastal squeeze increases exposure as well as vulnerability by the loss of a buffer zone between the sea and infrastructure behind the habitat undergoing coastal squeeze. The clear implication is that coastal ecosystems progressively lose their ability to provide regulating services, including their defenses against SLR-driven inundation and salinization. As long as SLR impacts remain moderate, the dominant driving factor of coastal squeeze will be anthropogenic land-based development. With higher SLR scenarios and in the case of no further development at the coast, SLR may become the dominant driver before the end of this century (IPCC, 2019).

1.2.4 Climate change

In order to understand the mechanisms of climate change and assess its effects on coastal flood risk, we will refer mainly to the work of the IPCC (2007; 2014; 2019; 2021).

Mechanisms of climate change

Based on the IPCC (2021) report, each of the last four decades has been successively warmer than any decade that preceded it since 1850. Thus, as shown in figure 20, global surface temperature¹⁰ was :

- in the first two decades of the 21st century (2001-2020), 0.99 [0.84-1.10] °C higher than 1850-1900 ;
- in 2011–2020, 1.09 [0.95 to 1.20] °C higher than 1850–1900, with larger increases over land (1.59 [1.34 to 1.83] °C) than over the ocean (0.88 [0.68 to 1.01] °C).

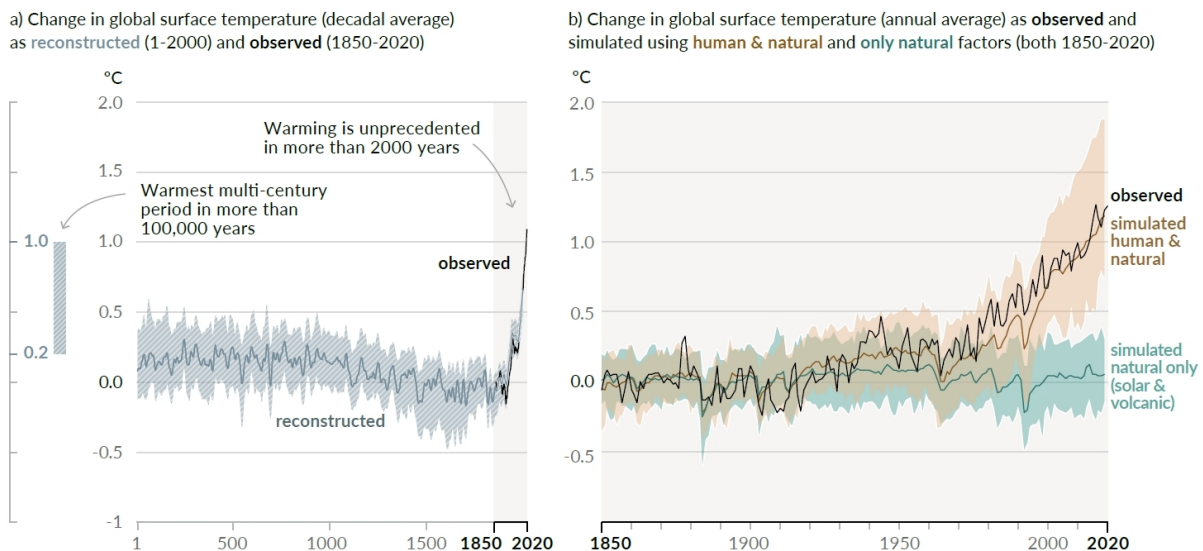


Figure 20: History of global temperature change and causes of recent warming (from IPCC, 2021: Summary for Policymakers, figure SPM.1).

This warming is caused by greenhouse gases and gaseous constituents of the atmosphere (both natural and anthropogenic), that absorb and emit radiation at specific wavelengths within the spectrum

¹⁰ The term « global surface temperature » is used in reference to both global mean surface temperature and global surface air temperature (IPCC, 2021).

of radiation emitted by the Earth's ocean and land surface, by the atmosphere itself, and by clouds. This property causes the greenhouse effect. Water vapor (H₂O), carbon dioxide (CO₂), nitrous oxide (N₂O), methane (CH₄), and ozone (O₃) are the primary greenhouse gases (GHGs) in the Earth's atmosphere.

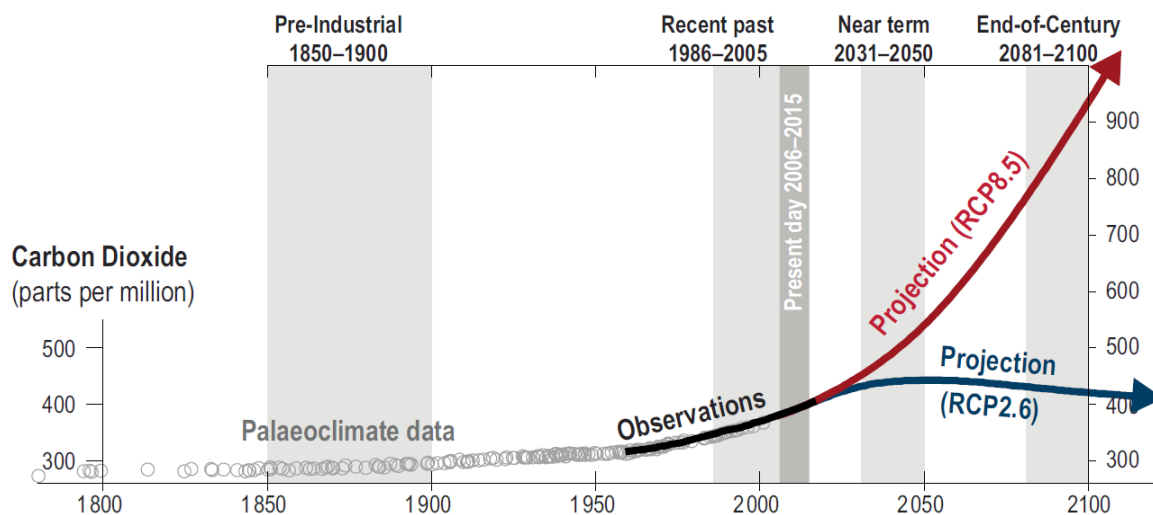
The term « radiative forcing » is used with the specific meaning of a disruption of the radiative balance of the Earth's climate system. Its definition by the IPCC (2007) is as follows¹¹ :

« Radiative forcing measures the impact of certain factors affecting climate on the energy balance of the Earth/atmosphere coupled system. The term « radiative » is used because these factors alter the balance between incoming solar radiation and infrared radiation emissions from the atmosphere. This radiative balance controls the temperature on the surface of the planet. Radiative forcing is generally quantified as « the rate of energy transfer per surface unit of the globe, measured in the upper layers of the atmosphere » and is expressed in « watts per square meter » (W/m²) ».

Projections and assessments of future climate, ocean, and cryosphere changes are commonly based on coordinated climate model experiments forced with Representative Concentration Pathways (RCPs) of future radiative forcing scenarios. RCPs are a set of time series of plausible future concentrations of greenhouse gases, aerosols, and chemically active gases, as well as land use changes (Moss et al., 2008; Moss et al., 2010; van Vuuren et al., 2011)¹². The word « representative » signifies that each RCP provides only one of many possible pathways that would lead to the specific radiative forcing characteristics. The term « pathway » emphasizes that not only the long-term concentration levels, but also the trajectory taken over time to reach that outcome are of interest (IPCC, 2019).

The IPCC (2019) mainly uses scenarios RCP2.6 and RCP8.5 (referring the radiative forcings of 2.6 and 8.5 W.m-2 respectively achieved in 2100). The RCP2.6 illustrates a future marked by low greenhouse gas emission due to significant climate change mitigation efforts, which gives a two out of three chance of limiting warming by the end of the century to less than 2 °C above pre-industrial. In contrast, the RCP8.5 is a scenario of high greenhouse gas emissions in the absence of policies to address climate change, leading to a continuous and sustained increase in atmospheric greenhouse gas concentration. Of all RCPs, RCP8.5 is the highest greenhouse gas emission trajectory.

Figure 21 shows the evolution of the average atmospheric CO₂ concentration from the pre-industrial period and projections to the end of the 21st century.



11 IPCC, Extract from the Report of Working Group I, Frequently Asked Questions, FAQ 2.1 Box 1.

12 In IPCC (2021), the names of the scenarios link the socio-economic development (SSP) with the RCP indices, for example « SSP2-4.5 ». In this report, references cited using the previous naming convention, SSP and RCP will be mentioned separately.

Figure 21: Observed (Keeling et al., 1976) and reconstructed (Bereiter et al., 2015) atmospheric CO₂ concentrations, as well as the RCPs of CO₂ for low (RCP2.6) and high (RCP8.5) future emission scenarios (from Abram, N., J.-P. Gattuso, A. Prakash, L. Cheng, M.P. Chidichimo, S. Crate, H. Enomoto, M. Garschagen, N. Gruber, S. Harper, E. Holland, R.M. Kudela, J. Rice, K. Steffen, and K. von Schuckmann. In: IPCC, 2019: Framing and Context of the Report, figure 1.3 (upper panel)).

Until 2019, in line with the RCP8.5 trajectory, global fossil CO₂ emissions rose more than 2% in 2018 and 1.6% in 2017, after a temporary slowdown in emissions during the period of 2014–2016 (Peters et al., 2012; Le Quéré et al., 2018). In 2020, growth in CO₂ emissions slowed. The COVID-19 pandemic caused a drop in emissions of about 7% in 2020 relative to 2019, but strong policy is needed to address underlying drivers and to sustain a decline in global emissions beyond the current crisis (Le Quéré et al., 2021).

According to a study by Raftery et al. (2017), it is unlikely that the Paris Agreement's aim of keeping global warming below a 2°C increase by the end of the 21st century will be met. The likely range of global temperature increase is 2.0–4.9°C, with median of 3.2°C and a 5% (1%) chance that it will be less than 2°C (1.5 °C).

The effects of climate change

Ocean and cryosphere changes are pervasive and observed from high mountains, to the polar regions, to coasts, and into the deep ocean. The IPCC 5th Assessment Report (2014) confirmed that the ocean is warming, sea level is rising, and ocean acidity is increasing. Most glaciers are shrinking, the ice sheets in Greenland and Antarctica are losing mass, sea ice extent in the Arctic is decreasing, Northern Hemisphere snow cover is decreasing, and permafrost temperatures are increasing (IPCC, 2019).

Figure 22 provides a representation of historical changes (observed and modelled) and projections for key coastal flood risk indicators based on the five scenarios used by the IPCC (2021).

GMSL rise is the first factor to consider for coastal flood risk, taking into account in particular that a RSL rise favors the propagation of waves to the coast (CIRIA et al., 2013). The GMSL is increasing with an acceleration in recent decades due to an increasing loss of ice from the ice caps of Greenland and Antarctica, in addition to the continuous loss of glacier mass and thermal expansion of the ocean.

At the end of the century the two scenarios RCP2.6 and RCP8.5 forecast a rise in sea levels centered on the values 0.43 m and 0.82 m. Over the year 2300 horizon, according to the IPCC, the variation of the GMSL is uncertain, ranging from 2 to 7 m for the most likely range of the RCP 8.5 scenario.

However, accelerated and stronger evolutions could occur:

- if ice sheets melt faster in Greenland and Antarctica, Bamber et al. (2019) support the use of scenarios of 21st century GMSL rise exceeding 2 m for planning purposes. That could lead to land loss of 1.79 million km², including land utilized for agricultural production, and the displacement of 187 million people;
- RSL change is not globally uniform. Thermal expansion, ocean dynamics, and land ice loss contributions will generate regional deviations from the average of about 30% around the GMSL rise. Differences from the global mean may be greater than 30% in areas of rapid vertical land movements, including those caused by local anthropogenic factors such as groundwater extraction (IPCC, 2019).

The temperature, acidity and oxygenation of the ocean are also important parameters to consider because they condition the state of certain ecosystems that have a protective effect on coastlines: warm-water coral reefs and rocky shores dominated by immobile, calcifying (e. g., shell and skeleton-producing) organisms, are currently impacted by extreme temperatures and ocean acidification. Marine

heatwaves have already resulted in large-scale coral bleaching events at increasing frequency causing worldwide reef degradation since 1997, and recovery is slow (more than 15 years), if it occurs (IPCC, 2019).

Human activities affect all the major climate system components, with some responding over decades and others over centuries

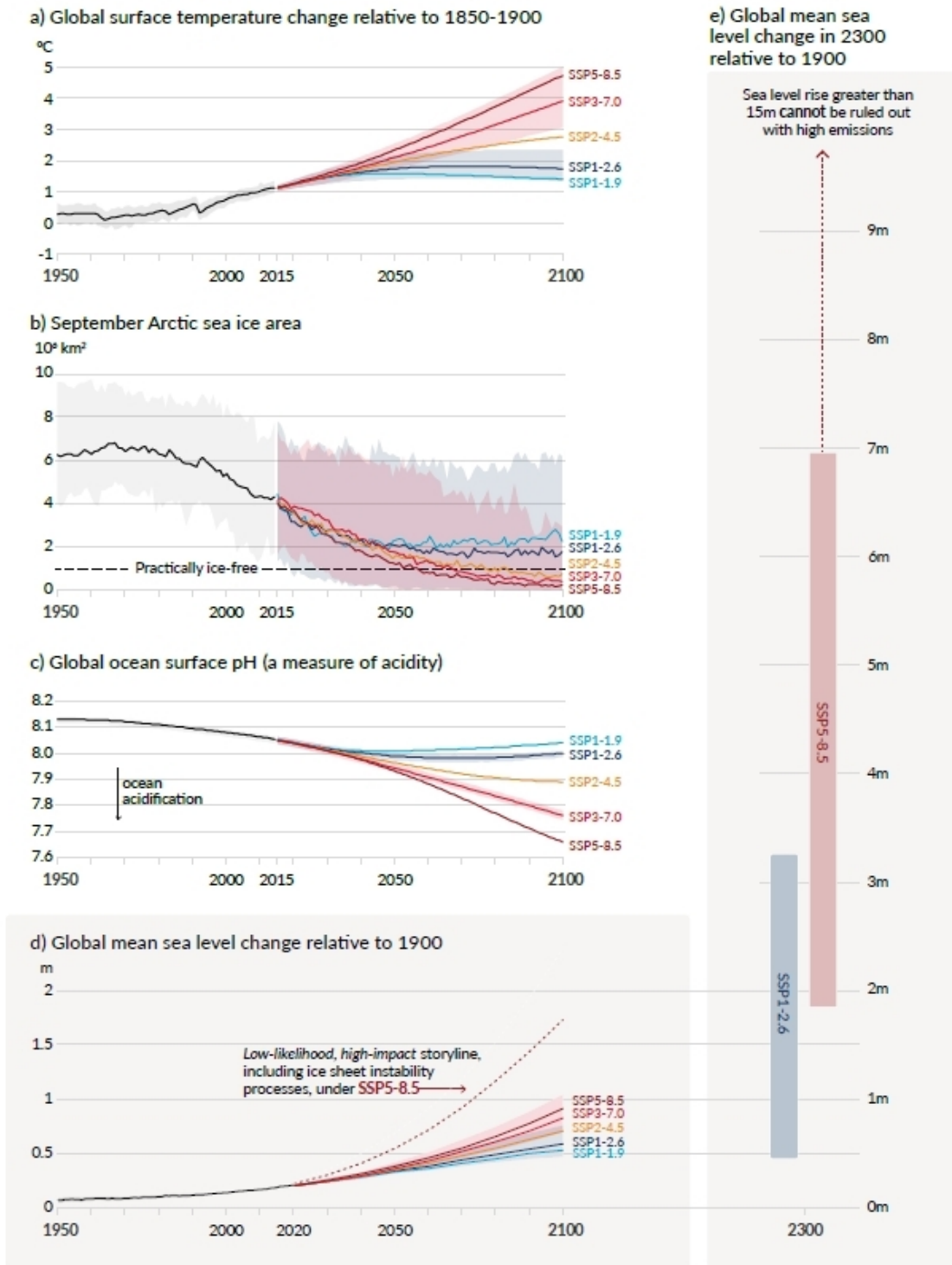


Figure 22: Selected indicators of global climate change under five illustrative scenarios (from IPCC, 2021: Summary for Policymakers, figure SPM.8).

Slow onset changes, for example, sea level rise, ocean warming and acidification, should be considered in combination with extreme events, for example, marine heat waves¹³, tropical and extratropical storms, associated storm surges, and heavy precipitation, to explain part of observed climate impacts and projected risks. For example:

- accelerating sea level rise combines with storm surges, tides, and waves to generate extreme sea level events that affect flooding, shoreline changes, and salinization of soil, groundwater, and surface waters ;
- ocean acidification combines with ocean warming and deoxygenation to impact ecosystems (e. g., coral reefs and oyster beds) and the associated services benefiting human societies, including coastal flood protection;
- in the polar regions, accelerating permafrost thaw is promoting rapid erosion of ice-rich sediments (Lantuit et al., 2011). Melting of ice and associated thaw subsidence may induce instability of various infrastructure components. Arctic SLR and sea surface warming have the potential to substantially contribute to this thawing (Lamoureaux et al., 2015). Moreover, the decrease in seasonal sea ice extent in the Arctic, together with a lengthening open water season, provide less protection from storm impacts, particularly later in the year when storms are prevalent (Forbes, 2011).

The frequency of extreme sea levels will vary significantly across coastlines (Buchanan et al., 2016), as shown in figure 23.

The combination of tide and storm surge phenomena requires a statistical approach to assess the evolution of the marine flood hazard. Thus, the change in ESL events is commonly expressed in terms of the amplification factor and the allowance. The amplification factor denotes the amplification in the average occurrence frequency of a certain extreme event, often referenced to the water level with a 100-year return period during the historic period. The allowance denotes the increased height of the water level with a given return period. This allowance equals the regional projection of RSL rise with an additional height related to the uncertainty in the projection (Hunter, 2012).

In figure 23, the grey bands represent the 5–95% uncertainty range in the fit of the extreme value distribution to observations. The upper left hand panel provides an example illustrating the relationship between ESL events and the return period for historical (reference period 1986-2005) and future (reference period 2081-2100) conditions. The colored lines for the different locations show these expected ESL events for different RCP scenarios. The horizontal line denoting the amplification factor expresses the increase in frequency of events which historically have a return period of 100 years. In the example, a water level of 2.5 m above mean sea level, recurring on average every 100 years in the recent past climate, will occur on average every 2 to 3 years under future climate conditions. The allowance expresses the increase in ESL for events that historically have a return period of 100 years.

It appears that amplification factors are strongly determined by the local variability in ESL events. Locations where this variability is large due to large storm surges and astronomical tides (e. g., Cuxhaven, see figure 23a) will experience a relatively moderate amplification of the occurrence frequency of extremes. In comparison, locations with small variability in ESL events (e. g., Lautoka and Papeete, see figure 23g,k) will experience large amplifications even for a moderate RSL rise (Vitousek

¹³ Marine heatwave : A period of extreme warm near-sea surface temperature that persists for days to months and can extend up to thousands of kilometers.

et al., 2017). Globally, this contrast between regions with large and small amplification factors becomes clear for projections by mid-century and considerable in the coming centuries.

In particular, many coastal areas in the lower latitudes may expect amplification factors of 100 or larger by mid-century, regardless of the scenario. By the end of the century and in particular under RCP8.5, such amplification factors are widespread along global coastlines (Vousdoukas et al., 2018).

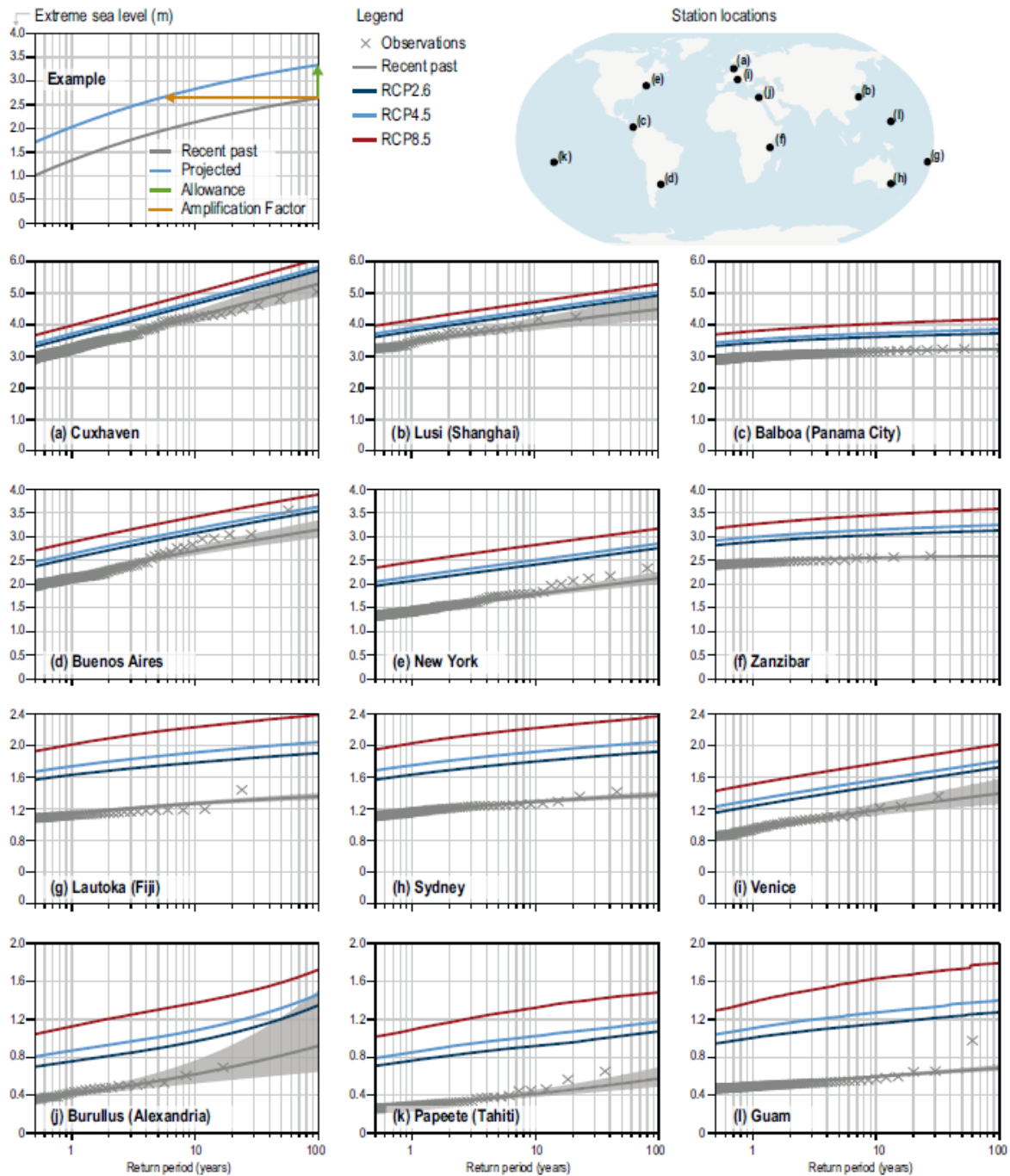


Figure 23: The relation between expected extreme sea level (ESL) events and return period at a set of characteristic tide gauge locations (see upper right for their location), referenced to recent past mean sea level, based on observations in the GESLA-2 data base (grey lines) and 2081–2100 conditions for three different RCP scenarios. From Oppenheimer, M., B.C. Glavovic, J. Hinkel, R. van

de Wal, A.K. Magnan, A. Abd-Elgawad, R. Cai, M. Cifuentes-Jara, R.M. De Conto, T. Ghosh, J. Hay, F. Isla, B. Marzeion, B. Meyssignac, and Z. Sebesvari. In: IPCC, 2019: Sea Level Rise and Implications for Low-Lying Islands, Coasts and Communities, figure 4.11.

1.3 Conventional flood risk management concepts and strategies

In this section, conventional flood risk management concepts and strategies will be presented. Scientific references are numerous on these essential aspects and the definitions of the terms used may be subject to considerable variation. This is why it will be mainly referred to collegial productions to use the most consensual definitions. Thus the European project FLOODsite provides a complete insight on these concepts (FLOODsite, 2009a) and the terms used (FLOODsite, 2009b), as well as the International Levee Handbook (CIRIA et al., 2013).

1.3.1 Concepts associated with flood risk

Flood risk management uses all the concepts generically associated with the concept of risk, in particular the concepts of hazard, vulnerability, and exposure. In order to better understand the meaning of these terms as they apply to flood risk, the « Source-Pathway-Receptor-Consequence (SPRC) » model will be presented beforehand.

The « Source-Pathway-Receptor-Consequence » conceptual model

To understand the link between hazard and risk, it is useful to consider the commonly adopted SPRC model (see figure 24). This is a simple conceptual model for representing processes that lead to a particular consequence. For a risk to arise, there must be :

- a hazard that consists of a « source » or initiator event (e. g., a cyclone);
- a « receptor » (e. g., people or properties) that has the potential to be affected by the hazard; and
- a pathway between the source and the receptor (i. e., flood routes including through or over defenses).

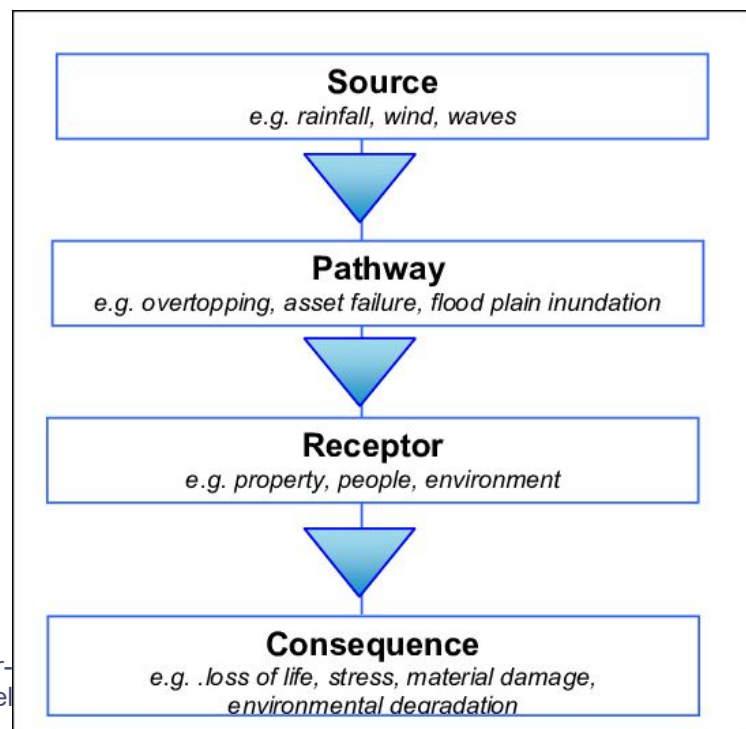


Figure 24: « Source-Pathway-Receptor-Consequence » conceptual model (adapted from FLOODsite, 2009b).

A hazard does not automatically lead to a harmful outcome, but identification of a hazard does mean that there is a possibility of harm occurring, with the actual harm depending upon the exposure to the hazard and the characteristics of the receptor (FLOODsite, 2009b).

Two definitions of risk

Flood risk is defined in at least two alternative ways, the first being more suited to qualitative approaches and the second to quantitative approaches (FLOODsite, 2009b).

The SPRC conceptual model considers risk to be the result of the exposure of a vulnerable stake to a hazard, which is reflected in the following formula:

$$(1) \quad \text{risk} = \text{hazard (flood)} * \text{exposure} * \text{vulnerability (of the society/ area)}$$

This first definition is often preferred by urban planners, who usually consider the hazard as a given and utilize spatial planning and crisis management as the means to adapt to that given.

Figure 25 illustrates the application of this concept in the case of the impact assessment of coastal flooding on the Sangatte municipality (France). The cartographic representations of the hazard and the vulnerable exposed stakes give, by superposition, a representation of the risk.

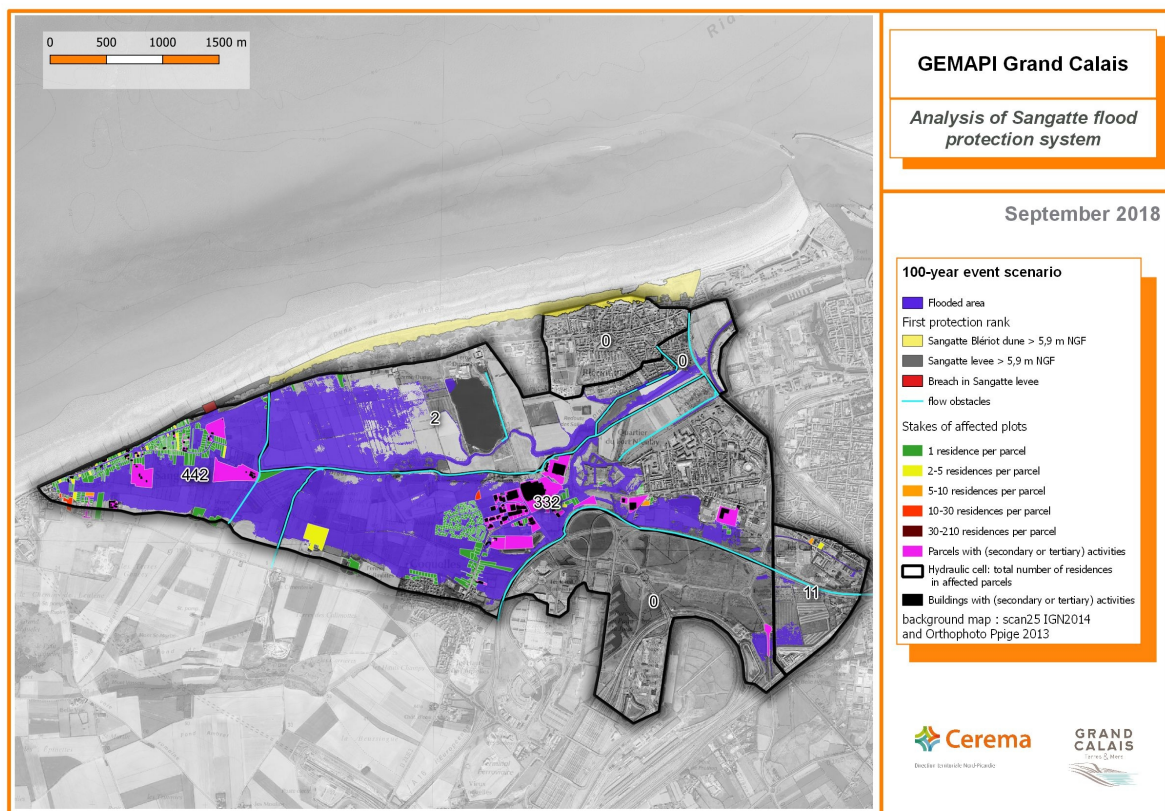


Figure 25: Flood risk analysis in the municipality of Sangatte (Cerema, 2020). Credit: Kevin Corsiez and Bruno Kerloc'h, Cerema.

However, in an attempt to quantify risk, and considering that the word « risk » suggests a probability of occurrence, a second definition may be sought. To do this:

- the two terms « exposure » and « vulnerability » are substituted by « consequences », with the consequences being generally more quantifiable (for example, in number of fatalities and economic damage) than the previous two terms;
- the hazard can be represented by its probability distribution.

This yields the second definition:

$$(2) \quad \text{risk} = \text{probability (of the flood)} * \text{consequences}$$

The second definition is preferred by engineers, who usually strive for a reduction of the probability of flooding with protection means, and hence need to be able to calculate risk.

Prime et al. (2016) illustrated this approach. These authors examined the Dungeness and Romney Marsh coastal zone (UK), a region of high value in terms of habitat and energy assets. The objective was to redesign aging coastal defenses in order to protect against a 0.5% annual probability event of flooding and to reduce consequences of storm surges to an acceptable level.

Considering two parameters – the joint significant wave height (Hs) and water level (WL) –, Prime et al. (2016) associated a storm impact model (simulating the overwashing discharge at the defense crest) with a flood inundation model (simulating the inundation extent and volume for the Hs and WL combination). Thus, they explored which combinations of wave and water levels generated the greatest threat, as shown in figure 26.

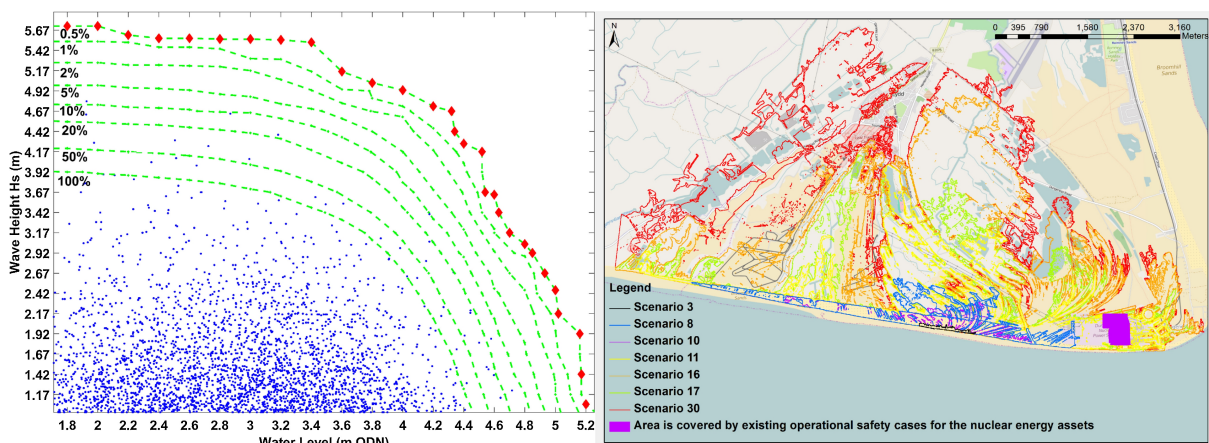


Figure 26: Left : joint Hs and WL probability curves of the observed conditions at Dungeness. Right : maximum flood extent outlines for seven selected scenarios (Prime et al., 2016).

The following comments may help to understand the probability curves represented in figure 26:

- the blue dots represent wave height and water observations at Dungeness;
- the green lines are the probability curves (the annual probability of occurrence shown ranges from 100% down to 0.5%);
- the red diamonds show the 30 selected combinations of wave height and water level that are modeled in the figure on the right.

1.3.2 Flood risk management

Before flood risk management became the generally accepted approach, a sequence of dominant approaches emerged. The concepts discussed above provide a framework for assessing past developments and understanding the foundations on which current strategies are based.

Evolution of the principles of flood risk prevention

In the 1950s to the 1970s, flood defense, focused on keeping floods off the land using strong engineering means. The aim was to reduce the probability that communities would experience floods, generally through investing in such measures as flood embankments, channel enlargement, pumping schemes, and sea walls. The use of the term « flood control » suggested (incorrectly) that we might control the floods themselves.

Then in the 1980s and 1990s, the term « flood management » implied that we might at least manage floods, if we could not control them, but still with a focus on controlling the flood water, using engineering measures (FLOODsite, 2009a).

From the 2000s, the main objective became the reduction of risks for people and property. Therefore, measures to reduce the vulnerability of society were considered with the same attention as water management measures.

This development in the approach to flood risk management can be linked to two societal trends:

- in the last century, there was a tendency towards increasing faith in technological solutions culminating in a sense of full control over the environment, but this has been followed by criticism of the negative environmental consequences of technology and a decreasing faith in its potential;
- since the period of Enlightenment, there has been a slow, but steady trend of ever-increasing specialization in science and governance, but this too has been followed by criticism and a strong call for multidisciplinary integration over the last decades. This is reflected by the appearance of approaches such as integrated water management and also by the steady integration of water management with spatial planning and environmental management at large.

Because a balance of economic, social, and environmental considerations is necessary, flood risk management can now be seen as part of an overall management policy for sustainable development, which aims for a similar balance. However, the nature of this balance varies across communities and countries (FLOODsite, 2009a).

The current predominant principles of risk prevention

In general and particularly in the context of climate change adaptation, risk can be reduced by addressing one or more of the three risk factors: hazard, exposure, and/or vulnerability. The reduction of these three risk factors can be achieved through different policy and action choices over time until limits to adaptation might be reached (IPCC, 2019).

Figure 27 identifies actions that can be taken on each of the risk factors in order to reduce it.

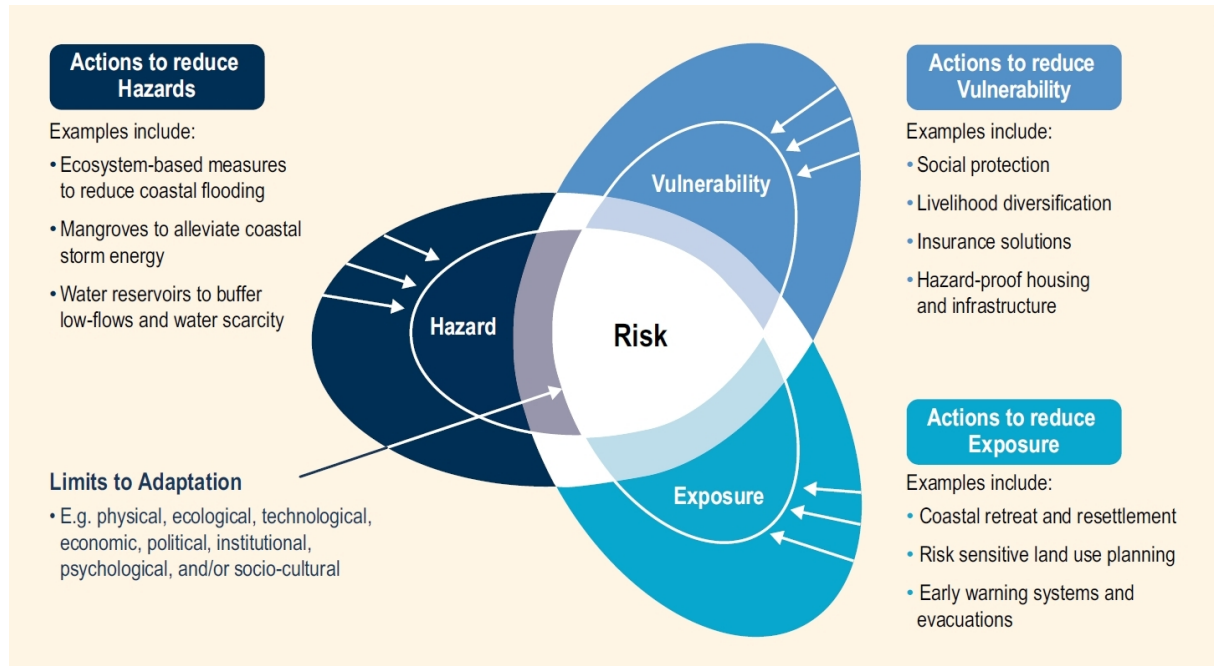


Figure 27: Options for risk reduction through adaptation. From Hock, R., G. Rasul, C. Adler, B. Cáceres, S. Gruber, Y. Hirabayashi, M. Jackson, A. Kääb, S. Kang, S. Kutuzov, Al. Milner, U. Molau, S. Morin, B. Orlove, and H. Steltzer. In: IPCC, 2019, figure CB2.1.

Seeking to concurrently reduce hazard, exposure, and vulnerability leads to the development of synergies between measures. For example, better spatial planning to keep urban and other vulnerable development out of hazard zones may mean smaller scale engineering works to protect these areas. Adequate emergency response during floods can reduce flood damage and thereby lower insurance premiums (FLOODsite, 2009a).

Figure 28 is a classic illustration of the range of measures adopted in flood risk management, following a segmented SPRC approach.

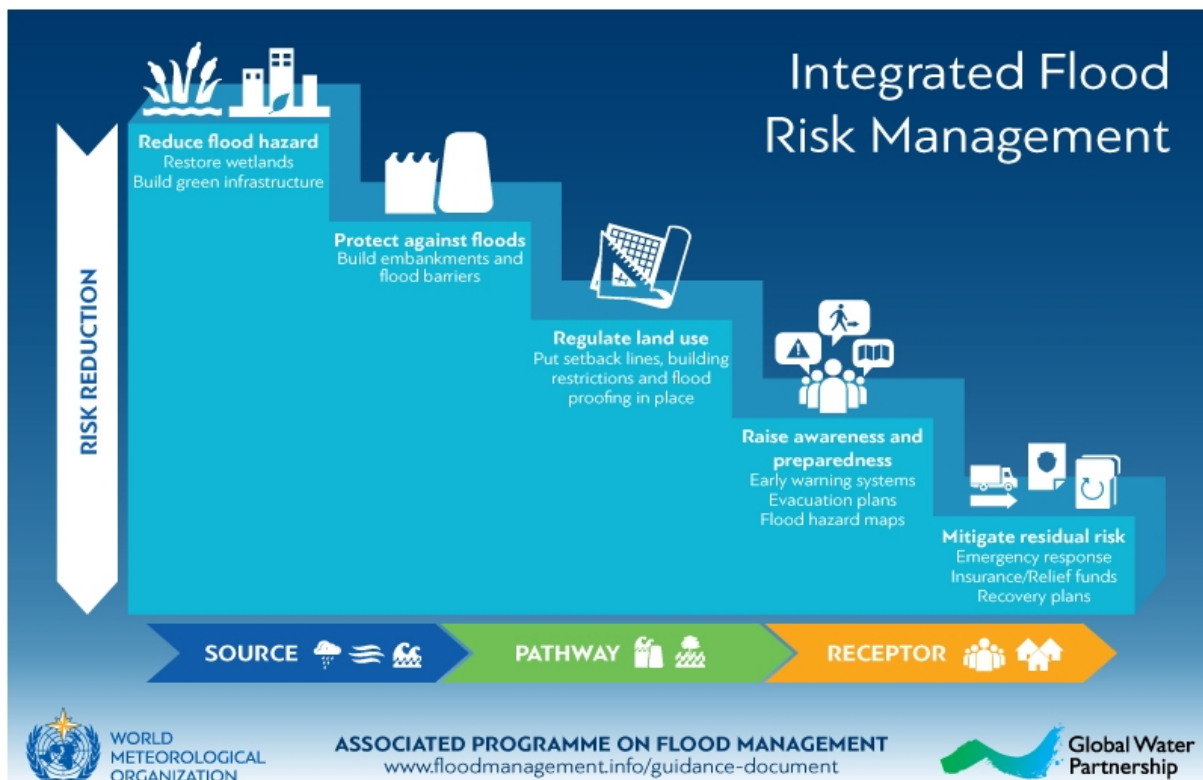


Figure 28: Integrated flood risk management (WMO, 2017).

Flood risk management is not a one-time activity, such as building an embankment or a dam. It is a continuous process, characterized by repeated activities: analysis of the flood risk, consideration of measures and policy instruments to reduce the risk, making policy decisions, implementing measures and instruments, monitoring their effects, etc. This permits constant adaptation to changing environmental circumstances and changing societal requirements (FLOODsite, 2009a).

Flood risk management is also a cyclical activity, punctuated by flood episodes, as shown in figure 29.



Figure 29: Emergency management life cycle (CIRIA et al., 2013).

Flood risk management is an approach based on the notion that risks cannot be taken away entirely but only partially. In this context, each modification of the prevention system must be based on an analysis of flood risks, with the aim of identifying the residual risks that will in turn be assessed to determine whether they are acceptable or tolerable for stakeholders. The purpose of the risk assessment is to manage flood protection structures and risks within a framework common to all major

risks. While it is difficult to draw the line between what is tolerable and what is not tolerable (in particular because the perception of risk varies from one individual to another), this assessment makes it possible to take into account values and judgements from societal, regulatory, and legal points of view in management and decision-making processes (CIRIA et al., 2013).

Urban Risk Management Principles

Climate change and the concentration of population and assets in urban areas are main factors likely to affect flood risk in the future. Urban systems contain assets of high value and complex and interdependent infrastructure networks (e. g., power supplies, communications, water, transport, etc.). The infrastructure networks are critical for the continuity of economic activities as well as for the population's basic living needs. The availability of these resources is also required for fast and effective recovery after flood disasters. Damage to critical infrastructure assets during flooding can result in significant secondary consequences which may be more serious than the direct damage caused by the flood. For example, the widespread disruption to infrastructure caused by Hurricane Sandy in 2012 to the East coast of North America and the Caribbean has led this hurricane to be ranked as one of the costliest storm events for insurers (FloodProBE, 2013).

Considering that flood risk management is only one of the many challenges of our society and that there are opportunities to incorporate flood risk management into other policy domains such urban planning, which would lead to significant societal and economic benefits, the European project FloodProBE (2013) contributed to determining cost-effective means for flood risk reduction in urban areas, focusing on:

- the identification and improvement of weak links in flood defense systems ; and
- flood-induced failures of particular critical infrastructure, assessment of damages caused by these failures and development of new intervention modes.

Application of these principles in Europe and France

In Europe, the directive 2007/60/EC of the European Parliament and of the Council on the assessment and management of flood risks (« Flood Directive ») is implemented by the Member States. The purpose of the directive is stated in Article 1: to establish a framework for the assessment and management of flood risks, aiming at the reduction of the adverse consequences for human health, the environment, cultural heritage, and economic activity associated with floods in the Community.

The flood directive requires:

- preliminary flood risk assessment;
- flood hazard mapping and flood risk mapping;
- flood risk management plans.

Updates are made every six years (2011, 2017, 2023, etc.), in particular to take into account the effects of climate change.

The map of the French territories at high risk of flooding established during the second cycle of the flood directive is presented in figure 30. It appears that all maritime coastlines have areas prone to coastal flood risk, especially at the mouth of rivers, which can be simple (estuaries) or branched (deltas)¹⁴.

14 For more information on the development of these coastal formations: <https://www.eaufrance.fr/les-estuaires-lagunes-et-deltas>

High flood risk territories in France (2^d cycle of the flood directive)



Figure 30: Map of high flood risk territories in France corresponding to the second cycle of the flood directive. Credit: Cerema, based on DREAL, DGPR, IGN.

The flood directive requires management plans to address all phases of the flood risk management cycle. These plans should focus particularly on :

- prevention (*i. e.*, preventing damage caused by floods by avoiding construction of houses and industries in present and future flood-prone areas or by adapting future developments to the risk of flooding);
- protection (*i. e.*, taking measures to reduce the likelihood of floods and/or the impact of floods in specific locations such as restoring flood plains and wetlands); and
- preparedness (*e. g.*, providing instructions to the public on what to do in the event of flooding).

In France, in accordance with the flood directive and following a national consultation with the general public, a national flood risk management strategy has been established (MEDDE, 2014). This strategy aims to ensure the coherence of the actions carried out on the territory and pursues three priority objectives:

- increase the safety of exposed populations;
- stabilize in the short term, and reduce the cost of flood damage in the medium term;
- significantly shorten the time to return the affected areas to normal.

This strategy responds to a strong expectation from all partners, including local and regional authorities, of a shared framework guiding national flood risk management policy. This strategy includes the implementation of major projects at the territorial level through « flood prevention action programs », which are based on the following principles:

- from a diagnosis to characterize the vulnerability of the territory to flooding, a global strategy of shared intervention between prevention actors is established at the level of the risk basin and is set out in a program of actions;
- this action program covers all aspects of flood risk management: improvement of risk knowledge and awareness (Objective 1), monitoring, flood and inundation forecasting (Objective 2), crisis alert and management (Objective 3), consideration of flood risk in town planning (Objective 4), reduction of vulnerability of people and assets (Objective 5), flow management (Objective 6), and management of hydraulic protection structures (Objective 7).

It should be noted that a socio-economic evaluation of the projects of Objectives 6 and 7 is requested, with cost-benefit analysis or multicriteria analysis, based on the cost of the project.

1.4 Protection systems

Worldwide, in many coastal areas with high stakes, protection systems play a central role in flood risk management strategies. The hydraulic conditions to which the stakes will be exposed depend largely on the reaction of the structures (natural or anthropogenic) that compose these systems.

1.4.1 Development of protection systems

Polderization was known to the Sumerians and Etruscans before the Dutch became masters of this art (Gamblin, 2021). The development of levee systems is inseparable from the history of the Netherlands, where these techniques have been progressively developed, with the dual aim of protecting against coastal flood risk and installing activities on land gained from the sea, initially crops, pastures, salt marshes, or peat extraction (Sarrazin, 2014). These techniques were then exported to other European countries and to other continents.

As part of a retrospective, Guében-Venière (2015) analyzed the evolution of the Netherlands' low-lying coastal plains, where the tides of the North Sea and the flows of three major European rivers, the Rhine, the Meuse, and the Scheldt, converge. Schematically, the following phases emerged:

- the so-called Dunkirk I¹⁵ was a marine transgression that made it impossible to install humans near the shore. The Dutch Frisians had the idea of building the first *terpen* to cope with the rising waters. These artificial earthen mounds, with a surface of a few hectares and a height of only a few meters, then multiplied during the marine transgression known as Dunkirk II beginning in the fourth century. *Terpens* are thus the first form of adaptation of Dutch housing to hazards;
- the ninth century marks the beginning of a new era, that of the organized struggle against water. The problem of overcrowding coupled with a resurgence of severe storms at that time prompted the Frisians not only to adapt, but also to control the risk of flooding by pushing the hazard beyond the levees. Between the years 1200 and 1665, 190,000 hectares were conquered on the sea, or 4% of the country's current area. Technical progress (on the construction and maintenance of levees and drainage systems), and organizational progress (coordinated water management) of this period marked the beginning of Dutch hydraulic engineering, which has since continued to grow and spread beyond the country's borders;
- the 1953 storm flooded more than 200,000 hectares of land (an area of the same order of magnitude as the land gained on the sea in 500 years) and caused the death of 1,800 people, along with considerable economic damage. The aftermath of this storm was the trigger for the development of a technical plan to ensure coastal protection of the country close to zero risk: the Delta Plan. No less than ten dams have been built in 30 years, definitively modifying the natural functioning of the Zeeland Delta (see figure 31). In addition, levees have been systematically raised and widened by a factor 2;
- although the Delta Plan is a reflection of the knowledge and know-how of Dutch engineers, since the 1970s there have been many questions and strong challenges regarding the ecological and economic consequences. Since then, new approaches to environmental protection have developed: integrated management of the coastline based on better knowledge of its hydro-sedimentary functioning and a higher proportion of area dedicated to water within the country.

¹⁵ The Dunkirk transgression took place in two stages: during the Dunkirk I transgression, the North Sea invaded the Flemish sea plain and created the Calais Step (around -5000 to 2000 years before our era); during the Dunkirk II transgression, the Flemish plain was again invaded (3rd to 8th c. AD).

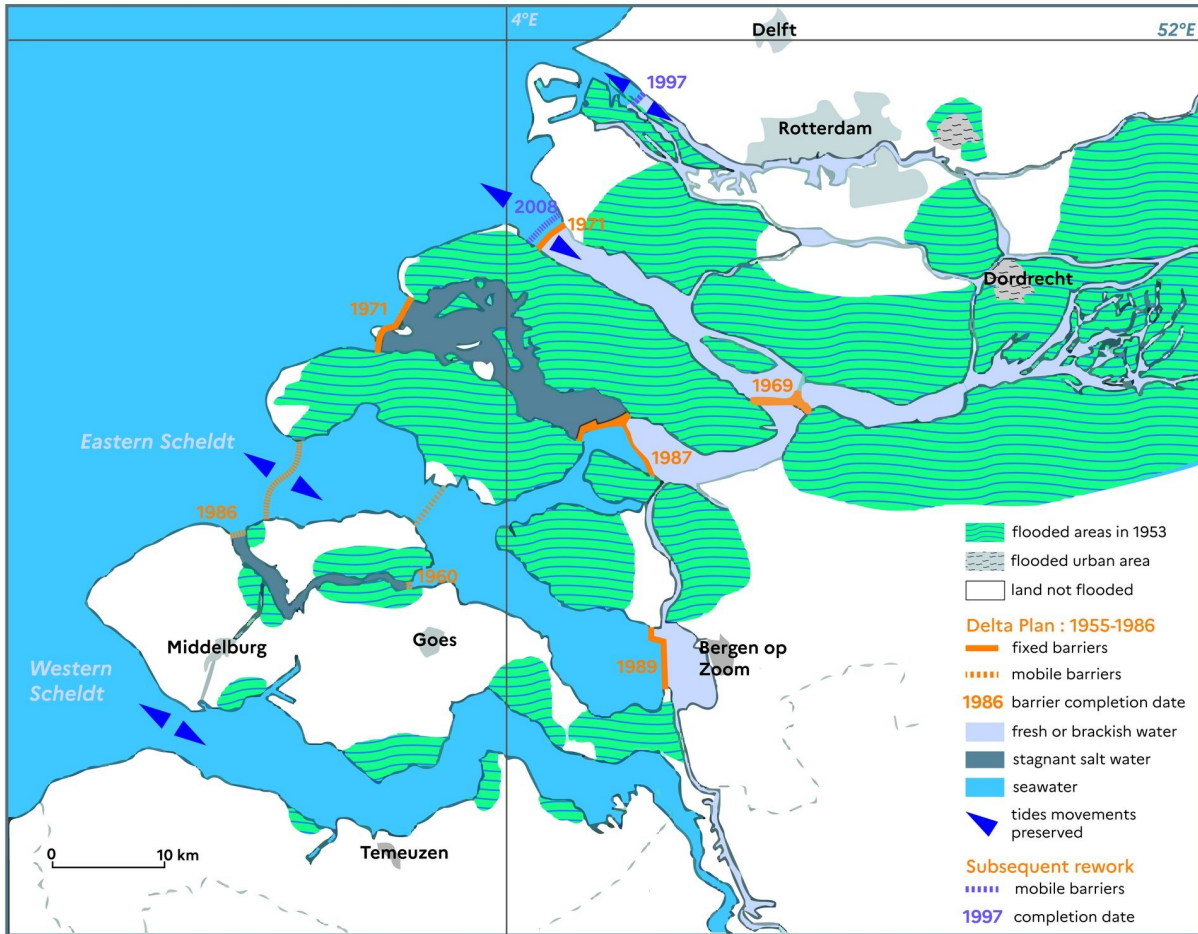


Figure 31: The Delta Plan dams. Credit : Cerema, after Guében-Venière (2015).

This retrospective shows that the development of protection systems is inseparable from the creation of « polders ». This word of Dutch origin (polder: leveed area), which appeared for the first time in a charter of Middelbourg (in the Dutch province of Zeeland) in 1219, means:

« An area of land which, naturally covered with water, is surrounded by levees, thus forming an artificial closed depression, and which has its own hydraulic regime: rain water or that which has infiltrated through the defenses is pumped out or, when circumstances allow it, by gravity (Gamblin, 2021) ».

Gamblin (2021) distinguished three types of polders:

- the leveed polder or coastal landing (in Dutch, *bedijking*). This type of polder results from the delimitation by a levee of a *schorre*, that is to say of a coastal strip which is covered only by spring tides, unlike the *slikke*, which is covered by all tides. Water flows by gravity through locks at low tide;
- the dewatered polder (in Dutch, *droogmakerij*), where the levees may be natural or not, results from the delimitation by a levee of an area normally occupied by water and drained by pumping; in addition to the dike, it is usually surrounded by a circular channel (in Dutch, *ringvaart*); the need for pumping (by windmills and steam pumps) explains why this type of polder appeared later (in 17th century);
- and finally the *zuidzee*, which is both coastal and dewatered, results from an area occupied by the sea which is delimited by a levee and dried by pumping. Of recent creation, it presupposes a very high technicality.

In all cases, the ground level in a polder is lower than the maximum level of the nearby water body, which makes the construction and maintenance of levees essential.

Following the Dutch model, in North-West Europe, 15 000 km² of coastal marshes have been leveed on low-lying coasts and estuaries since the eleventh century (Deboudt and Goeldner-Gianella, 2015).

During periods of colonization, these techniques were also imported to other continents. Globally, polders cover at least 22 000 km², spread across North America (in the U.S.A. and Canada) and South America (along the coast of Guyana), East Asia (in South Korea and Japan in particular), South Asia (in Vietnam, Indonesia, India, etc.), and West Africa (in Guinea). Across the world, these projects have helped to achieve several objectives such as: cleaning up wetlands that are sometimes affected by malaria, increasing agricultural production, expanding the space available, and improving the protection against the sea (Bertrand and Goeldner, 1999).

Engineered adaptations have led to an increase in agricultural development, due to the stability provided. Agriculture has become increasingly beneficial, providing food security and the opportunity to export excess produce and earn an income from the land. This has led to increases in population and hence a greater demand for space for both agriculture and settlement, which often results in reclamation of land that was not previously habitable (Welch et al., 2017).

Now, deltaic environments are often densely populated and have high socio-economic value (development of cities, even megacities, such as Cairo or Shanghai). Engineered interventions on levee systems interact with the morphological evolution of the delta, reducing or removing sedimentation and accelerating subsidence, increasing the consequences of flooding, and necessitating further adaptation. They also encourage further development, reinforcing this feedback in a coevolution process (Welch et al., 2017).

Beyond the case of deltas, coastal protection through civil engineering measures is widespread throughout the world, although it is difficult to provide estimates on how many people benefit from them (IPCC, 2019). Currently, at least 20 million people living below the normal high tide level (excluding surges caused by rare weather events and tsunamis) are protected by hard structures (and drainage) in countries such as Belgium, Canada, China, Germany, Italy, Japan, the Netherlands, Poland, Thailand, the UK, and the USA (Nicholls, 2010). Many more people living above high tides are also protected against ESL by hard structures in major cities around the world. There is a concentration of these measures in northwest Europe and East Asia, although extensive defenses are also found in and around many coastal cities and deltas. For example, large scale coastal protection exists in Vancouver (Canada), Alexandria (Egypt) and Keta (Ghana; Nairn et al., 1999) and 6 000 km of polder levees have been constructed in coastal Bangladesh. There are also defenses built and raised for tsunami protection, such as in post-2011 Japan (Raby et al., 2015).

1.4.2 Protection system composition

According to the International Levee Handbook (CIRIA et al., 2013), a levee system consists of a set of structures or protective elements, presenting an overall hydraulic coherence to ensure the effective protection of a previously identified group of stakes.

However, this definition does not explicitly include natural formations, the essential role of which must be stressed in protecting against coastal flooding. Moreover, the term « levee system » refers only to one of the two essential functions of protection systems; that of containing water by obstructing its passage. But a protection system must perform a second function; that of draining the water that accumulates inside the system by facilitating its flow outwards. Therefore, a broader and more explicit definition will be adopted for coastal flood protection systems, namely:

A set of anthropogenic structures and natural formations, that are coherent from the hydraulic point of view to ensure the effective protection of a previously identified group of stakes against coastal flooding of marine, fluvial, pluvial, or phreatic origin.

The components of this system may be levees and other civil engineering structures (e. g., breakwaters, groynes, seawalls, etc.), natural structures (e. g., sand or cobble beaches and dunes), as well as storage and drainage systems. These latter devices, positioned on land, must not be neglected, as they ensure the actions of water management, that must complement the actions of defense against water inflows (Ilgibel et al., 2022).

Figure 32 shows a photo of a protection system in the salt marshes of Guérande (France) after it was submerged by Storm Xynthia. Strangely, the tide having receded, the water only appears inside the system, which displays the water-holding capacity and buffering capability of the system.



Figure 32: The Guérande salt marsh (Pays de la Loire), after the storm Xynthia. Credit: J. Mornet, DDTM85.

The protection systems therefore comprise multiple structures (levees, associated structures, transition structures, etc.), and each of these structures has a specific design that must be appropriate for the environment in which it fits. Failure modes are also multiple, and the design and dimensioning rules, as well as monitoring, maintenance, repair or reinforcement, relate to these failure modes, which will be presented in the next section.

It should be noted that coastal flood protection systems may include several lines of defense as shown in the figure 33. Systems with multiple levees have been described in literature in a variety of contexts, using different names. For example, a second levee behind the primary levee can be referred to as a « sleeper levee », a « ring levee » if it encircles an area of interest, and a « compartment levee » if it is designed to limit the flood extent after a breach (Marijnissen, 2021).

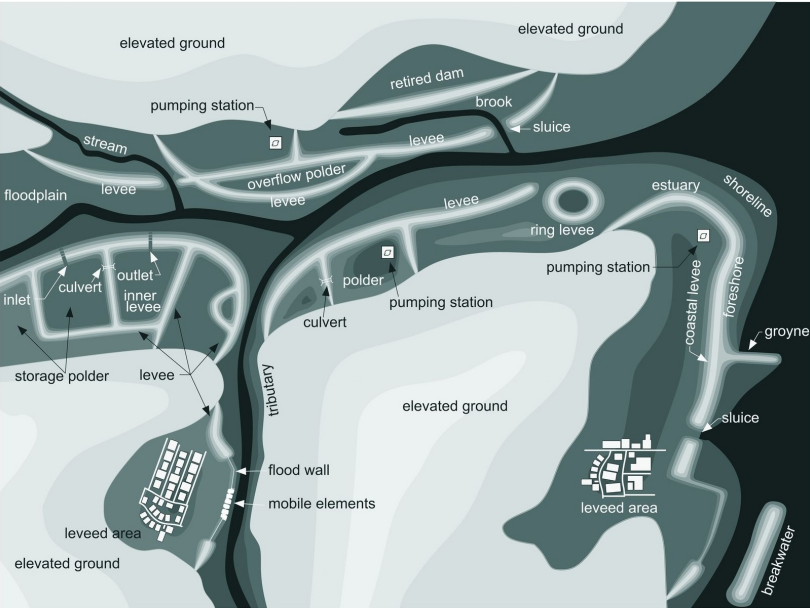


Figure 33: Schematic representation of a coastal flood protection system (CIRIA et al., 2013). Credit: Reinhard Pohl, Technische Universität Dresden.

1.4.3 Levee composition and failure modes

Levees (also called dikes), by their length and by their composition, often represent the most critical structures in levee systems and deserve special attention. The International Levee Handbook (CIRIA et al., 2013) defines levees as:

« Raised, predominantly earth structures whose primary objective is to provide protection against fluvial and coastal flood events along coasts, rivers, and artificial waterways that are not reshaped under normal conditions by the action of waves and currents ».

Levees can take different forms and have different components in relation to the functions sought, the hydraulic actions, and their environment. The basic principles of design and management can be clarified by drawing on the standard section in figure 34¹⁶.

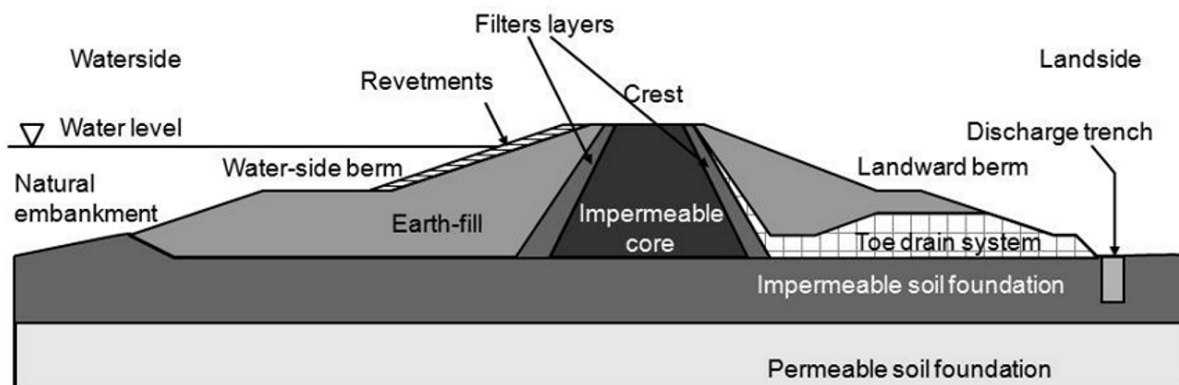


Figure 34: Schematic from the International Levee Handbook (CIRIA et al., 2013).

The first principle governing the design of a levee is its resistance to the actions of the environment to prevent the development of failure mechanisms. These mechanisms can be classified into three categories (CIRIA et al., 2013):

- external erosion which, by definition, can occur at the toe, slopes and crest, mainly due to overflowing and wave overtopping;
- internal erosion which, by definition, is generated by flows in the body of the structure;
- instabilities that may affect all or part of the structure and its foundations and subsoil.

In order to prevent the development of these mechanisms, the following basic functions (CIRIA et al., 2013) must be provided (each time involving one or more components):

- external protection against hydraulic, morphological, meteorological, anthropogenic, vegetative (in particular the roots of trees), and animal (in particular burrowing animals): it is provided by a natural (bare vegetation) or artificial covering (rock, masonry, concrete, etc.);
- management of the water circulating in the levee body (circulation of water in the earth-fill materials constituting the levee body and in its foundations cannot generally be avoided. They are acceptable if controlled). This function is provided:

¹⁶ This figure is intended only to indicate the position of the components and does not represent a real case. In this figure, the subsoil is only an example of a geological configuration characterized by an impermeable layer superimposed on a permeable layer.

- limiting the amount of water entering the levee by using materials of reduced permeability in the water side coating and in the core of the structure;
- by draining water that manages to penetrate the levee body and its foundations and thus limiting the increase of interstitial pressures that cause internal erosion and instability. A toe drain, or even a discharge trench, can be used for this purpose. The land side coating must be permeable;
- by filtering the water passing through the levee body to prevent these internal flows from carrying soil particles and damaging the essential characteristics of the materials (mass, permeability). Filtration can be achieved by selecting suitable particle size materials, which may require the integration of filter layers in addition to the earth-fill materials that compose the bulk of the levee body;
- protection against instabilities. Stability must be provided in particular in response to three types of solicitations:
 - the hydrostatic pressure associated with loading that exerts a force on the entire structure. The mass of the dike and the anchoring of its foundations in the subsoil must make it possible to balance this force ;
 - the increase in water content which, by increasing the mass of the components while reducing shear forces, can generate instability of part of the structure. This instability can be manifested in different forms: rotational or translational sliding, tilting, settlement, liquefaction, creeping, etc.
 - mechanical solicitations (overload on the crest, action transmitted by the roots of a tree exposed to strong wind, etc.).

Determining a mode of action on a levee therefore implies first having identified the failure mechanism or mechanisms likely to develop.

The integrity of the surface layer and the control of the water content of the materials constituting the levee body and its foundation appear to be two essential points for the proper functioning of a levee. This involves careful selection of construction materials, appropriate use (including compaction of earth-fill materials), and regular maintenance (especially for vegetated surfaces). Additional constructive provisions, such as berms, may be adopted to increase the strength of the levee. Over time, levees are often upgraded and widened to compensate for settlement and erosion or with the sole intention of better protection (Igigabel, 2017). For example, this is what was done in the Netherlands after the storm of 1953, as shown in figure 35. The proportions of the new dikes were more than doubled in height and width. To control costs, soil and clay, the preferred materials of the first dikes, were replaced by sand, a less expensive but also less stable material (Guében-Venière, 2015).

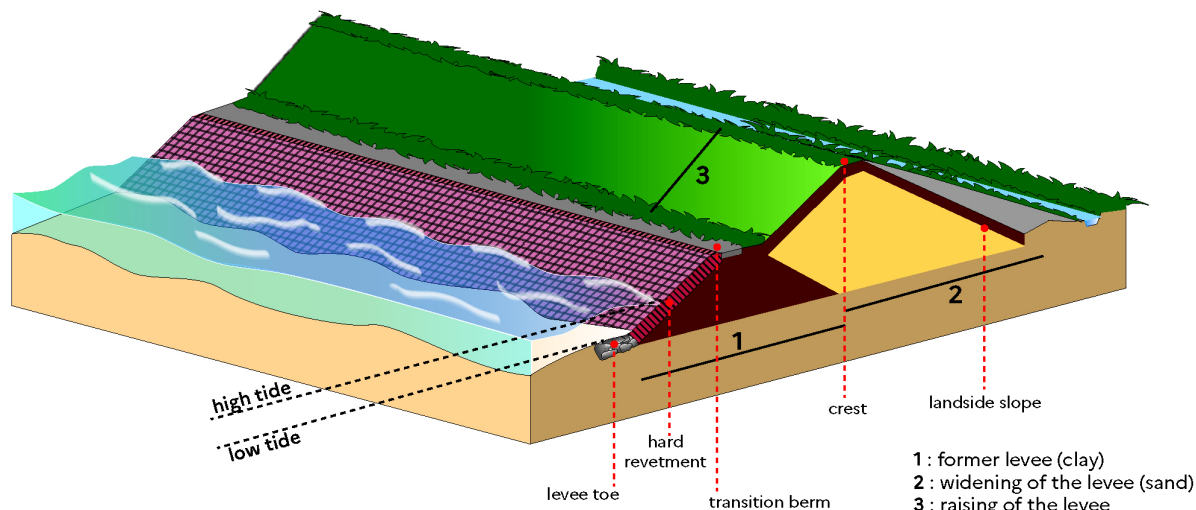


Figure 35: Cross-section diagram of a Dutch levee before and after 1953. Credit: Cerema, after Guében-Venière (2015) and Zeeweringen (2010).

The management of the structure during its life-cycle requires expertise in engineering, as well as significant human and financial resources. For further information, the International Levee Handbook (CIRIA et al., 2013) is a modern reference of the state of the art methods in design and construction, diagnosis and risk assessment, and maintenance and emergency response.

1.4.4 Limited protection and possible hazard increase

The multiple natural and anthropogenic actions to which the levees are exposed, as well as the heterogeneity of the structures and their very long length, requires the consideration of significant margins of uncertainty of the structure's behavior. The protection provided by levee systems is therefore always limited, and must be considered as such: when natural phenomena exceed a certain intensity, the structures allow water to pass through, either by overflowing or wave overtopping, or through a breach in the event of an accidental rupture. In either case, the risk may increase, in particular by an acceleration of hydraulic phenomena. Since the positive effect of reducing flood frequency is more immediately apparent than its potential negative effects, levee systems often produce a false sense of security.

This has led to an extensive literature on:

- modeling and assessing the risk of levee failure (e. g., Zhang et al., 2017; Wu and Li, 2017; Stanczak and Oumeraci, 2012). The effect of transitions, whether in the geometric design of the structure or in materials used, should not be overlooked in assessments as shown for example by van Bergeijk et al. (2019) and Simm et al. (2019);
- estimating flows across embankments exposed to swell under either emerged (e. g., Suzuki et al., 2017) or submerged (e. g., Formentin and Zanuttigh, 2018) conditions. Note that in the latter case, the calculation of the flow through a breach can also be considered.

Chapter 8 of the International Levee Handbook (CIRIA et al., 2013) reviews good engineering practices for structural dimensioning by combining hydraulic and geotechnical approaches. It can also be used to analyze the risk of failure.

The problem of performance limits and the increase in risk in the case of an event exceeding the nominal operating conditions should be tackled within a broader framework than that of a single structure with only the protection function. On this topic, Marijnissen et al. (2021) assessed the safety of a double-levee system (see figure 36). This system consists of two parallel lines of flood defenses, which enable their use in multifunctional flood protection strategies : a culvert can be implemented for

the tidal exchange of sea water to enable new land-uses in the area between the dikes such as aquaculture, saline agriculture, salt marsh restoration, and clay extraction.

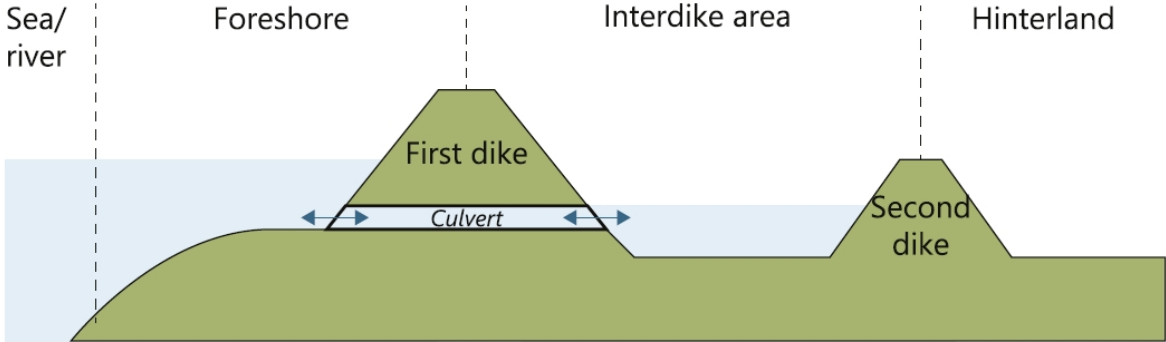


Figure 36: Double dike system (Marijnissen et al., 2021).

The evaluation of the reaction of this system to hydraulic stresses, taking into account the kinetics of the flows in the space between the dikes, was envisaged by Marijnissen et al. (2021) as shown in figure 37. This assessment was based on a typology of failure modes, as mentioned above, as well as on different modes of transmission: monitoring, wave crossing and flows through the lock. Within this framework, hydraulic solicitations (S) such as water levels and waves, are transmitted through the dike (T) and then compared with some critical criteria (R) to decide on the probability of an event (P_f). This method was tested through an application to the double dike between Eemshaven and Delfzijl (the Netherlands).

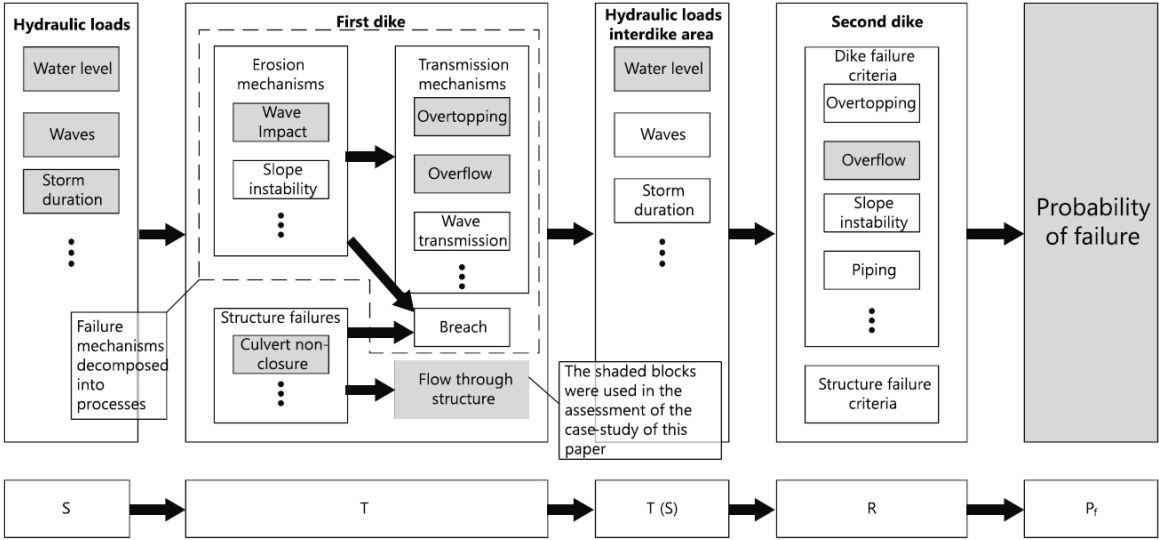


Figure 37: A general framework for assessing the probability of failure for a double dike system (Marijnissen et al., 2021). The shaded boxes represent the mechanisms that were considered in the assessment of the case study between Eemshaven and Delfzijl (The Netherlands).

The study of the reaction of protection systems to the Xynthia storm (Ilgigabel et al., 2016; Ilgigabel et al., 2022) adopted a similar approach, but considered different geographical configurations in regard to the positioning of levees and other obstacles to flow (e. g., natural formations and linear transport infrastructures).

1.5 Synthesis and conclusion

The phenomena at the origin of marine submersions are complex in both their mode of generation (weather-marine phenomena or tsunamis) and in their propagation to the coast, including their last phase of interaction with the coasts. Figure 38 summarizes the hydraulic processes in relation to the morphological evolutions that take place on the time scale of an event or on longer time scales.

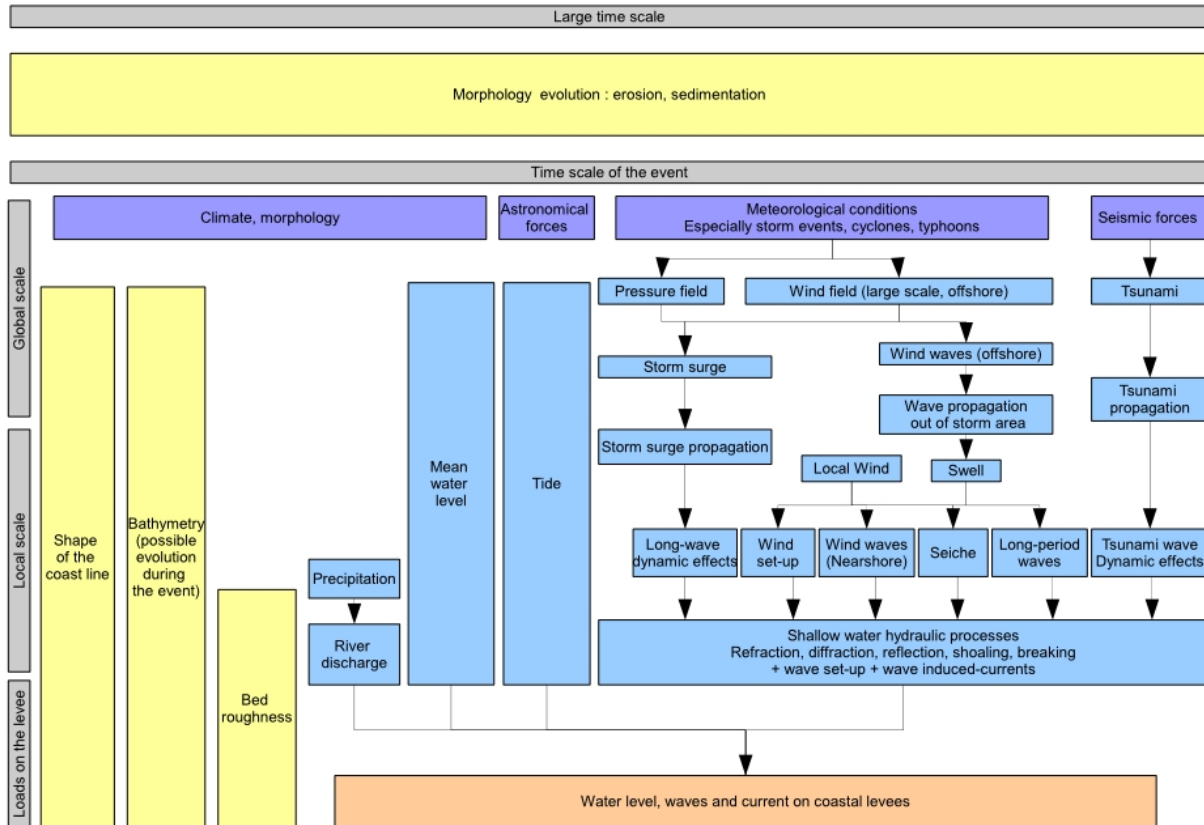


Figure 38: The process of hydraulic load generation.

The risk of coastal flooding is also generated by other phenomena that occur separately or jointly, such as the overflow of rivers, the accumulation of rainwater, and a rising water table. This situation requires special arrangements to be made in the design of protection systems : drainage of water in vulnerable areas must complement the defenses against sea and river waters.

Depending on the coastline, the risk of coastal flooding can vary. Nevertheless, on a global scale, there are three cases of particular concern:

- deltas : the long-term sustainability of populated deltas is often more affected by large-scale engineering projects and accelerated soil compaction associated with petroleum and groundwater pumping than by sea-level rise. Consequences include shoreline erosion, threatened mangrove swamps and wetlands, increased salinization of cultivated land, and hundreds of millions of humans that are put at risk;
- low-lying islands can be extremely exposed when they experience low variability in their water level (for statistical reasons, they then experience the effects of RSL rise more frequently) and this situation is compounded when the coral reefs or mangroves that protect the coasts suffer from the effects of climate change and local anthropogenic actions;

- arctic regions whose coastlines are eroding as a result of thawing permafrost and reduced frozen sea surfaces, which promotes the formation and propagation of higher waves to land. These phenomena also lead to an increase in the risk of marine flooding.

If we consider the Lisbon tsunami of 1755 as a founding event of risk prevention strategies, it is undeniable that since then, great progress has been made in terms of scientific knowledge and technological development. Strategies have been developed for both protective devices and vulnerability reduction. In this context, the point of balance between the regulation of urbanization and the performance of the protection system has often been debated.

This approach to risk prevention constitutes a form of rationalization of risk-taking through cost-benefit analyses guiding the definition of protection projects. However, it should be kept in mind that protection systems for many sites have been designed and constructed in reference to events of the recent past (on the order of the century, or even the decade for recently urbanized areas), with a relatively stable environment at these time scales and they already have limited performance levels under these conditions. However, the high population growth on the coasts, the anthropogenic disturbances of the environment (effects of subsidence and deterioration, or destruction of natural formations and ecosystems contributing to the protection), and the effects of climate change are likely to exacerbate the risk in all of its components (*i. e.*, increased hazard, exposure and vulnerability). As a result, protection systems will increasingly encounter situations where their nominal operating conditions are exceeded, and when this is the case, the damage will be greater.

These considerations lead to an interest in new approaches to managing the risk of coastal flooding, with the aim of taking better account of the evolutions previously identified.

2 RESILIENCE AND ADAPTATION: FROM CONCEPTS TO DECISION MAKING

The importance of adaptation to changes and disaster risk reduction is recognized in several global agreements, such as the Paris Agreement (UN, 2015) and the Sendai Framework for Disaster Risk Reduction (UNISDR, 2015). In particular, the overall objective of the Sendai Framework is the substantial reduction of disaster risk and losses in lives, livelihoods, and health and in the economic, physical, social, cultural, and environmental assets of persons, businesses, communities, and countries.

This general objective applies to coastal flooding, but also other risks where appropriate and concurrently: to better take into account events such as the tsunami that triggered the Fukushima nuclear accident in 2011, the Sendai Framework widens the scope of its action from natural hazards to anthropogenic hazards¹⁷, thus admitting that it is difficult to consider the former without taking the latter into account. It should be noted that this combination of natural and anthropogenic hazards is a concept already familiar to levee system managers, with the failure of a structure being ultimately nothing but a technological accident.

This approach is particularly necessary because urbanization, the development of other human activities and climate change are causing an increasing amount of rapid changes with cumulative effects. Under these conditions, flood risk should no longer be considered in isolation, but should also take into account other natural or anthropogenic hazards that emerge in combination, or by the « domino effect ». Therefore the conceptual framework needs to evolve. While prevention was the primary basis for flood risk management strategies in a stable environment, other concepts, particularly resilience and adaptation, should be used to mobilize additional levers for action and to take into account that sector-specific actions are not enough to stop the processes at work. By applying the concept of resilience, which takes into account systemic effects and utilizes collective action, a path can open up towards finding the appropriate responses. Such approaches are ambitious and require major investment from all the parties involved (Cerema, 2019a).

To progress in this direction, here the concepts of resilience, adaptability, and transformability will be presented in a generic way, with special attention to variations that may have appeared in the definition of terms, depending on the nature of the objects (technical, ecological, social, or « mixed ») to which they were applied. The concepts of adaptation limit and inappropriate action (maladaptation) will also be explained.

On the basis of this generic presentation, a specific conceptual framework will be proposed by formally distinguishing three objects: the territory subject to coastal flooding, its protection system, and the components of this system. For this purpose, each object will be considered separately, and particular attention will also be paid to the relationships between these objects: as the objective of this conceptual framework is to take into account systemic effects and to promote collective action, relations of interdependence between the territory and its protection system will occupy a central place in reflection. Relations with larger sets (the planet, the region) or subsets (a protection structure or even a component of this structure) will also be studied.

This conceptual framework will be used to present the methods relating to the territories and their coastal flood protection systems and is intended to:

- understand the risks as part of a global approach;
- define adaptation strategies in a changing environment.

¹⁷ Anthropogenic risks are particularly related to the handling, transport, or storage of substances dangerous to health and the environment (e. g., industrial, nuclear, and biological risks).

2.1 Generic definitions of resilience and adaptation concepts

Resilience has a variety of definitions, although these all share a commonality in referring to the ability of a system to recover from a disturbance. Definitions vary regarding what defines a « system » and as to what recovery means (Gersonius et al., 2016).

Resilience enables people and ecosystems to cope with the shocks and stresses associated with changes, and to adapt and even transform themselves as needed. Indeed some changes are so substantial (and, often, abrupt) that they fundamentally alter the functioning of the system. Scientists call such largely irreversible changes « regime shifts » (Arctic Council, 2016).

The concept of resilience has evolved considerably over the past few decades. This leads us to consider four main variations of the concept. We will present them by considering:

- technical resilience, ecological resilience, and social resilience that correspond to sectoral approaches; and
- social-ecological resilience, which corresponds to a more global approach and is based on another concept, that of a social-ecological system.

The concept of resilience and its different variants is essential to address the concepts of systems adaptation and transformation, whether these systems are engineering systems, ecosystems, human societies, or systems encompassing all of these components (social-ecological systems). The limits to adaptation, as well as the inappropriate actions (maladaptation) are also fundamental notions that need to be explored.

In terms of protection against coastal flooding, adaptation to the effects of climate change in the context of demographic growth, poor land management, unsustainable use of natural resources, and declining ecosystems remains the main challenge.

It should be noted that the effects of climate change are varied, evolve over time, depend on the territory considered, and are only partially known. Under these conditions, the concepts of adaptation, adaptation limits, or inadequate adaptation (maladaptation) developed as part of the reflections on adaptation to climate change (IPCC, 2019), will be adopted and deemed applicable to other forms of anthropogenic disturbance.

2.1.1 Engineering resilience, ecological resilience and social resilience

In his pioneering article, Holling (1973) made the distinction, without opposing them, between stability and resilience, later renamed « engineering resilience » and « ecological resilience » (Holling, 1996):

- engineering resilience is « the ability of a system to return to an equilibrium state after a temporary disturbance. The more rapidly it returns, and with the least fluctuation, the more stable it is ». Engineering resilience measures the resistance to disturbances and the speed with which the system returns to equilibrium. The faster the system bounces back, the more resilient it is, with the emphasis on return time : for a « fail-safe » engineering design, efficiency, constancy, and predictability are all sought-after qualities;
- ecological resilience determines the persistence of relationships within a system¹⁸ and is a measure of « the ability of these systems to absorb changes of state variables, driving variables, and parameters, and still persist ». In this definition resilience is the property of the system and persistence or probability of extinction is the result. Ecological resilience is not

¹⁸ In this article relating to the conservation of populations or species, Holling focuses primarily on the persistence of relationships (predation or competition) within ecosystems. The preservation of populations (or species depending on the scale considered) and finally the persistence of the system itself depends on the persistence of these relationships.

based on the equilibrium paradigm but considers multiple equilibria possible (Gunderson, 2000). Hence, resilience is not just about being persistent but also about developing new trajectories and evolving in a new system (Folke, 2006).

With these definitions in mind, a system can be very resilient and still fluctuate greatly, *i. e.*, have low stability. What engineering and ecological resilience have in common is the existence of an equilibrium point, be it a pre-existing state to which the system bounces back (engineering resilience) or a new state to strive for (ecological resilience) (Davoudi, 2012).

Lastly, resilience has been translated from the natural to the social world. Thus, social resilience is used to describe « the ability of groups or communities to cope with external stresses and disturbances as a result of social, political, and environmental change (Adger, 2000) ».

Social resilience is based on the concept of « human agency », which refers to the human capacity to consciously and deliberately choose and carry out a course of action. This capacity can be exercised individually or in conjunction with others (Emirbayer and Mische, 1998). The authors conceptualize agency as « a temporally embedded process of social engagement, informed by the past (in its iterational or habitual aspect) but also oriented towards the future (as a « projective » capacity to imagine alternative possibilities) and towards the present (as a « practical-evaluative » capacity to contextualize past habits and future actions within the contingencies of the moment) ».

Moberg and Galaz (2005) argue that social resilience differs fundamentally from ecological resilience by having the added capacity of humans to anticipate and plan for the future. Knowledge of social and ecosystem interactions may guide the exercise of agency both in the form of decisions and subsequent actions (Arctic Council, 2016).

2.1.2 Social-ecological resilience

To address the issues arising in the context of global changes such as climate change and other major anthropogenic disturbances, the concept of resilience has been developed to cover social and ecological aspects more broadly. In a search for coherence with the conceptual framework adopted by the IPCC (2019), social-ecological resilience will be defined as follows:

« The capacity of interconnected social, economic, and ecological systems to cope with a hazardous event, trend, or disturbance, responding or reorganizing in ways that maintain their essential function, identity, and structure. Resilience is a positive attribute when it maintains capacity for adaptation, learning, and/or transformation (Walker et al., 2004) ».

This definition explicitly establishes a link between the development of resilience and the evolutionary capacities of a system in the face of changes, whether these changes are rapid or slow, and whether they are localized or diffuse (in the case of certain types of pollution for example). Therefore, the utilization of the concept of resilience appears as a prerequisite for the definition of adaptation strategies in evolutionary contexts.

It should also be noted that this definition of resilience refers to a social-ecological system (SES). Such a system is defined by the IPCC (2019) as:

« An integrated system that includes human societies and ecosystems, in which humans are part of nature. The functions of such a system arise from the interactions and interdependence of the social and ecological subsystems. The system's structure is characterized by reciprocal feedbacks, emphasizing that humans must be seen as a part of, not apart from, nature (Arctic Council, 2016; Berkes and Folke, 1998) ».

SESs are therefore integrated systems linking societies and nature (Liu et al., 2007), which ultimately aim to redefine ecosystems by explicitly considering all actors, thus integrating humans as an active

component of the system (Lagadeuc and Chenorkian, 2009). Conversely, studies dedicated to human-environmental interactions or ecosystems that position this major player outside the natural system limit our ability to consider the complexity of existing human-nature interactions (Liu et al., 2007).

Building on this critical idea, Biggs et al. (2012) define resilience as:

« The capacity of an SES to sustain a desired set of ecosystem services (ES) in the face of disturbances and ongoing evolution and change ».

According to Millenn. Ecosyst. Assess. (2005), SESs produce a « bundle » of ES, categorized as provisioning (e. g., freshwater, crops, and meat), regulating (e. g., flood and climate regulation), and cultural services (e. g., recreation and spiritual values).

Within this framework, SESs should be considered as Complex Adaptive Systems (CAS): a system of interconnected components characterized by emergent behavior¹⁹, self-organization, adaptation, and substantial uncertainties about system behavior (Biggs et al., 2012).

2.1.3 Adaptation

In the context of climate change, beyond mitigation to limit the concentration of greenhouse gases in the atmosphere, adaptation is a key avenue to reduce risk. Adaptation can reduce risk by addressing one or more of the three risk factors: existing and future vulnerability, exposure, and/or (where possible) hazards (IPCC, 2019).

Adaptation can be defined in the context of the major challenges of climate change by distinguishing:

- human systems : « the process of adjustment to actual or expected climate and its effects, in order to moderate harm or exploit beneficial opportunities (IPCC, 2019) »; and
- natural systems : « the process of adjustment to actual climate and its effects; human intervention may facilitate adjustment to expected climate and its effects (IPCC, 2019) ».

On this last point, it should be stressed that human intervention on natural systems may in the first place be intended to benefit humans themselves. The term used for this type of action is « Ecosystem-based Adaptation », which is defined as:

« The use of ecosystem management activities to increase the resilience and reduce the vulnerability of people and ecosystems to climate change (Campbell et al., 2009) ».

In order to better understand the nuances relative to the concept of adaptation, some authors, e. g., Walker et al. (2004), make a clear distinction between resilience and adaptability versus transformability. Resilience and adaptability reference the dynamics of a particular system, or a closely related set of systems, while transformability refers to fundamentally altering the nature of a system.

Details of this distinction are given below. It should be noted, however, that some authors consider that in some cases, incremental adaptation can accrue to result in transformational adaptation (Tàbara et al., 2018; Termeer et al., 2017).

¹⁹ Emergence is an overall system behavior that comes out of the interaction of many participants' behavior that cannot be predicted or even envisioned from knowledge of what each component of a system does in isolation (Lissack, 1999).

Incremental or evolutionary adaptation

The concept of adaptability is expressed differently for human and natural systems:

- for human systems, the term used is « incremental adaptation », which is defined as :

« Adaptation that maintains the essence and integrity of a system or process at a given scale (Park et al., 2012). Incremental adaptations to change in climate are understood as extensions of actions and behaviors that already reduce the losses or enhance the benefits of natural variations in extreme weather/climate events (IPCC, 2019) »;

- for natural systems, the term used is « evolutionary adaptation », which is defined as :

« The process whereby a species or population becomes better able to live in a changing environment, through the selection of heritable traits. Biologists usually distinguish evolutionary adaptation from acclimatization, with the latter occurring within an organism's lifetime (IPCC, 2019) ».

Transformation

Because they do not fundamentally alter the nature of the systems under consideration, progressive or evolutionary adaptations may refer to changes limited to a natural or human system. Conversely, in the event of a transformation on the fundamental attributes, the corresponding adaptation must refer to a more global system, hence the connection of transformational adaptation to the concept of SES:

« Adaptation that changes the fundamental attributes of a social-ecological system in anticipation of climate change and its impacts; and adaptation responses that will be required in the face of a global failure to mitigate the causes of anthropogenic climate change and are characterized by system-wide change or changes across more than one system (IPCC, 2019) ».

Transformational adaptation leads to a focus on the future and long-term changes and to recognize and address the inefficiency of existing systems, social injustices and power imbalances.

Much of the adaptation and resilience documented in literature highlights the need for transformations that enable effective climate change mitigation, most notably by decarbonizing the economy (Riahi et al., 2017), and that support adaptation (e. g., Pelling et al., 2015; Few et al., 2017).

Adaptation and transformation: a continuous process

Adaptation is an ongoing process of adjusting to changes, with no end point. This means that defining successful adaptation is more about the sustainability of processes and the principles of fairness and equity than it is about measuring outcomes at any given point in time (Stafford-Smith et al., 2011; Hurlimann et al., 2014; Barnett et al., 2015). Successful adaptation is therefore a matter of « socially and environmentally sustainable development pathways, including both social justice and environmental integrity » (Eriksen et al., 2011).

Similarly, when fundamental attributes of a social-ecological system change, as stated by Clarke et al. (2014), transformation pathways to long-term climate goals are best understood as a process of sequential decision-making and learning.

The definition of the adaptation strategies for coastal territories and their flood protection systems should therefore consider process continuity as one of its guiding principles. A good understanding of the limits of adaptation is also necessary for strategy development.

2.1.4 Adaptation limits

Limits to adaptation are reached when adaptation no longer allows an actor or ecosystem to secure valued objectives or key functions from intolerable risks. Defining tolerable risks and key system functions is, therefore, of central importance for the assessment of limits to adaptation (IPCC, 2019).

It is also possible to distinguish between:

- the hard adaptation limit – No adaptive actions are possible to avoid intolerable risks ; and
- the soft adaptation limit – Options may exist but are currently not available to avoid intolerable risks through adaptive action.

Indeed adaptation requires adaptive capacity, which for human systems includes assets (financial, physical, and/or ecological), capital (social and institutional), knowledge, and technical know-how (Klein et al., 2014). The extent of adaptive capacity determines adaptation potential, but does not necessarily translate into effective adaptation if awareness of the need to act, the willingness to act, and/or the cooperation needed to act is lacking. For example, the ability to adapt to sea level rise depends, in part, on the elevation of the low-lying islands and coasts in question, but also on the capacity to successfully negotiate protection or relocation measures socially and politically (IPCC, 2019).

Limits to adaptation are sometimes considered as something different from barriers to adaptation. Barriers can in principle be overcome if adaptive capacity is available (*e. g.*, when funding is made available), even though overcoming barriers is often hard in reality, particularly for resource-poor communities and countries, or those whose governance is not adapted.

Adapting requires changes in the organization of societies. However, reforms are often hampered by dependency on previous choices, which prevents a complete departure from the trajectory of past reforms. This process, known as « path dependency » is analyzed in particular by Pierson (2000). The path-dependent nature of the institutions that govern natural resources and public goods is a deep driver of barriers and limits adaptation. Such path dependency structures social vulnerability, creates patterns in trade-offs among adaptation actions, and inhibits changes for adaptation. In particular, when this resistance causes the changes necessary for adaptation to be slower than the effects of climate change, then it becomes a limit to adaptation (Barnett et al., 2015).

2.1.5 Inappropriate actions (maladaptation)

Maladaptation is a term used to describe inappropriate adaptation actions. It is defined as:

« Actions that may lead to increased risk of adverse outcomes, including via increased greenhouse gas emissions, increased vulnerability to climate change, or diminished welfare, now or in the future. Maladaptation is usually an unintended consequence (IPCC, 2019) ».

The relationship between resilience and maladaptation has been studied by several authors: resilience may be used descriptively as a system property that is neither good nor bad (Weichselgartner and Kelman, 2014). For example, a system can be highly resilient in keeping its unfavored attributes, such as poverty or institutional rigidity (Carpenter and Brock, 2008). If resilience is considered a positive attribute when it maintains the capacity for adaptation, learning, and/or transformation, it can also be considered as a negative attribute in the opposite case.

2.2 System adaptability

Considering that the objective of developing the resilience of systems meets the objectives of sustainable development and reducing their vulnerability, it is essential to assess the capacities of adaptation (adaptability) and even transformation (transformability) systems have to achieve these objectives. The generic definitions of resilience and adaptation must therefore be supplemented by the modes of representation of the evolution of the resilience of systems according to their nature and characteristics. For this purpose, the distinction will be maintained between sectoral approaches relative to technical, ecological, and social systems and more comprehensive approaches relative to

social-ecological systems. In addition, the distinction between adaptation and transformation (similarly, adaptability and transformability) will be applied whenever necessary.

It should be noted that this section, like the previous one, presents generic content and therefore does not prejudge the relevance of its application to territories and their protection systems. This critical analysis will be conducted in the following sections.

2.2.1 Adaptability of technical, ecological, and social systems

Depending on the type of systems considered (technical, ecological, or social), the concept of adaptability may assume different meanings. This concept can be specified in relation to the variants of the resilience concept previously identified for each type of system.

Adaptability of technical systems

In the engineering resilience concept, the target goal is to maintain the system at an idealized state. When a disturbance occurs, recovery work is oriented at returning the system back to its previous state (Disse et al., 2020).

Figure 39 shows a representation of technical resilience based on two characteristics:

- resistance to change and return to an original state of equilibrium (figure 39, left panel). No other steady-state is envisaged, which means that outside of its nominal operating range, the system ceases to function and it can be considered as disappearing ;
- the time required for the system to return back to normal (figure 39, right panel). The graph shows system functionality over time given an acute disturbance at time t_0 . Trajectory A is that of a more resilient system compared with trajectory B, as less time is required to return to 100 % functionality (Disse et al., 2020).

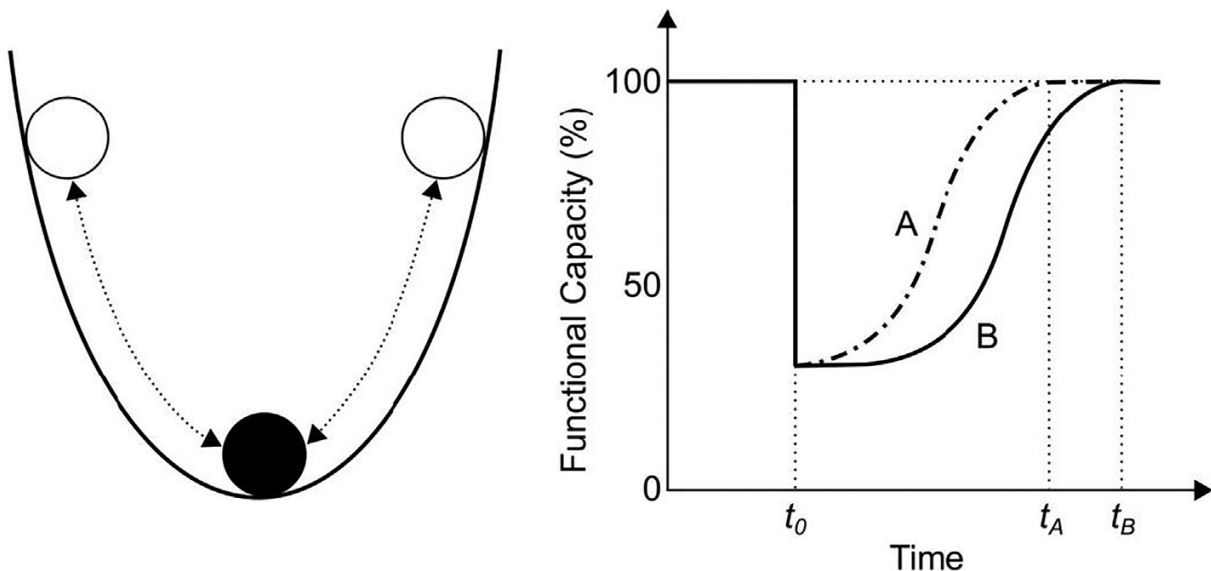


Figure 39: Engineering resilience representation. Credit: Disse et al. (2020) after Liao (2012).

The modes of representation of technical systems reflect the search for constancy and predictability which are guarantees of reliability. However, for these systems, adaptability and, *a fortiori*, transformability are not commonly required characteristics.

Adaptability of ecological systems

To characterize ecological resilience, resistance to change and time to return to normal are not sufficient. The concept of a threshold must be used as a complement to account for the susceptibility of the system to change from one stability regime to another (see figure 40) :

- the system remains in a stability regime as an engineering system until a certain disturbance threshold is reached and the system is pushed into a new regime ;
- line A demonstrates a more resilient system than line B. System B is more easily forced past the threshold into an undesirable regime (Disse et al., 2020).

In addition to this representation, it must be considered that once a threshold is crossed, a system will not necessarily regain another stability regime: it may also collapse and disappear.

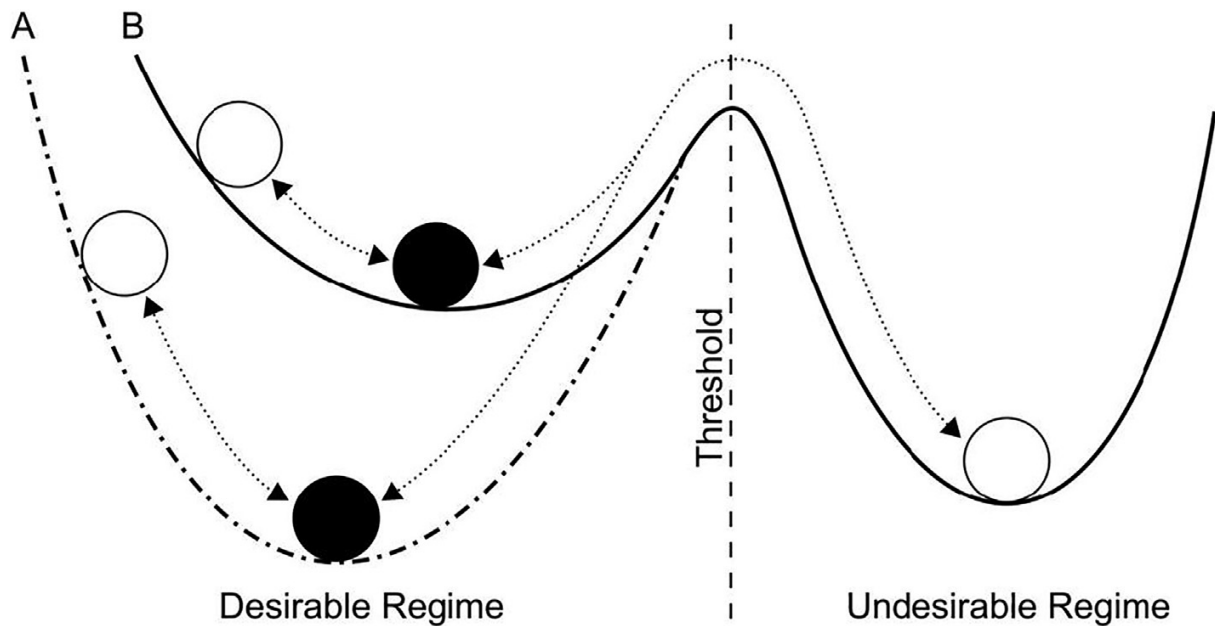


Figure 40: Ecological resilience representation. Credit: Disse et al. (2020) after Liao (2012).

In conclusion, the ecological resilience of a system can be characterized by its resistance to change and its distance from a « threshold not to be crossed ». The adaptability of the system can be seen as its ability to maintain or increase this gap to avoid the transition to an undesirable regime.

Adaptability of social systems

As well as for technical and ecological systems, the scientific literature sheds light on the evolution of social resilience under various influences (as before, these methods of representation also illustrate the adaptability or transformability of the system).

Schleussner et al. (2016) stated that zones of social disruptions are characterized by inadequate resources, *e. g.*, having a low development index and poor governance, which failed to take action for problem solving, and thus reached a diminishing marginal return²⁰ (Schleussner et al., 2016).

Regarding the evolution of resilience, Bhowmik (2017) highlighted a risk of social collapse emerging under the conditions illustrated in the figure 41.

²⁰ In economics, the « law of diminishing returns » states that in a production process, as one input variable is increased, there will be a point at which the marginal per unit output will start to decrease, holding all other factors constant (Adam, 2021).

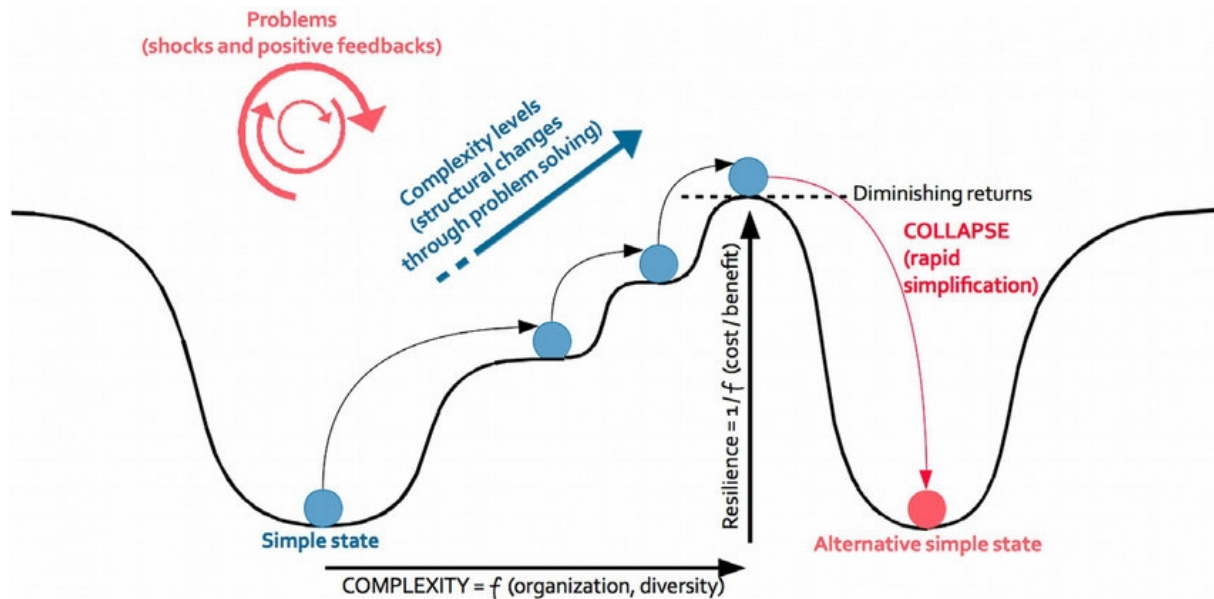


Figure 41: Convergence of complexity and resilience theories is necessary for modeling social collapse. In the event of multiple and amplified shocks, system resilience erodes as a result of diminishing marginal return on the cost of complexity (Bhowmik (2017) after Tainter (1990)).

It appears that one of the necessary conditions for the resilience of a social (or socio-economic) system and therefore its adaptability, is its effectiveness, which is represented by a cost-benefit ratio.

This model is based on complexity theory. According to this theory, social complexity is a function of diversity and organization of social institutions: a complex society is composed of a large number of institutions organized in a single system (Tainter, 1990). The level of complexity increases through problem-solving (Bhowmik, 2017).

However, Bhowmik (2017) concluded, based on a review of scientific literature, that climate change and associated extreme events demand increasing complexity, *i. e.*, formation of new social institutions to engineer, mitigate, and adapt to climate problems, which, in turn, increased climate related expenditures.

Increasing complexity leads to a diminishing marginal return on the cost and consequently, the collapse of societies through a rapid simplification process.

In the case of adaptation to climate change, this kind of process appears earlier in zones characterized by inadequate resources, which failed to allow increasing complexity and cost of problem solving with the increasing intensities of shocks. But, according to Bhowmik (2017), climatically triggered social collapse can also appear in complex society with the same symptoms : structural changes (*e. g.*, migration) and catastrophes (*e. g.*, armed conflicts and epidemics).

Bhowmik (2017) illustrated this process for the case of the droughts of 2003 and 2010 in Syria that amplified the social instability and pushed the system to a tipping point, triggering a civil war that finally resulted in the war and refugee crisis.

2.2.2 Adaptability of social-ecological systems

In SESs, adaptability is the capacity of actors to influence resilience (Walker et al., 2004). Characterizing the resilience of SESs requires considering the influence of the actors of this system, but also the intentional or unintentional character of their actions *vis-à-vis* the development of resilience: a characteristic feature of complex adaptive systems is self-organization without intent

(Levin, 1998), and although the dynamics of SESs are dominated by individual human actors who do exhibit intent, the system as a whole does not, as in the case of a market (Walker et al., 2004).

Social-ecological resilience is mainly represented in two ways :

- by the evolution over time of SESs (the adaptive cycle model). In this model, SESs are nested at several levels to form a « panarchy »;
- by the evolution of the resilience of an SES according to the conditions imposed by higher-level SESs (« basins of attraction » model).

The adaptive cycle model and panarchies

The dynamics of SESs was described and analyzed by Holling et al. (2002) in terms of a cycle, known as an adaptive cycle (see figure 42). This model was derived from a comparative study of the dynamics of ecosystems. This study focuses on processes of destruction and reorganization, resulting in the release of energy and material, which are often neglected in favor of growth and conservation (i. e., the slow accumulation and storage of energy and material).

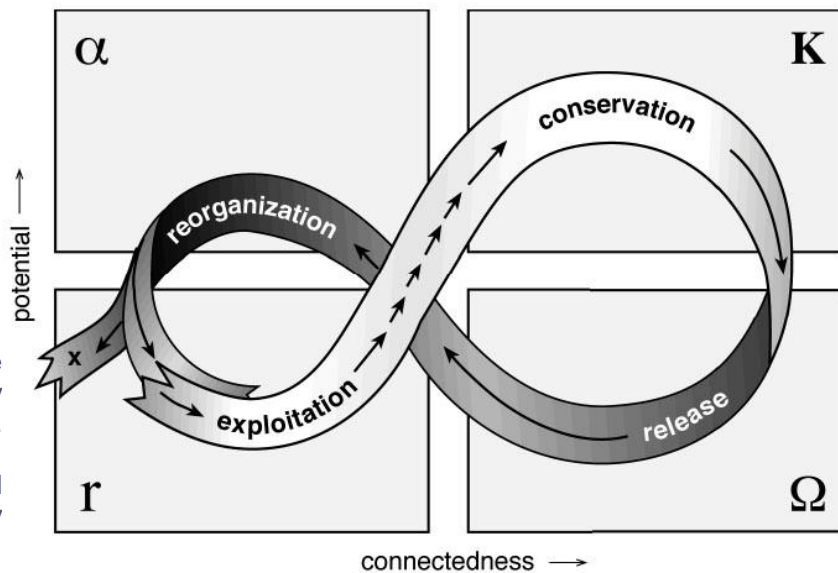


Figure 42: The Adaptive Cycle (from Panarchy, edited by Lance H. Gunderson and C.S. Holling: Figure 2-1 (page 34). Copyright © 2002 Island Press. Reproduced by permission of Island Press, Washington, DC).

This cycle passes through four phases (Walker et al., 2004):

- two of the phases—the growth and exploitation phase (r), which merge into a conservation phase (K)—comprise a slow, cumulative forward loop of the cycle, during which the dynamics of the system are reasonably predictable. As the K phase continues, resources become increasingly locked up and the system becomes progressively less flexible and responsive to external shocks ;
- eventually, this is inevitably followed by a chaotic collapse and release phase (Ω) that rapidly gives way to a phase of reorganization (α), which may be rapid or slow, and during which, innovation and new opportunities are possible. The Ω and α phases together comprise an unpredictable backloop. The α phase leads to a subsequent r phase, which may resemble the previous r phase or may be significantly different.

Adaptive cycles occur at a number of scales and SESs exist as « panarchies », i. e., as a nested set of adaptive cycles, as shown in the figure 43 (Gunderson and Holling, 2002).

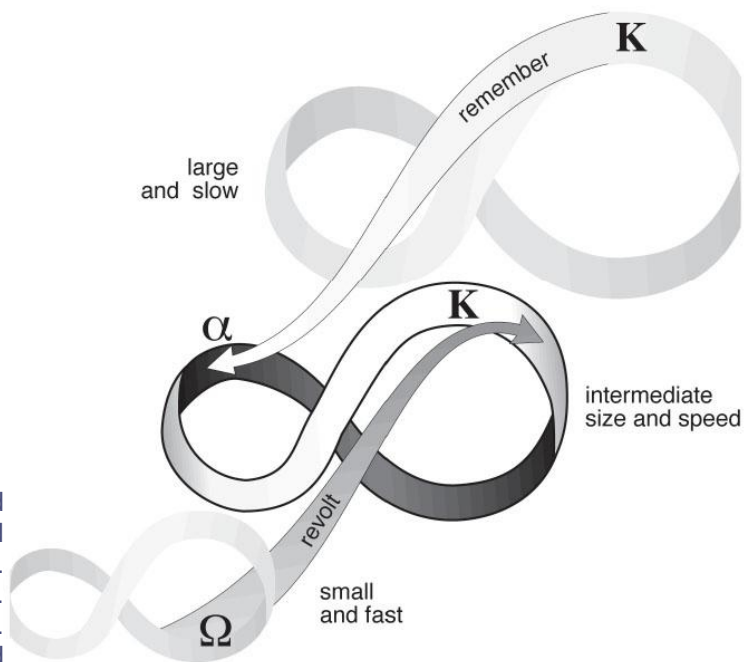


Figure 43: Panarchy of nested adaptive cycles (from Panarchy, edited by Lance H. Gunderson and C.S. Holling: Figure 3-10 (page 75). Copyright © 2002 Island Press. Reproduced by permission of Island Press, Washington, DC).

The panarchy aims to capture the structures envisioned in hierarchy theory (Allen and Starr, 1982), as well as acknowledge top-down and bottom-up processes that account for many observed dynamics in nature. The panarchy can provide quantitative and qualitative underpinning for risk management (Angeler et al., 2016).

According to this theory, no SES can be understood by examining it at only one scale. At any particular scale, the system is actually a sub-system of the whole panarchy, and influenced by what is happening in the panarchy at scales above and below the scale of interest (Walker et al., 2004). Thus, cross-scale effects are of great significance in the dynamics of SESs. For this reason, a panarchy may be a particularly apt heuristic²¹ for framing environmental phenomena that are characterized by complexity (Walker et al., 2004).

It should be noted that systems of larger spatial scales are considered to have greater inertia and to evolve over longer time scales. Thus the interconnectedness of hierarchical scales in a panarchy contributes to system resilience because disturbances at one scale can be absorbed by other scales in the system (Nash et al., 2014).

Some loss of resilience, at some scales, is an inevitable feature of the cross-scale dynamics in complex adaptive systems. However, losses can be managed so as to be confined to smaller organizational scales, with less consequent social and environmental dislocation (Walker et al., 2004).

The concept of the panarchy was illustrated by Angeler et al. (2016) in the case of the evolution of a lake in relation to phenomena occurring at the scale of the continents, these phenomena being themselves in interaction with climate change. In figure 44, the panarchy is shown with three spatio-temporal scales.

21 According to the Littré, heuristics (from the ancient Greek εὐρίσκω, *heuriskô*, « I find ») is « the art of inventing and making discoveries » by solving problems from incomplete knowledge. This type of analysis leads to reasonable conclusions in a limited time. These conclusions may deviate from the optimal solution.

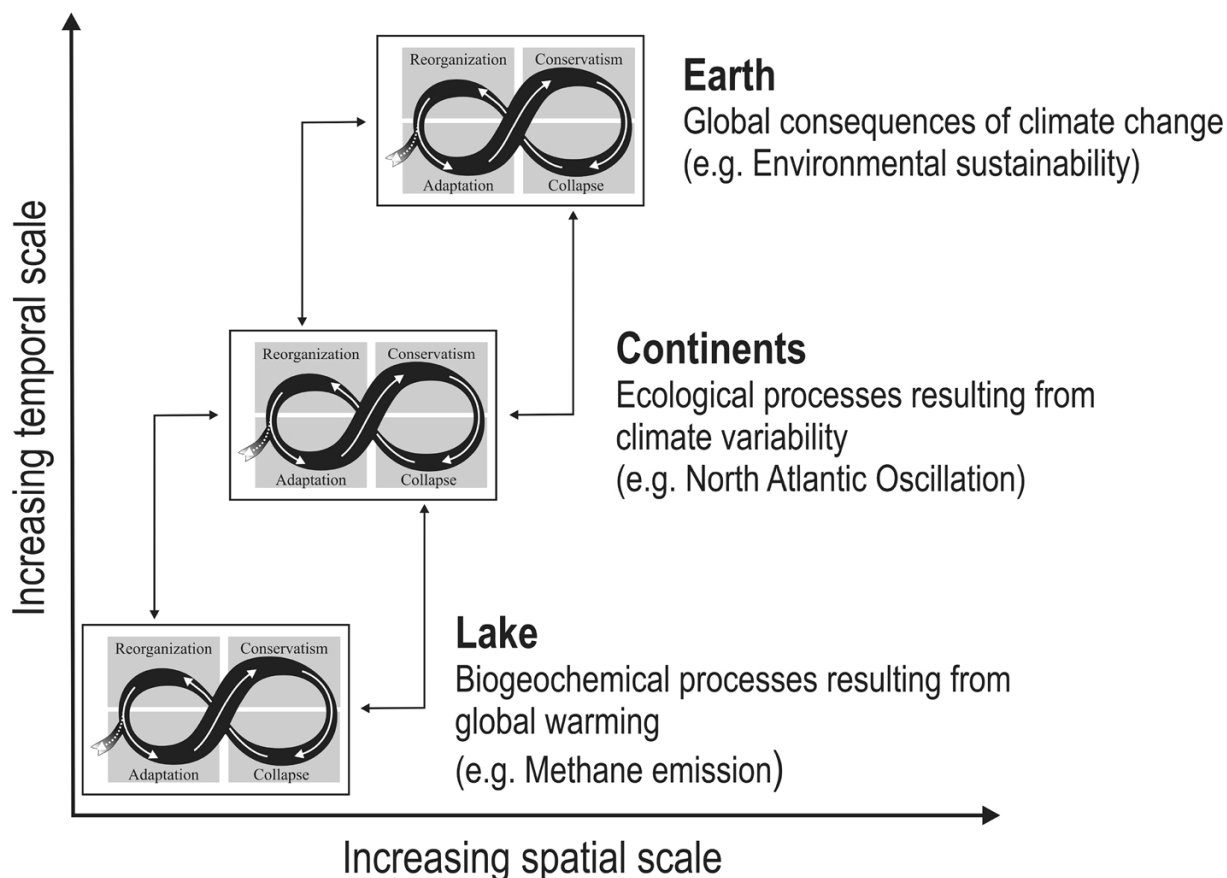


Figure 44: Diagram of a panarchy showing complex system dynamics (adaptive cycles), and their relationship between spatio-temporal scales (Angeler et al., 2016).

The « basins of attraction » model

In addition to the model of adaptive cycles organized in panarchy, the « basins of attraction » model can be used to describe the evolution of the resilience of an SES in relation to the evolution of SESs at higher levels. In this model, the basins of attraction, together represent, by definition, a « stability landscape ».

According to Walker et al. (2004), resilience can be characterized by four aspects:

1. latitude: the maximum amount a system can be changed (basin width) before losing its ability to recover (before crossing a threshold which, if breached, makes recovery difficult or impossible);
2. resistance: the ease or difficulty of changing the system (*i. e.*, how « resistant » it is to being changed);
3. precariousness: how close the current state of the system is to a limit or « threshold »;
4. panarchy: because of cross-scale interactions, the resilience of a system at a particular focal scale will depend on the influences from states and dynamics at scales above and below. For example, global climate change can trigger local unexpected developments and regime shifts.

These four aspects of resilience can be represented by the « basins of attraction » model. Figure 45 shows two landscapes (basins of attraction) and their constituent resilience attributes:

- (A) a 3D stability landscape showing two basins of attraction (dotted lines). In the smaller basin, the current position of the system (black dots) and three aspects of resilience, L, latitude (width of the basin), R, resistance (depth of the basin), and Pr, precariousness (proximity to the basin lip);
- (B) changes in the broader stability landscape can result in contraction of the basin and expansion of an alternate basin. Without changing itself, the system has changed basins of attraction and is precariously positioned for additional changes (Hessburg et al., 2019).

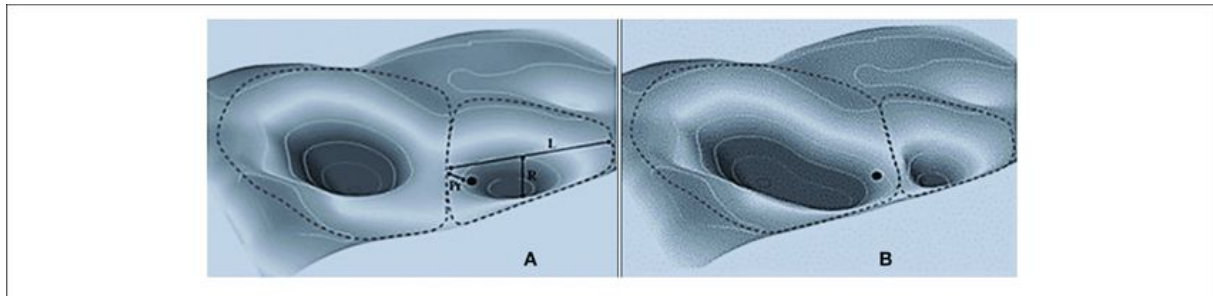


Figure 45: Two landscapes (basins of attraction) and their constituent resilience attributes (Walker et al., 2004).

Walker et al. (2004) showed that the collective capacity of individuals and groups to manage resilience intentionally determines whether they can successfully avoid crossing into an undesirable system regime, or succeed in crossing back into a desirable one. There are four ways to do this, corresponding to the four aspects of resilience: the ability to control the trajectory of the system (by altering precariousness), change the topology of the stability landscape (by altering latitude and resistance), or change the processes in response to dynamics at other scales (by altering panarchy), is a measure of adaptability (Walker et al., 2004).

2.3 Resilience and adaptability of protection systems

The previous two sections focused in a generic way on :

- the concepts of resilience, adaptation, and system transformation;
- the evolution of the resilience of systems, their representation through models, and the corresponding lessons in terms of adaptability and transformability.

The objective of this section is to explore the application of these concepts and models to coastal flood protection systems. This research must be carried out with discernment, not considering that these concepts are applicable *a priori*, but making sure beforehand of their applicability. Based on the fundamentals outlined in the previous chapter, this method consists of:

- identifying a panarchy of SESs to which the concept of social-ecological resilience can be applied and specifying the expected functions of these SESs ;
- characterizing the resilience of each SES by using the « basins of attraction » model ;
- describing the adaptive cycles of these SESs, to better understand the evolution of their resilience and their adaptability.

The concepts of technical resilience, ecological resilience, and social resilience will also be utilized occasionally to provide complementary insights to those contained in the central concept of social-ecological resilience.

2.3.1 Identification of social-ecological systems and their functions

The utilization of concepts requires a precise description of the objects to which they apply. This is why it is necessary successively to identify SESs and specify the expected functions of each of them.

Identification of social-ecological systems

The first question that must be answered is whether coastal flood protection systems can be considered as SESs. The same question arises for the components of the system and for the territory protected by the system.

According to the definition adopted in the fundamentals (see section 1.4.2), a protection system is considered to be a system composed of:

- engineering elements: retention structures (e. g., levees and storm barriers) and drainage structures (e. g., canals, ditches, and pumping systems); and
- natural features: coastal formations (e. g., mangroves, salt marshes, and coral reefs) and inland wetlands (e. g., floodplains, lakes, and marshes).

Considering that the technical elements correspond to social components and the natural elements to ecological components, it would be tempting to conclude that, for this reason, protection systems are SESs. This conclusion, however, would be too hasty and would even constitute a counter-sense in relation to the definition of SESs, since it would be based on the distinction between the work of man and that of nature, even though an SES is « an integrated system in which humans are part of nature ». Other justifications must therefore be sought. At the level of the protection system, the technical and natural elements do not provide protection separately, but rather, in a combined way. In addition, a careful examination of the two categories of elements distinguished above reveals that each of them inevitably has an ecological and a social component:

- regarding the technical elements, let us first consider the most emblematic type of work: levees that are made of earth. If, in the event of exposure to waves, levees may be partially or completely covered with rock, concrete or masonry, they are generally covered with short vegetation. This vegetation is an effective means of protecting against erosion since it is regularly renewed in normal weather conditions. The vegetation, maintained by man, in particular by mowing (or by grazing activities), helps to maintain the geometry of the structure and other characteristics (such as the moisture content) essential to the flood protection function; the same analysis applies to low-lying structures, such as ditches or infiltration ponds in which well-maintained vegetation contributes to the protection function. For civil engineering works, if vegetation and animals play no positive role in the service rendered, they are considered to play a negative role. Thus, plants, by their roots, and animals, by the burrows they dig, are likely to exert their action not only on the structures, but also on their foundations, and thus damage their proper functioning;
- concerning « natural » formations, man being part of nature, it cannot be considered that any action of man on these formations constitutes a disturbance. Moreover, since these elements actually contribute to protection, it means that human stakes are involved and that man can therefore legitimately question the actions he must carry out. It is clear from the fundamentals that while these actions can be voluntary and positive (*i. e.*, preservation and restoration of ecosystems to ensure their protection function), they can also be counterproductive when they result in the degradation of ecosystems and reduced protection performance, which is frequently the case. Because of man's global impact on the environment (notably through the

effects of climate change, but also through other environmental damage such as plastic pollution), no ecosystem can be considered as not interacting with society.

In conclusion, natural structures and formations evolve in their composition and in their protective function against coastal flooding under the influence of anthropogenic and non-anthropogenic factors. In accordance with the definition of an SES, « their functions derive from the interactions and interdependence of social and ecological subsystems ». This applies both to the components of the protection systems and to the protection system as a whole. This conclusion can also be extended to the territory under the influence of the protection system. This territory can indeed be considered as a system encompassing not only the components of the system of protection, but also all types of «natural» features, anthropogenic works (buildings, infrastructures, and networks), as well as the human community present in the territory or exerting an influence on this territory. These components are in much higher number and of a much greater diversity than the components of the protection system. Their interactions are innumerable, which makes it a highly complex SES.

At the regional scale, it is also possible to define an SES corresponding for example to a delta, a watershed, or an island. This scale is relevant to consider the effects of a marine-weather event or to assess sediment flows that may alter the state of the systems mentioned above.

Finally, the planet is an SES that interacts with lower hierarchical systems through the effects of climate change, but also, for example, through international trade, migration flows, and tourism.

We therefore have a panarchy composed of five SESs, shown schematically in figure 46:

- the planet;
- the region;
- the territory under the influence of the protection system;
- the protection system; and
- the component of the protection system.

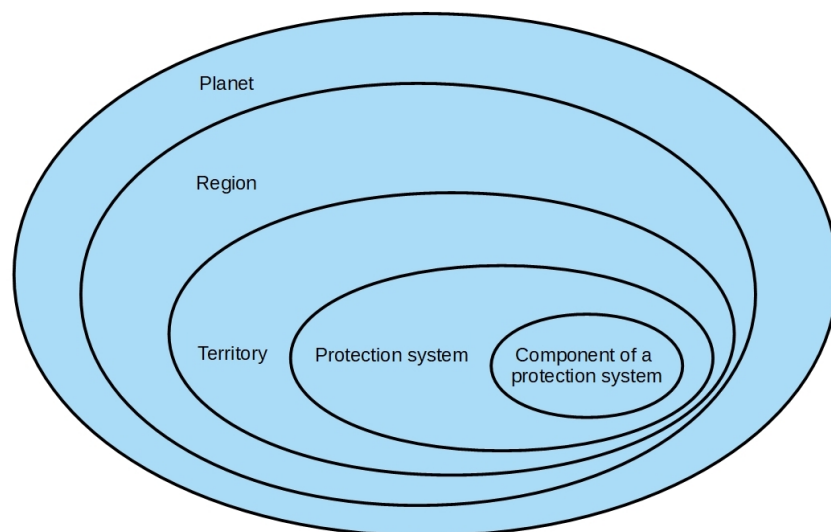


Figure 46: Panarchy in which a protection system is positioned.

The application of the concept of social-ecological resilience can be applied to each of these SESs by considering its own characteristics, but also its relationships with systems at lower and higher levels. This analysis is presented below for the SESs « component of the protection system », « protection system » and « territory under the influence of the protection system ». Following this analysis, the SES « region » and « planet » will also be studied, but only through their interactions with the three aforementioned SESs.

Functions of social-ecological systems

Since a system is basically « a set of elements in dynamic interaction and organized according to a goal » (ImdR, 2018), the status of an SES must be determined primarily in relation to the expected services gained from it.

For each of the identified systems, the functions are as follows:

- for the components of the protection system: flow control (retention or canalisation) under the conditions assigned at the scale of the protection system;
- for the protection system: protection of an area with vulnerable stakes, so that the expression of hazard (especially with parameters of water height, current speed and wave flow) at each point in the area corresponds to the protection objectives for defined reference events;
- for the territory under the influence of the protection system: protection of people and property against the risks of coastal flooding and other natural and anthropogenic hazards. Other additional objectives, such as welfare and social justice for the population, exist at this level.

2.3.2 Characterization of the resilience of the social-ecological systems

The resilience of the SESs can be characterized by studying the topology of the stability landscapes in which these systems may evolve. An SES is in a desirable basin of attraction as long as its condition allows it to fulfill its functions.

In accordance with the framework established by Walker et al. (2004), the topology of stability landscapes can be described by two state parameters, latitude and resistance. For each of the three SESs studied, considering their respective functions, these parameters can be defined as follows:

- for the components of the protection system, in relation to the flow control function:
 - resistance: the ability of the component to maintain its state under various stresses;
 - latitude: the ability of the component to evolve in its state while maintaining its function (retention, canalisation, infiltration, or evacuation) and the possibility of being restored;
- for the protection system, in relation to its function of protecting an area with vulnerable stakes:
 - resistance: ability to maintain a state compatible with the protection objectives for various reference events;
 - latitude: the ability of the system to experience changes (e. g., dune erosion or filling a water reservoir for flood regulation), while maintaining its function and the possibility of being restored;

- for the territory impacted by the protection system, in relation to the functions of protecting persons and property against natural and anthropogenic risks, while also promoting welfare and social justice:
 - resistance: ability to maintain the territory and its population in a satisfactory general condition (using a protection system, reducing the vulnerability of buildings and infrastructure, developing crisis management plans and providing aid for disadvantaged people);
 - latitude: the ability of the territory to evolve, while maintaining levels of risk consistent with protection objectives and recovery capacity after a crisis.

2.3.3 Evolution and adaptability of social-ecological systems

The knowledge and the representation of resilience evolution of the SESs can be improved through the use of the adaptive cycle model. By these means, it is also possible to assess the adaptability of SESs. Thus, for each of the three identified SESs (component of the protection system, protection system, and territory impacted by the protection system), the characteristics of adaptive cycles will be specified. Then the evolution of the resilience of SESs during these cycles will be described, in relation with the « basins of attraction » model.

In addition, the interactions between the SESs organized in a panarchy will be studied.

Adaptive cycles of the protection system components

Each structure, from its construction until its eventual decommissioning, should be subject to multiple actions of monitoring, maintenance, and in the case of deterioration, repair. If the protection objectives change, the structures may also be subject to reinforcement operations. This is reflected in the concept of « life cycle » of a structure, shown in figure 47.

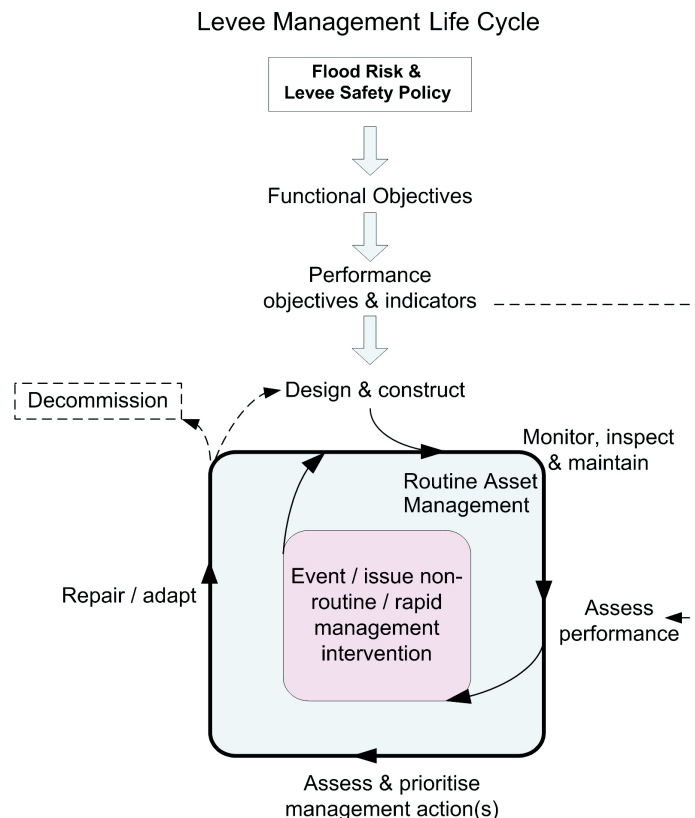


Figure 47: Life cycle of a protection structure (CIRIA et al., 2013).

In fact, several cycles appear in this diagram: a routine cycle (main cycle) corresponding to the ordinary management of the works, an internal cycle corresponding to an event degrading the state of the work, and an external cycle corresponding to a change in the design of the structure. The last two cycles lead to a return to the routine cycle (except if the structure is decommissioned).

Although the concept of « life cycles » does not commonly apply to natural formations, when they are integrated into a protective system, their fate is quite similar to that of structures: there is a routine cycle corresponding to seasonal variations (e. g., the annual accretion-erosion cycle of beach-dune systems and seasonal variation of mangrove vegetation) and human interventions take place either in an emergency situation to maintain or restore the protective function, or in anticipation to reinforce a natural formation whose state is considered too precarious.

The life cycles of structures (including natural formations) have the main characteristics of adaptive cycles. For better perception, it is necessary to « deploy » the different loops and reposition them on the Möbius ring of the adaptive cycle (see figure 42) in which:

- the routine cycle corresponds to the operational and conservational phases;
- the inner cycle corresponds to the chaotic phase of collapse and release (the materials and the natural or artificial order of which made it possible to perform the function of protection, are partially or totally dispersed). It is a short phase corresponding to a marine-weather event or a tsunami. This phase includes any repairs carried out under emergency conditions;
- the external cycle corresponds to the reorganization phase, which can be fast or slow, and can create new opportunities and foster innovation.

It should be noted, however, that the analogy with the adaptive cycle of Holling et al. (2002) is valid only if the anthropogenic structure or natural feature is damaged sufficiently such that a new cycle can be considered initiated.

The way in which these adaptive cycles affect the characteristics of social-ecological resilience may differ quite markedly depending on whether the structures are anthropogenic or natural. This emerges from the analysis of the four resilience state parameters described by Walker et al. (2004):

- latitude: natural features, due to their fluctuation over time, generally exhibit latitudes of evolution superior to those of masonry or concrete civil engineering structures whose functioning does not allow any deformation. Nevertheless, the design of some « dynamic » structures, such as a armourstone carapace, whose pieces can move during a marine-weather event like a pebble beach exposed to waves, makes it possible to consider the latitude of these structures as being quite close to that of natural features;
- resistance: natural formations may show, in some cases, low resistance (for example, a dune can be very sensitive to hydraulic and wind actions). A poorly dimensioned structure may also have low resistance, but in general, engineering aims to ensure sufficient resistance to the identified reference events;
- precariousness: this parameter of resilience characterizes the state of the system at a given moment and is highly dependent on the two preceding parameters. This parameter can therefore evolve either slowly over the seasons, or abruptly during an event. For example, a component of low resistance, when degrading, can remain in an acceptable state because a high latitude that keeps it away from precarious situations. This is the case for most natural features; conversely, a strong resistance does not prevent precarious situations: a structure subject to loads exceeding the design basis assumptions may suddenly leave the basin of attraction where its manager would like to keep it;

- SES panarchy: the resilience associated with each of the components can be enhanced by measures to protect them from excessive stresses (for example by positioning breakwaters in front of a coastal levee, or by promoting sedimentation at its toe and thus reducing the action of the waves), but also by more regular monitoring and maintenance actions.

Adaptive cycles of protection systems

Unlike a protection structure that can be decommissioned as part of a review of the flood risk management strategy, the protection system as a whole is intended to be maintained over time, except when the community considers that it is no longer appropriate anymore. This generally corresponds to cases of force majeure (a particularly devastating event demonstrating the danger of the occupation of an area). The conventional management schemes for protection systems are therefore naturally not intended to represent the elimination of the system. Thus, in figure 48, as well as for a particular structure, there appears a routine cycle corresponding to an operating phase (main cycle in the figure) and a cycle initiated by an event temporarily challenging the capacity of the system to perform its function (internal cycle in the figure). However, the disappearance of the system is not envisaged.

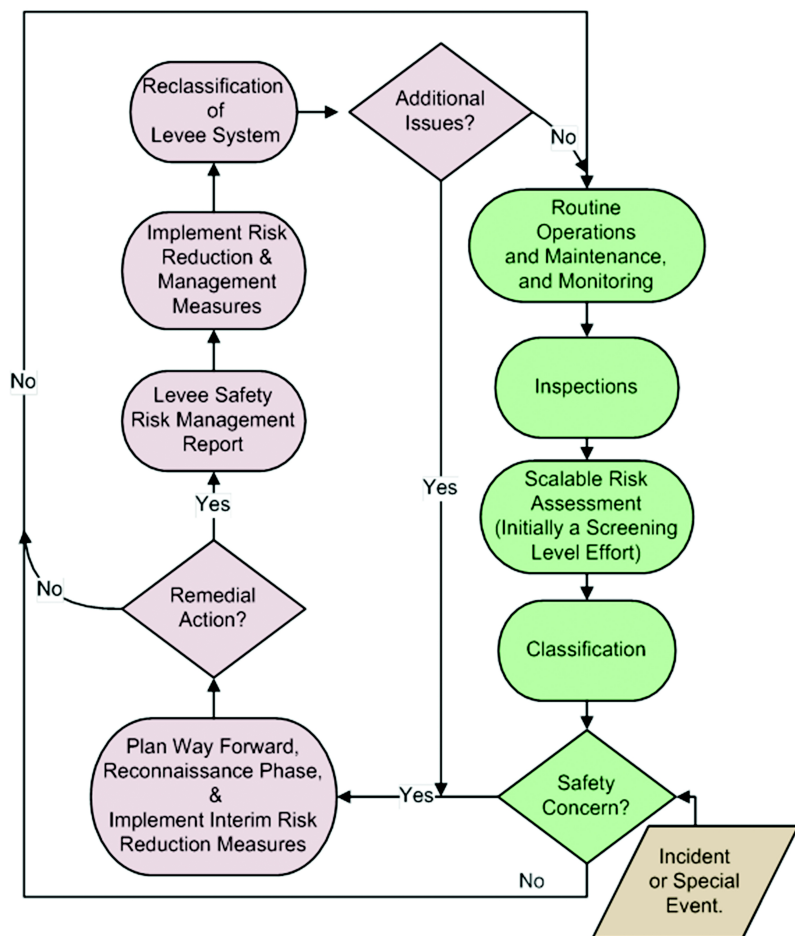


Figure 48: The recommended framework for levee management representing the exploitation and conservation phases of a protection system adaptive cycle (CIRIA et al., 2013). Credit : USACE.

To justify the analogy with the adaptive cycle of Holling et al. (2002), the damage to the system should be so great that a complete revision of the system should be considered, as was the case, for example, in New Orleans after Hurricane Katrina. Otherwise, the successive cycles correspond more to an « incremental adaptation » for anthropogenic works (or to an « evolutionary adaptation » for natural features) and then, are part of the growth and exploitation phase of the adaptive cycle.

All the interventions, regular or exceptional, carried out on protection systems show to what extent the social component of this type of SES is decisive. The activities of managers of anthropogenic

structures and natural features influence all the state parameters of resilience during the phases of growth and conservation of the adaptive cycle:

- resistance: by analyzing the behavior of the system exposed to reference events, managers ensure that hydraulic conditions are controlled in areas with vulnerable stakes. If necessary, the performance of the system can be improved by adding structures or by strengthening existing structures;
- latitude : when considering the protection provided by the system in the event of a failure of one or more of its structures, managers can identify additional measures to be implemented to « widen » the basin of attraction in which they wish to maintain the protection system. Thus the performance of the system is not only improved when the structural state of the system is maintained, but also when this state is degraded;
- precariousness: the actions mentioned above that are intended to increase resistance and latitude also promote the maintenance of the system in a wider and deeper basin of attraction. However, regular monitoring and maintenance of the structures remains necessary. Without these activities, multiple degradation factors (anthropogenic, biological, meteorological, and hydro-sedimentary) will bring the system closer to the limits beyond which the protection function is no longer properly ensured;
- the position of protection systems in a panarchy where the upper level is represented by the protected territory is a favorable condition if a common strategy is defined between the managers of the protection system and those responsible for spatial planning. If this condition is met, then any weaknesses in the protection system may be offset by measures to limit exposure to insufficiently protected areas, or failing that, by measures to limit vulnerability in those sectors.

The resilience of protection systems and their evolution in the adaptive cycle are influenced by other social factors (more precisely, socio-economic factors): the maintenance of the system is conditioned by access to material and financial resources, and the existence of an appropriate mode of governance (Schleussner et al., 2016). With this point, it should be noted that the inclusion of a protection system in a panarchy is a favorable condition if the financing of these systems and the supply of equipment and materials can be provided at a regional or national level according to priorities. This solidarity is particularly valuable when it comes to restoring a system after a major event.

However, in regard to these aspects, it is necessary to revisit the process highlighted by Bhowmik (2017) that concerns both rich and poor regions: in case of multiple and amplified shocks, the system, by its organization and mode of governance, becomes more and more complex, and reaches a point where adaptation measures lose their effectiveness, which can lead to the collapse of the system. However, the management of protection systems is already very complex without taking into account added stressors. If, thanks to the talent of its author, figure 49 does a good job at information synthesis, it does not obscure the multitude of skills required for system management, including field inspection, risk analysis, economics, and engineering. If the conditions to which the protection systems are exposed deteriorate in the proportions predicted in terms of the annual frequency of weather events, the capacity of institutions to manage protection systems could become insufficient despite their strengthening.

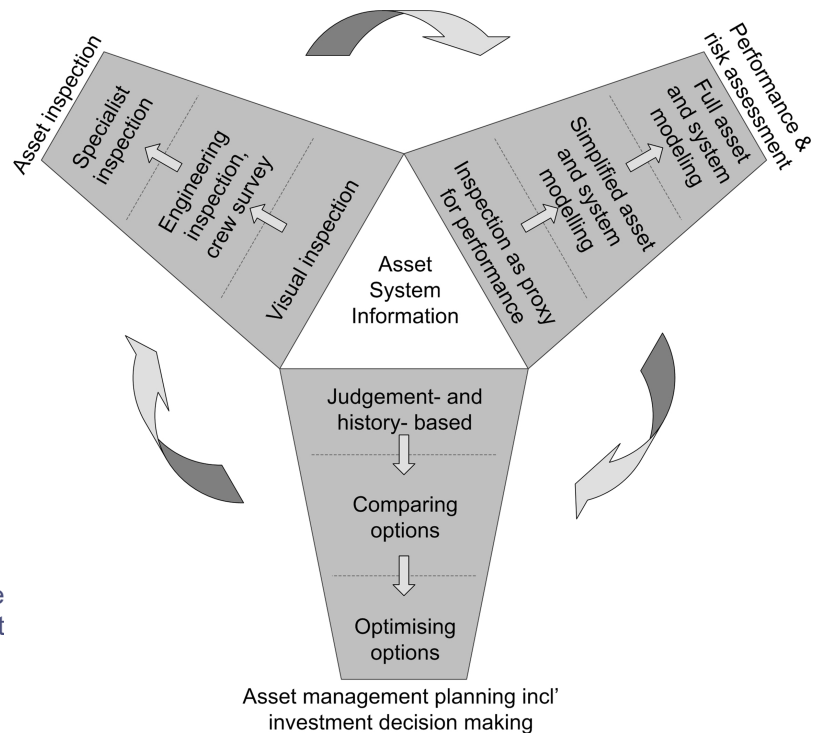


Figure 49: Asset performance tool propeller (Environment Agency, 2011).

The description of the conservation phase by Holling et al. (2002) is representative of the situation of levee systems facing both an increase in biophysical and urbanization constraints :

- the system becomes progressively less flexible and responsive to external shocks : the saturation of land use by the urbanization process prevents the repositioning of levees, or even their simple widening and raising; and
- resources become increasingly locked up : the difficulty of changing the system leads to an increase in maintenance expenditures to the detriment of capital expenditures.

Holling et al. (2002) predict that this phase of conservation is « eventually, inevitably, followed by a chaotic collapse and release phase ». At the level of the protection systems, the predictions are alarming, especially since increased urbanization and intensification of phenomena generating hazards often occur at regional or higher scales. This is detrimental to the ability to allocate additional resources as a priority to protection systems whose conditions would be particularly degraded.

Finally, it should be noted that the precariousness of protection systems is not only linked to changes affecting the systems themselves, but also to external changes (in particular urbanization, subsidence, and RSL rise) *i.e.*, changes at the higher levels of the panarchy. In the Walker et al. (2004) model, the stability landscape evolves, placing the system in an undesirable basin of attraction, although the system has not changed. If adaptation paths exist, they must therefore also be sought at higher levels of the panarchy.

Adaptive cycles of territories

Integrated flood risk management can be represented as a cycle as shown in figure 50. Provided that a cycle profoundly alters the protection strategy, it may be considered as an adaptive cycle of a territory. Otherwise, in the same way as at the lower levels of the panarchy, if the actions taken during this cycle correspond only to minor adaptations, then the territory will continue to progress in the growth and conservation phase of the same adaptive cycle.

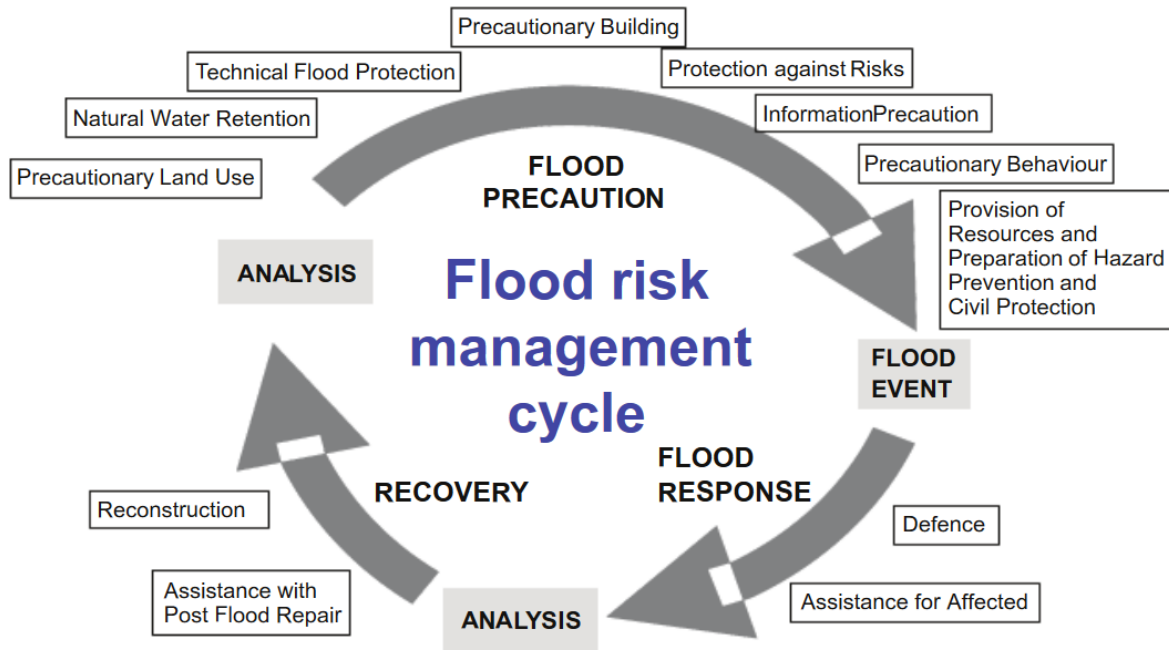


Figure 50: The flood risk management cycle. Credit : Cassel and Hinsberger (2017), from LAWA (2010).

Protection strategies are generally organized in relation to major events, around phases of preparedness, crisis management, and recovery. These three phases can be linked to the adaptive cycle of Holling et al. (2002):

- the growth and conservation phases are represented by prevention, protection, and preparedness measures ;
- the chaotic phase of collapse and liberation is represented by the crisis; and
- the reorganization phase is represented by a recovery phase that may, depending on the description of the adaptive cycles, result in a system fundamentally different from the initial system.

For the territory under the influence of the protection system, in relation to the functions of protection and the complementary objective of promoting welfare and social justice, the four state parameters of SES resilience evolve as follows during the growth and conservation phases:

- latitude: increased exposure of vulnerable stakes and deterioration of natural formations combined with RSL rise lead to a reduction in the territory's ability to evolve in order to maintain levels of risk in line with protection objectives at all sites affected by these phenomena. In addition, except if very proactive policies are put in place to combat social inequalities, the most disadvantaged populations are concentrated in the most exposed areas;
- resistance: internal (increased exposure and reduction of protective capacities) or external (effects of climate change and reduction of sediment loads from rivers due to dams) factors to the system reduce its capacity to meet the objectives previously mentioned by structural means (*via* the protection system and the adaptation of infrastructure and the built environment). Innovation therefore focuses on the deployment of measures to reduce vulnerability by improving citizens' response to an event: utilization of early warning systems,

training, exercises and deployment of participatory science programs (Cassel and Hinsberger, 2017; McCrory and Veeckman, 2017);

- precariousness: if the effect of the measures to reduce vulnerability is sufficient, the precariousness of the system can be maintained at a level compatible with the protection objectives. Otherwise, increased exposure and protection reduction lead to increased risk. It should also be noted that the proliferation of activities in areas of influence of protection systems leads to more complex situations and the emergence of new risks, natural or anthropogenic, in combination or by « domino effect » with the risk of coastal flooding;
- the position of territories in the SES panarchy is quite clearly unfavorable: at the lower level, as explained earlier, the protection systems are in increasingly precarious situations; at the higher levels, systems (region and planet) pose additional constraints (ecosystem degradation, watershed water cycle disturbance, and climate change effects).

Even more so than in the case of protection systems, this situation in the « conservation » phase leads us to question the complexification of governance systems (which responds to the complexification of the territories to which they apply). The regulation of land cover and the limitation of disturbances of the natural environment seem to be the first measures to prevent very precarious situations, or even major crises.

Interactions between the SESs organized in a panarchy

Considering a panarchy of SESs that consists of the system of protection (its components constituting subsystems), the territory under the influence of the system of protection, the region to which the territory belongs, and the planet, the study of the evolution of SESs in their stability landscapes shows that:

- protection systems are largely dominated by external factors (e. g., urbanization and other local anthropogenic disturbances, climate change effects);
- the territories that benefit from protection systems evolve by internal factors (e. g., urbanization and other anthropogenic actions) and external factors (e. g., disruption of sedimentary flows, effects of climate change, etc.);
- regions are under the influence of climate change, but are also experiencing many internal changes, as previously mentioned;
- at time scales of coastal flood protection, variations in Earth's motion and variations in the Sun's activity are negligible in comparison with human disturbance to climate and the resulting effects (IPCC, 2019). Under this hypothesis, the evolution of the Earth depends mainly on internal factors and especially on the actions of humanity.

With regard to the latter SES, the planet, the extent of human influence over global systems has resulted in challenges for which the scale and complexity are generally unprecedented (Angeler et al., 2016). The complex interdependencies of environmental problems, for example those deriving from climate change, transcend local, regional and global scales, and result in a thorny issue that seriously challenges our ability to sustain human welfare and healthy ecosystems (Rittel and Webber, 1973).

The panarchy chosen for the study of protection systems reveals a paradoxical situation: while the higher-level system of greater inertia (the planet) should have a regulatory role, it is evolving at such a speed that not only does it no longer play this role, but on the contrary, it causes a destabilization of the systems at lower levels. Considering, for a system of protection, the region and the territory as systems of intermediate ranks, actions such as deforestation, the disturbance of sedimentary flows, or the acceleration of urbanization are likely to generate instability as well.

An analysis in terms of ESs shows that extensive and rapid global changes, including growing human populations, urbanization, rising consumption, and increased global connections, have led to a large and growing demand for provisioning services. Meeting these needs has resulted in large-scale conversion of natural ecosystems to cropland, which has eroded the capacity of ecosystems to produce other ES essential to human health and security—especially regulating services (Raudsepp-Hearne et al., 2010). Furthermore, extensive anthropogenic changes to the world's ecosystems are increasing the likelihood of large, nonlinear, and potentially irreversible changes, such as coral reef degradation (IPCC, 2019). Such events often have substantial and sometimes catastrophic impacts on ESs and human well-being (Millenn. Ecosyst. Assess., 2005 ; Bishop, 2010). The translation of factors increasing the risk of coastal flooding into the ESs typology is a valuable aid in defining methods for understanding risks and defining strategies.

2.4 Methods for risk assessment

Risk management decision-making requires first a proper understanding of risks in order to be able to subsequently consider reducing them. The methods relating to these two objectives will be explored successively in this section and in the following, based on the conceptual framework established above and more precisely, in relation to the two parts which constitute it:

- the characterization of the resilience of SESs. Characterizing the resilience of systems means not only estimating their capacities to perform their functions, but also recognizing the limitations of these capacities and therefore understanding the risks, by identifying events, trends, and disruptions that SESs would not be able to cope with. This part of the conceptual framework will therefore be used to address methods for understanding risk;
- the assessment of the adaptability of the SESs through the knowledge and the representation of the evolution of their resilience, using the adaptive cycle model. This part of the conceptual framework will therefore be used to address methods to reduce risks.

As for the development of the conceptual framework, the study of the methods will be conducted through a generic analysis followed by the identification of the modalities of application to the territories and their protection systems. The « region » and the « planet » SESs, as well as the components of the protection systems, will also be taken into account, but only through their interactions with the three previously mentioned SESs.

2.4.1 Generic principles of understanding risk

Risk understanding should not be limited to the application of analysis methods. It should include a preliminary review of the nature of the system studied, of its environment, and of the targeted objectives. Moreover, modalities for the observation and monitoring of the system are generally required. The presentation of generic principles will therefore focus on risk analysis and risk observation.

Generic principles of risk analysis

Two generic principles of risk analysis exist and are generally intended to complement each other: « analytical » approaches and « systemic » approaches.

Analytical approaches apply preferentially to stable systems, consisting of elements with so-called linear interactions, that is to say which can be described by fixed rules or by continuous mathematical laws. The guiding principle of these approaches is to proceed in the manner of Descartes (1637), whose principle was to « divide each of the difficulties examined into as many parcels as possible that would be required to best resolve them ». Subject to adequate knowledge and reliable data, the resulting risk analysis principle is:

- decomposition of the system into autonomous elements by functional analysis and study of the relations between the elements in pairs, as well as with the external environment;

- optimization of each element through risk analysis and cost-benefit analysis in order to achieve an overall optimum. These studies are carried out using available knowledge and deterministic and probabilistic approaches, the definitions of which have been recalled in the framework of the European project FLOODsite (2009b):
 - deterministic method : a method that adopts precise, single values for all variables and input values, giving a single-value output; and
 - probabilistic method : a method in which the variability of input values and the sensitivity of the results are taken into account to give results in the form of a range of probabilities for different outcomes. These methods are valuable for understanding the risks associated with events of a similar nature (for example, marine submersions), but whose characteristics may vary. These methods are also relevant for any prediction when future forcings are unknown and therefore uncertainties in analytical model inputs could lead to great uncertainties in prediction results (Tiberi-Wadier et al., 2021).

Analytical approaches were developed since the late 1930s and implemented in the industrial field, and then gradually extended to other sectors, including flood protection. Despite the undeniably positive results, the persistence of unanticipated disasters shows that this approach has limits. The emergence of non-detectable or uncontrollable risks through analytical approaches is due to the existence of complex systems, which include :

- the dynamics of interactions, especially the existence of feedback between the elements that makes it difficult to distinguish between causes and effects;
- the simultaneous presence of order and disorder that makes it difficult to predict changes;
- properties and « global » behavior of the system that are not directly deduced from the properties and behavior of each of its elements (IMdR, 2018).

Phenomena observed in a coastal megacity such as Semarang (Indonesia) illustrate the functioning of such a system. In this territory, as the urbanization degraded the natural process of water purification by wetlands, the inhabitants were forced to extract their drinking water from aquifers. The number of wells and volume of water extracted increased considerably: in 1930, the town of Semarang had less than 50 wells and less than 1 million m³/yr of water extraction ; in 2000, the number of wells exceeded 1 200 and the extraction exceeded 45 million m³/yr (Cerema, 2019a). These multiple individual water extraction initiatives, – which are not directly related to the other initiatives, also individual and multiple, that were the cause of the wetland degradation –, have led to the lowering of the water table and the subsidence of soil in parts of the city. These phenomena, in turn, had multiple unforeseen consequences, particularly on land use planning. So there are feedbacks between land use planning and water management. These city-wide feedbacks are the result of actions at much finer geographical scales.

Contrary to what analytical approaches imply, in a process of aggregating a set of locally controlled situations, risks can emerge at a higher level. The examination of linear processes and cause-effect pairs is insufficient to understand the dynamic behavior of the whole system (see figure 51). To understand the dynamics of these systems, it is necessary – but unfortunately not always sufficient – to represent the whole system as a « web » (Cassel and Hinsberger, 2017).

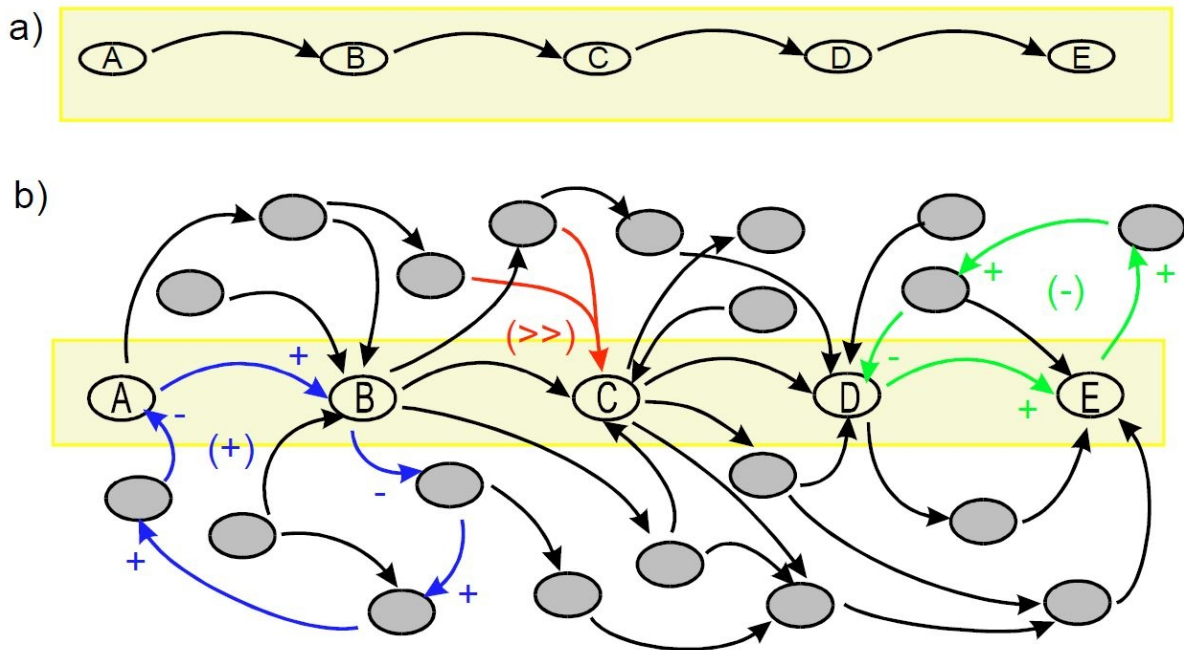


Figure 51: (a) A simplified notion of cause–effect chains: A causes B, B causes C, etc.; (b) a more realistic description of complex cause – effect webs with synergistic effects (>>), positive (+) and negative (-) feedback mechanisms (Cassel-Gintz, 2001).

In analytical approaches, a problem is often perceived as an externally-generated event. A systems dynamics approach may reveal that the internal structure of the system is more important for solving issues. For example, the most spontaneously identified causes of coastal flood risk are marine weather events, while the exposure of stakes to these events should be considered the primary cause. Moreover, in social and economical systems, the representation of mental models of individuals or teams can also help to solve problems (Forrester, 1996).

Furthermore, if the complexity of a system depends on the intrinsic parameters, it also depends on extrinsic parameters (ImdR, 2018) including:

- the observer: complexity generally increases with the degree of expertise and requirements;
- the time horizon: complexity is greater on distant horizons with more uncertainty;
- the operating conditions and the available data: when the operating conditions are met and the available data are sufficient, a problem can be relatively simple, and when this is not the case, it can become complex (hence the importance of observation and monitoring).

Generic principles for observing complex systems

Understanding how phenomena interact with one another, and their significance for people and ecosystems, requires a holistic approach that looks at human and natural dynamics together. The concept of social-ecological resilience contributes to provide this holistic view (Arctic Council, 2016).

The key starting point of this process is the integration of different kinds of knowledge and a variety of experiences in which scientists, the public, and decision-makers in policy and practice collaborate to generate not only scientifically reliable, but also context-appropriate, socially robust (van Hattum et al., 2020) and actionable knowledge (Weichselgartner and Kaspersen, 2010), while always keeping in

mind that knowledge integration is necessary but not sufficient: cooperation between actors must continue with resilience-building programs (Weichselgartner and Kelman, 2014).

Increased interest in resilience management has driven the development of standardized tools for:

- assessments that focus on deepening understanding of system dynamics ; and
- Iquantitative measures that aim to capture and quantify resilience in a rigorous and repeatable way. Resilience, however, as a property of CASs, is not easily measured.

Measuring and monitoring a narrow set of indicators or reducing resilience to a single unit of measurement may prevent a deeper understanding of system dynamics needed to apply resilience thinking and inform management actions (Quinlan, 2016). This observation only reflects the same problem as that identified for risk analysis: analytical approaches may prove inappropriate to understand complex dynamic systems. Observation of these systems should necessarily involve systemic approaches. To manage the systemic approach of a theme (« risks to a coastal area » is a possible theme, for example) or a territory, an observatory may be a pertinent tool for providing information, and also for disseminating this information. An observatory can be defined as an observation system set up by one or more organizations to monitor the evolution of a phenomenon, an area or a portion of a territory in time and space; most observatories take the form of computer applications in which data are aggregated and presented in the form of tables, maps, or statistical indicators. The objectives, the users, and the temporalities taken into account by the observatory should be precisely defined (Bourlier et al., 2020).

Conclusions on risk observation and analysis

Understanding risk can be considered through an observation and analysis approach that may involve systemic and/or analytical approaches. It is important to explain the approach chosen, because it determines the type of methods adopted, and ultimately the diagnosis formulated. The definition of the approach depends on the system in question, whose composition, limits, and environment should be clearly identified, while also considering the objectives of the analysis and the conditions under which the analysis is carried out.

Considering the conceptual bases previously outlined, the application of the principles of risk understanding will focus on the following SESs:

- the territory, which is an eminently complex system in terms of the number and diversity of the elements that constitute it (physical, biological, and anthropogenic constituents), and by the interconnection of these elements and their relations with the external environment;
- the coastal flood protection system, which may be regarded as a subsystem of the territory in which it is situated, which certainly has fewer and less diverse elements. However, a high degree of complexity is maintained when ecological and social dimensions are taken into account.

The objectives of risk understanding may vary depending on the situation, but in general, methods should:

- be adapted to heterogeneous territories with regard to their stakes and resources;
- consider short (less than a decade), mid-length (from a decade to a century) and long (several centuries) timescales.

If the focus in this section is on understanding risk, it is important to ensure that the approach chosen is also appropriate for the ultimate risk reduction objective. For this reason, it is preferable, with sufficient anticipation, to associate all types of actors and to utilize all types of theoretical substratum.

As the prerequisites for identifying the systems and objectives of the analysis are satisfied, it is necessary to consider what can be gained from the systemic and analytical approaches. These approaches are fundamentally different, to the point that they correspond to two distinct paradigms, of which Krob (2008), in his paper on complex industrial systems, made a comparison, which stated:

- a systemic approach aims for a comprehensive understanding, applies to heterogeneous systems, is based on views expressed in a collaborative framework, and produces relative conclusions (taking into account external constraints to the system) by utilizing logic and systems representation;
- an analytical approach seeks a comprehensive understanding, applies to homogeneous systems, is based on detailed representation modes, utilizes experts, and concludes with certainty, using scientific disciplines.

This comparison along with the other insights provided by Krob (2008) allow discerning better how systemic and analytical approaches can be articulated: in the same way as for a complex industrial system, the territories and their protection systems correspond to environments where everything evolves and can be constantly questioned (over a period of a few hours, particularly during a meteorological event, or over a period of a few decades due to poorly controlled urbanization). The dynamic nature and intrinsic complexity of these systems make their comprehension, design, and supervision extremely difficult and analytical approaches inoperative on a global scale. In this context, systemic analysis is intended to define « the architecture of a system », that is to say, its invariable part, which can reasonably be considered as fixed over time²². It is therefore also the one on which we can act to manage the evolution of a given system. According to Krob (2008):

« Architectural thought is in a way opposed to classical analytical thought. Reasoning as an architect is in fact absolutely not trying to understand in the slightest detail how the system we are dealing with will work (which would be what an analytical engineering approach would focus on), but much more identifying what the great structural invariants of the system are going to be, and then letting the system find its own balance within the architectural framework given to it (and that it will have to structurally preserve and respect). »

Despite this formal opposition, systemic and analytical approaches are in fact complementary in practice: once the processes of risk emergence have been identified by systemic approaches, analytical approaches are needed to accurately describe the mechanisms at work and quantitatively characterize the hazard. Similarly, since protection principles have been established by a comprehensive systemic approach, the relay should be taken by the engineering analyst to ensure the proper sizing of the system.

Finally, it is the overall scheduling of investigations and analyses that deserves the most attention. Considering that it is preferable to have a global vision of a system before considering more targeted studies, a systemic analysis should generally be undertaken first, within the framework of an integrated approach (taking into account the multiple components of the territory) and should be inclusive (involving multiple stakeholders). This systemic analysis may then include recommendations in its conclusions as to any necessary analytical extensions.

For the following, the emphasis will be more on systemic approaches, with the related analytical approaches being more relevant to the fundamental aspects mentioned in the first chapter

²² Krob (2008) points out that this way of extending to systems, the concept of architecture as it traditionally exists in urban planning is perfectly consistent with its usual understanding. The architecture of a building is in fact none other than its invariant part, that is, the part that will not change regardless of how the building is occupied and evolves over time.

(quantification of risk) and the implementation of the protection strategies referred to in the third chapter (technical and economic sizing of protection systems).

2.4.2 Understanding risks in territories and protection systems

In order to better appreciate the possibilities of observation and understanding of risks in coastal territories, the link between systemic and analytical approaches will be sought by considering « territory » and « protection system » SESs. The latter will be considered as a subsystem of the former. The study of the state of the art will therefore progress initially by following two axes that guide the preliminary systemic analysis:

- multiple risk assessment in a coastal territory;
- defining spatial-temporal analysis frameworks.

On the basis of the information available about these two axes, the methods applicable at the territorial level, and then at the level of the protection system will be presented. Taking into account the nature of SESs, guidelines will be sought in the social and ecological fields.

Multiple risk assessment

Traditional flood risk management frameworks do not sufficiently take into account certain phenomena that are often decisive during the onset or aggravation of risk, such as subsidence, natural morphological changes, disturbance of sedimentary transits, destruction of mangroves, disappearance of coral reefs, etc. In addition, other phenomena (for example, storms, heavy rains, erosion and scour, sludge flows (called « lahars » on the sides of volcanoes)) are associated with coastal flooding, either as an initiating event, as a consequence, or as a concomitant event. The adoption of a systemic approach to risk in the context of observed and projected global changes is required to comprehend, as openly as possible, the conditions for the emergence of risk. In this type of approach, the hazard should no longer be considered in a restricted manner resulting only from hydro-meteorological phenomena such as in the SPRC model, but rather as emerging from a combination of phenomena, potentially of various natures which develop across a range of timescales. The appropriately given definition of « hazard » in the Hyōgo Framework for Action 2005-2015 (UNISDR, 2005) is:

« A potentially damaging physical event, phenomenon or human activity that may cause the loss of life or injury, property damage, social and economic disruption, or environmental degradation. Hazards can include latent conditions that may represent future threats and can have different origins: natural (geological, hydrometeorological and biological) or induced by human processes (environmental degradation and technological hazards) ».

Gill et Malamud (2014) presented a broad overview of the interaction relationships between 21 natural hazards. Figure 52 represents a selection of 16 of them, drawn from six hazard groups : geophysical, hydrological, shallow Earth, atmospheric, biophysical, and space hazards.

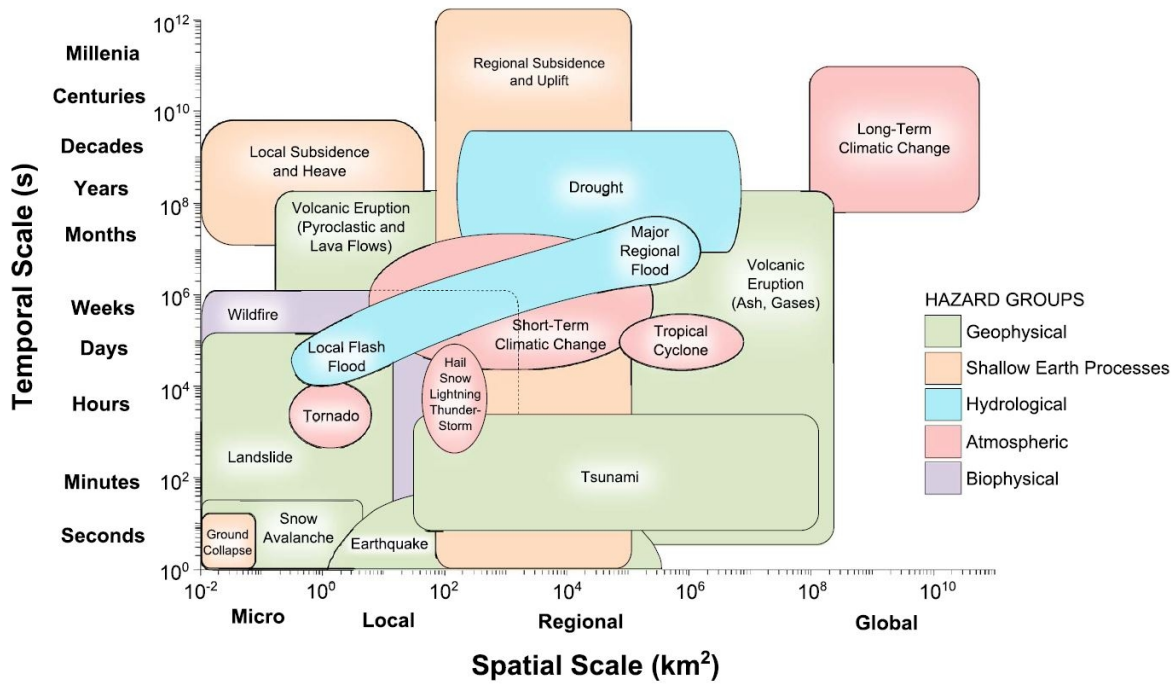


Figure 52: Spatial and temporal scales of 16 selected natural hazards. Shown on logarithmic axes are the spatial and temporal scales over which the 16 natural hazards act (Gill and Malamud, 2014).

As a necessary complement, Liu et al. (2016) provided a systematic hazard interaction classification based on the geophysical environment that allows for the consideration of all possible interactions (independent, mutual exclusion, parallel, and series) between different hazards, and for the calculation of the probability and magnitude of multiple interacting natural hazards occurring together. Figure 53 shows the guidelines of the proposed methodology.

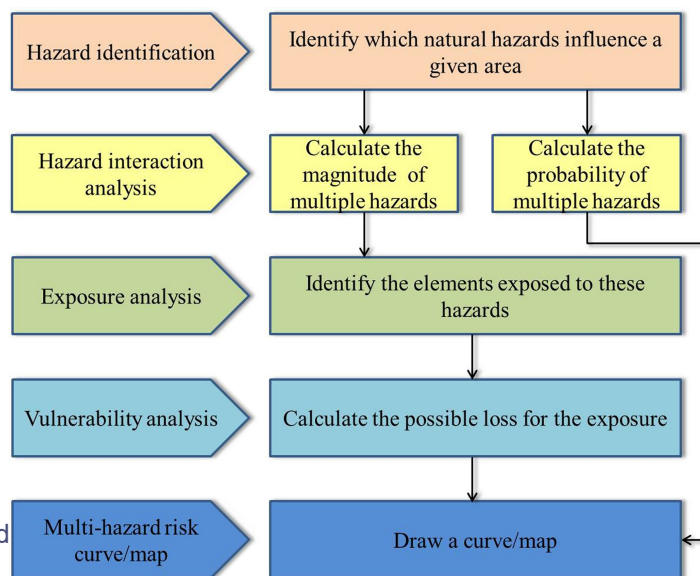


Figure 53: Basic framework of multi-hazard risk assessment (Liu et al., 2016).

Increasingly, multi-hazard risk assessments are undertaken at the coast (IPCC, 2019). For example, Kunte et al. (2014) characterized the vulnerability of coastal lands in India to erosion, submersion, and inundation, and demonstrated that the inclusion of socio-economic parameters should be taken into account in the overall assessment of vulnerability.

Van Hattum et al. (2020) also stressed the importance of socio-economic parameters and noted that poverty in particular magnifies the impact of floods as poor people are often highly exposed to floods, and are also more vulnerable and less resilient. However, traditional flood risk assessments focus mostly on asset damages and often conclude that it is inefficient to protect the poor. Based on this observation, the authors suggested a cost-benefit analysis based on the social welfare flood risk reduction benefits. It follows that poverty reduction through risk transfer mechanisms should be considered as a holistic approach to foster socioeconomic growth.

In addition, to comprehensively understand risk, Hagenlocher et al. (2018) have come to the conclusion that the definition of adaptation strategies and measures (including ecosystem-based options) requires spatially explicit information on the exposure, vulnerabilities, and risks associated with different combinations of hazards in an integrative manner, not only focusing on societal aspects or ecosystems alone, but also taking into account interactions with other systems, such as neighboring territories. In particular, the ecological dimension should be considered more systematically in risk assessments. Addressing this gap, the authors presented an innovative assessment concept and indicator-based methodology that is sensitive to the specific (multi-)hazard setting in a given territory (see figure 54). These modular sets of vulnerability indicators adapt flexibly to the hazard situation.

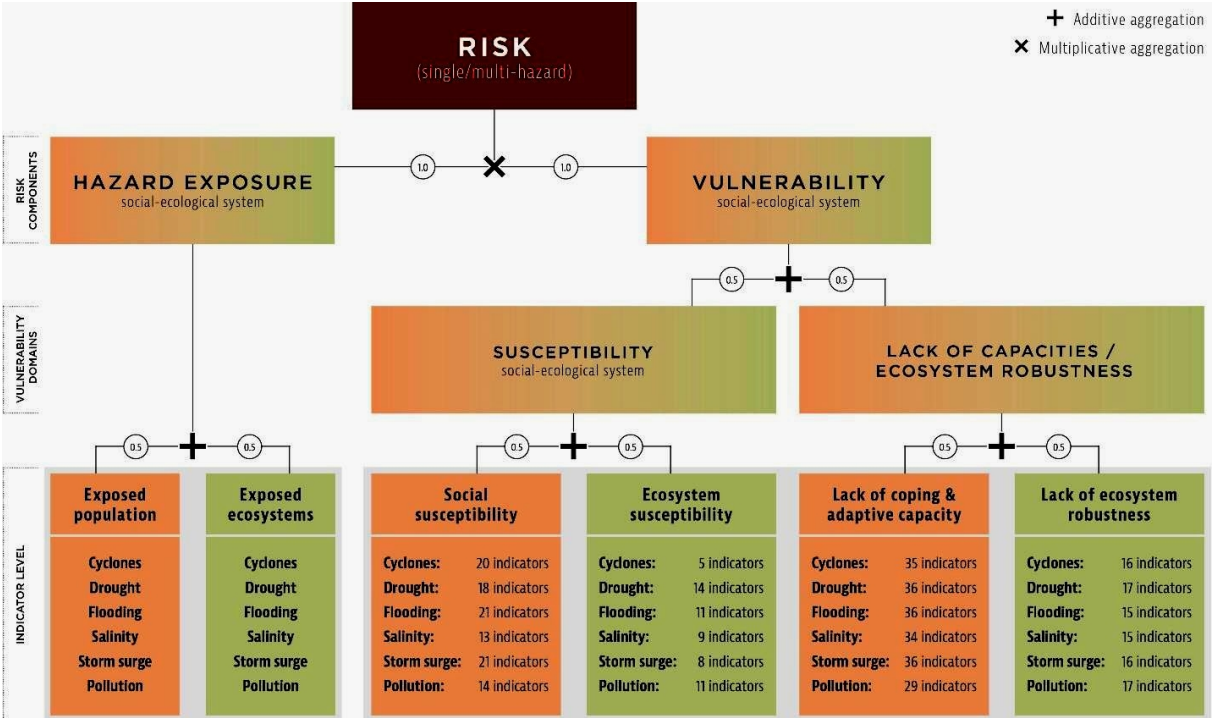


Figure 54: The Global Risk Index: concept and structure (Hagenlocher et al., 2018).

In this framework, risk is understood as a function of (i) hazard exposure and (ii) vulnerability of the SES. It is operationalized applying a modular, flexible indicator set consisting of both hazard-dependent and independent indicators while being responsive to the specific (multi-)hazard setting in a given territory.

It should be noted, however, that this methodology is based on quantitative indicators and cannot identify cascading effects and feedbacks. In addition, it ignores the hazards of biological origin, for example, the likelihood that floods degrade health conditions, in particular, by the deterioration of drinking water and sanitation systems. Analyses which widen the spectrum of investigations to include the emergence of risks should therefore be considered. Thus, for example, Cerema (2019) established, for the city of Semarang (Indonesia), a more open model of systemic functioning, with emphasis on the importance of domino effects and feedbacks (see figure 55).

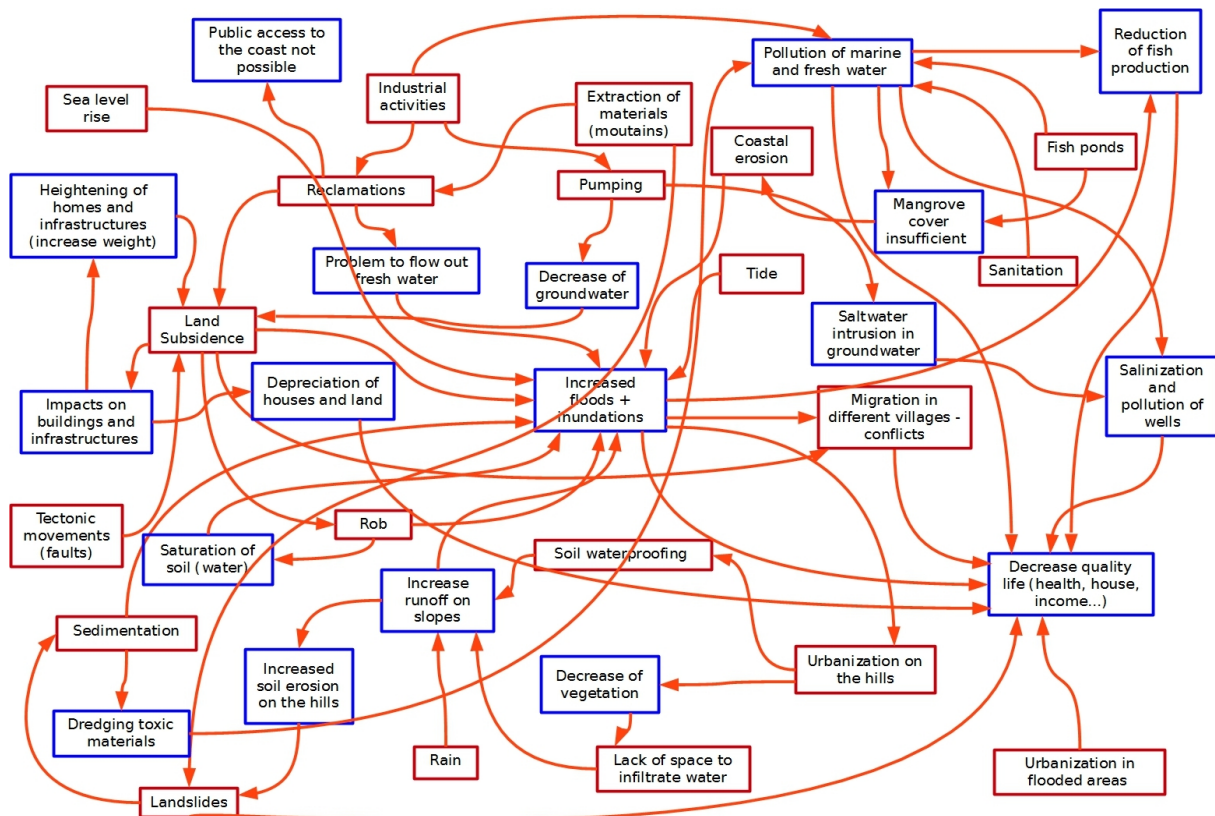


Figure 55: Systemic interactions of anthropogenic activities and natural processes (Cerema, 2019a).

In this example, depending on whether one considers forests located on land or mangroves, deforestation for the purposes of urbanization is the starting point of two processes of hazard generation:

- on land, deforestation favors run-off and soil erosion especially during intense rainy events. These phenomena accentuate the sedimentary filling of the canals and thus aggravate the inland flooding of the coastal strip;
- the destruction of the mangrove results in easier penetration of the sea and an increase in the salinity of the freshwater water tables.

Finally, it should be stressed that the multi-risk approach should not only apply at the level of the territories, but should also apply directly to protective structures since they are sensitive to a wide range of factors: meteorological, hydraulic, and morphological actions, as well as biological and anthropogenic actions. For example, the effects of prolonged periods of drought should be carefully considered, particularly in the context of climate change: levees are vulnerable to drought if the structure or its subsoil contains peat or highly organic clay in a zone/level below which the groundwater table may fall during drought. Dehydration of peat in levees causes shrinkage and a further loss of weight causes reduced stability. This may ultimately result in breaching due to horizontal sliding (CIRIA et al., 2013). An example of failure due to sliding occurred in Wilnis (see figure 56), the Netherlands, in 2003. Bottema et al. (2020) described in detail the drought effects and drought management practices for Dutch and English levees.



Figure 56: A breach in the Wilnis levee due to drought.
Credit : STOWA.

Definition of spatial-temporal analysis frameworks

Whether one considers several phenomena in a risk analysis, or after preliminary investigations, one chooses to focus on one of them, it is always necessary:

- spatially, to limit the territory in which the study is being carried out and within that territory, if necessary, carry out new spatial subdivisions (in particular if analytical approaches are to be considered);
- temporally, to assess the risks in relation to changes in the situation at various times.

This framing can progress only by iteration with investigations about the context and the phenomena likely to contribute to the manifestation of risk.

Regarding the risk of urban flooding, considering that this hazard cannot be managed in isolation at the city scale, and responses to potential flood impacts are complicated by interlinked political, socio-economic, and environmental changes, Zevenbergen et al. (2008) suggested to develop a framework in which spatio-temporal relations are further defined and investigated, in order to « provide clarity regarding both the feedback loops that cause vulnerability, as well as those that build resilience, and how they interact across differing spatial scales ».

To achieve this objective, cities can be considered as an intermediate-level SES between a higher-level SES (in this example, the watershed) and lower-level SESs, (buildings, infrastructure, and networks). Figure 57 is a schematic depiction of the propagation of a flood wave through a territory in the case of a failure or overtopping of the protection system. In addition to its particular role in flood risk management, a coastal flood protection system could be considered in this scheme in the same category as buildings and other networks. A protection structure or a natural formation could therefore appear in figure 57 in place of a building. As for buildings, transport infrastructure, or networks, redundancy of protection structures that aims at retaining water (such as levees or sea locks), or managing (piping, storage, infiltration, and pumping) water inside the system and the relations between these structures are major factors in building resilience within a territory.

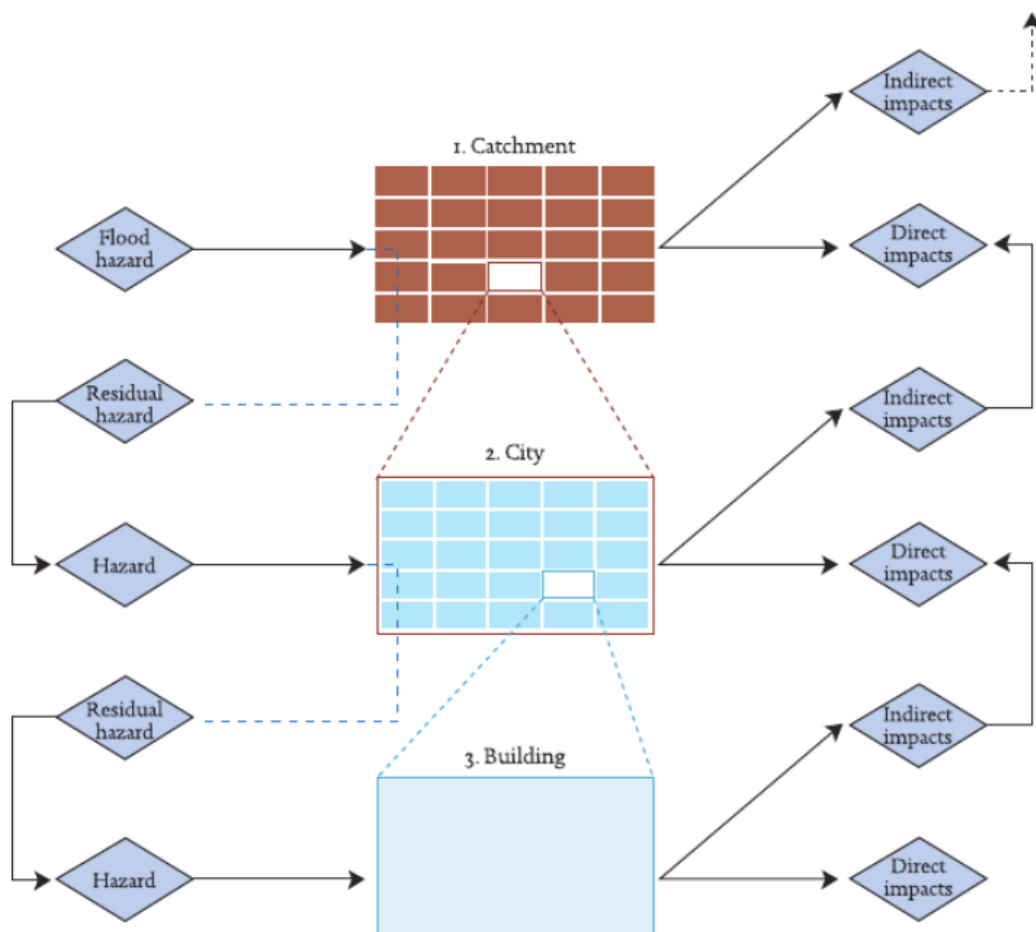


Figure 57: Flood resilience: traveling across spatial levels (Zevenbergen et al., 2008).

Apart from the spatial dimension of resilience, Zevenbergen et al. (2008) also addressed the temporal dimension, recommending the use of vulnerability indicators and the production of risk maps based on experience feedback.

Zevenbergen et al. (2008) provided spatio-temporal reference points for flood risk analyses for a « territory » SES. For a « system of protection » SES, additional guidance is provided by research on:

- the assessment of levee performance and the development of geographic information systems for their maintenance (Serre et al., 2009; Vuillet, 2012; Hathout, 2018);
- the development of a methodology for the analysis of the response of a protection system subject to a marine submersion event (Ilgigabel et al., 2022), which will be detailed in chapter 5.

Approaches analyzing risk within territories and protection systems are clearly complementary, and are intended to be coordinated in order to have a global view of the entire « production chain » of risk. But it is also necessary to integrate other issues of spatial planning into the review: using an analogy of the work by Gonzva et al. (2015) on transport systems in the urban environment, it is relevant to consider that neighborhoods and flood protection systems constitute two physically and functionally interlocking systems and therefore, the challenge is to determine how levees and other water management structures integrate into the technical functioning of neighborhoods and contribute globally to the resilience of cities facing flood risk.

Risk assessment at the level of a territory

At the territorial level, systemic approaches are predominant due to the high heterogeneity of these systems. However, analytical approaches may be appropriate when looking at particular components.

This section focuses on urban environments, where flood protection stakes are most prevalent²³. The scale of an urban zone is especially important because it is at this scale that cities carry out their transformation and/or development operations. The methods presented are selected for their overall operational character, as well as for the links established with flood protection systems. However, there are other models or approaches (Barroca et al., 2013; The Rockefeller Foundation, 2015) aimed at the analysis or assessment of urban resilience from a more general point of view.

The methods used to study an urban system consist of a double characterization of its structural and functional aspects. The structural aspect corresponds to the spatial organization of the system whereas through functional analysis, it is essential to characterize the temporal phenomena, such as flows, exchanges, and feedbacks. The understanding of risk at the scale of a territory can therefore be engaged by successively defining the limits of the system, its environment, its components, and finally by associating functions (Serre et al., 2018). In an urban system, this method shows the interdependence of the networks and critical infrastructures of the studied area, and hence, the domino effects and impact chains (Bourlier et al., 2020).

Figure 58 shows the application of a functional analysis at the neighborhood level. It indicates contact and normal operational flow relationships between a neighborhood's individual components and its external environment factors.

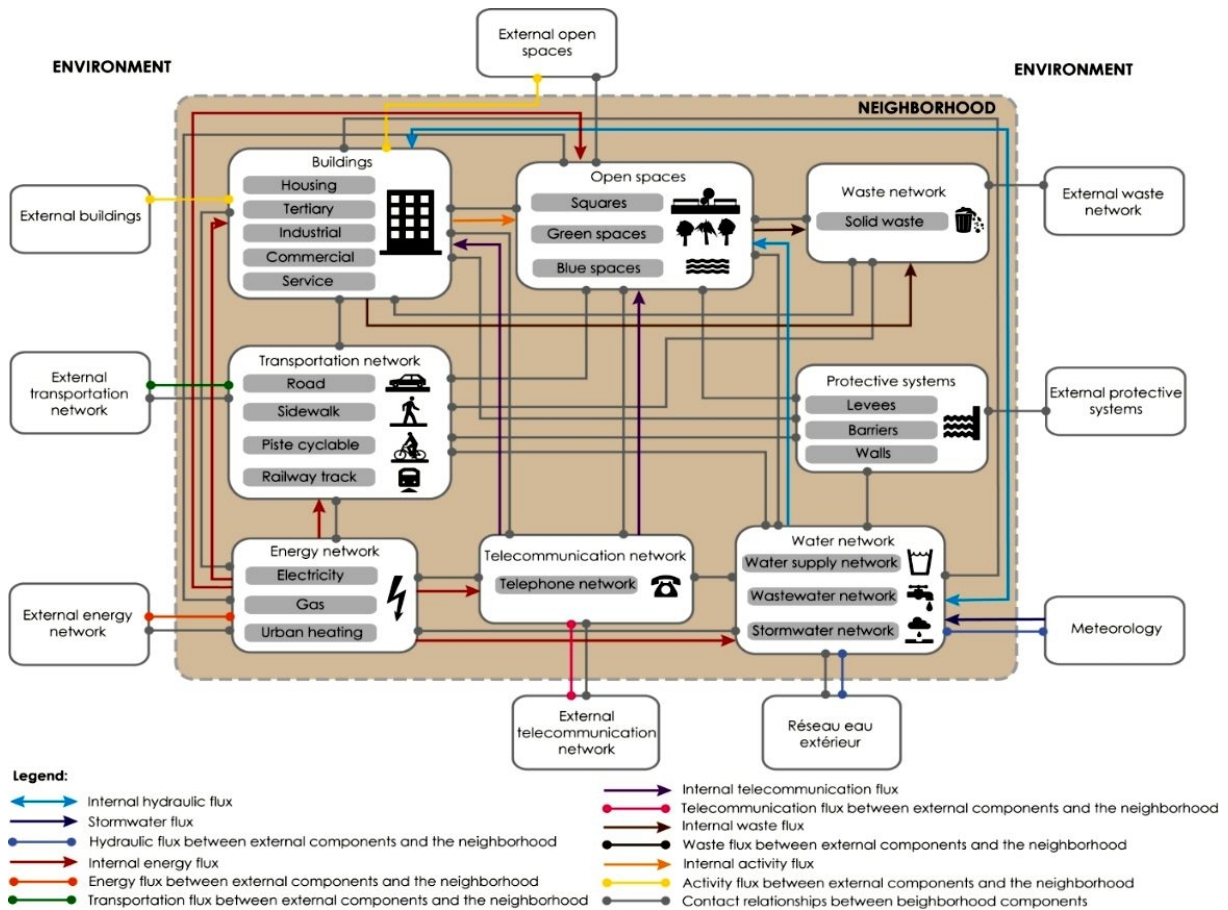


Figure 58: Functional diagram of a neighborhood system (Serre et al., 2018).

²³ Most of the work mentioned in this field was carried out at the Ecole des Ingénieurs de la Ville de Paris, in the research team led by Youssef Diab.

This type of analysis takes place in two stages:

- first, to formally distinguish the external and internal structures and within each of these two categories to identify sub-categories corresponding to the multiple functions. In terms of flood protection, the diagram thus identifies, in addition to internal structures (e. g., levees, storm barriers, and walls), other external structures with a protective role (for example, regulating structures on a river, or wetlands playing a buffering role). This operation to identify the boundary of a system and the relationships existing across the drawn border is typically a systemic approach;
- second, to represent the relationships between the internal components of the system. For example, the diagram shows the relationship between the internal protection system and the other components (including open spaces, buildings, water, transport, energy, and telecommunications networks). This step is also based on a systemic approach, supplemented if necessary by analytical approaches (for example, to assess the volumes of water that should be retained in low-vulnerability areas in order to avoid impacting vulnerable stakes, such as buildings and networks).

The predominance of the systems approach is marked by the focus of the study, which is mainly on the relationships between the elements, and avoids analyzing the resilience of a territory through a sectoral approach based on specializations (e. g., flood protection, energy and transport). It should be noted that analytical approaches can be efficient only if the limitations of the system – determining what is internal and what is external – have been well delineated and the internal organization of the system has been well described.

These analysis principles have been implemented by several authors. For example, by studying New Orleans' post-Katrina recovery, Balsells et al. (2012) concluded that a strong emphasis had been placed on improving the flood performance of buildings and protection systems, but other components and vital functions of the neighborhood had not been fully considered. Thus, in an urban system, the focus should in some cases be more on networks because high dependence and interdependence between some of the neighborhood components can become real issues during flooding. Further research on the effects of Hurricane Katrina by Heinzlef et al. (2019) showed that it is not only a natural hazard that occurred, but a natural hazard that impacted an urban world where anthropogenic activities are interdependent. The interdependence plays the role of a risk diffusion factor. And as Lhomme et al. (2013) stated, networks then act as vectors of risk propagation.

The methods of risk analysis have been adapted to take this reality into account. Thus risk analysis can be continued by studying failure mechanisms²⁴ for each function using the following methods:

- a functional analysis, which represents the components' interactions with each other and with the outside world as functional block diagrams. Figure 59 shows the analysis diagram for the energy network (which is particularly important because the normal operation of all other components depends on it); and
- a failure mode analysis²⁵, which is an inductive method for analyzing potential system failures. It focuses systematically on each component in the system to determine its failure modes, and their causes and effects (Balsells et al., 2012). At this stage, therefore, the analytical approaches appear to be relevant.

24 A failure mechanism is the relationship between causes and effects leading to the failure of the neighborhood.

25 A failure mode is the nonperformance of a function under system conditions: absence, loss, deterioration, or untimely operation of a function and the effects and consequences thereof.

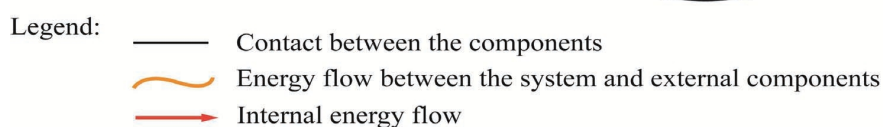
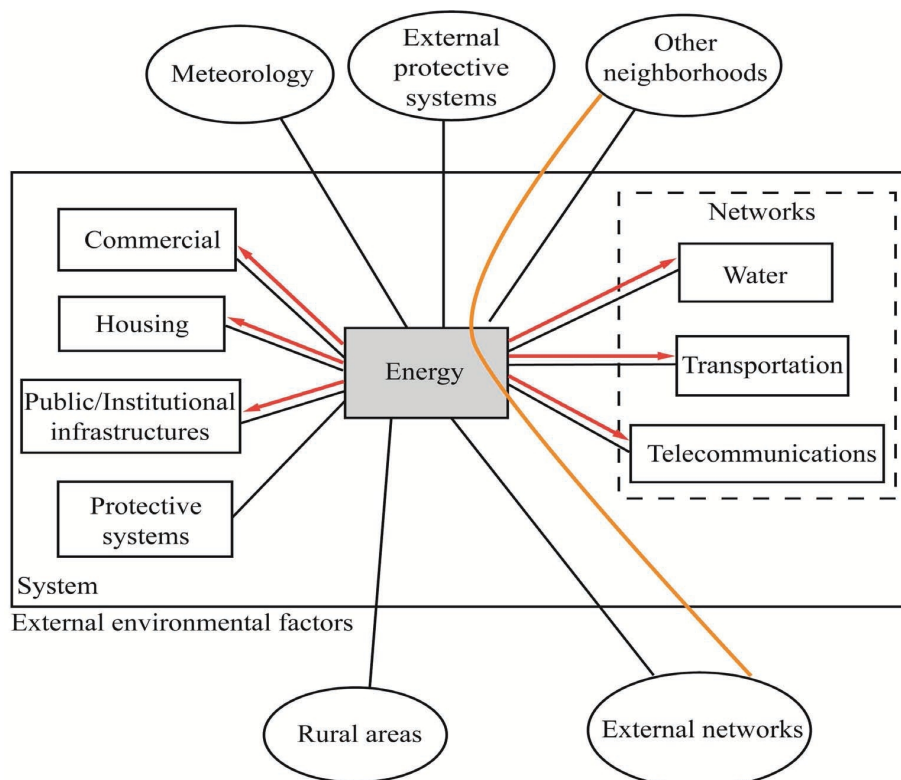


Figure 59: A functional block diagram of the energy network (Balsells et al., 2012).

As with the previous scheme, at this level, the relations within the territory in question (the neighborhood) and with the external environment of that territory are well identified, particularly in regards to the structures performing a protection function.

Although for Serre et al. (2018), a neighborhood is considered a social, economic, and physical/technical system, the above-mentioned authors generally placed more emphasis on the physical/technical dimension. In addition, other authors address :

- the human aspect of the management of the urban system. For example, Zevenbergen et al. (2015) presented a pragmatic screening procedure, referred to as a « Quick Scan methodology ». Its purpose is « to provide guidance for network operators and decision makers on identifying and rating those critical infrastructure networks and hot spot buildings that may be at risk from flooding, and assessing where intervention will be most feasible and cost-beneficial – the so-called quick wins »;
- social and urban aspects in addition to technical aspects. For example, Heinzlef et al. (2019) defined a territorial resilience index constructed on the basis of three indicators of urban, social, and technical resilience (see figure 60). Within this framework, urban resilience is defined by the proactive capacities that the urban system must develop in order to (re)act in the face of the disaster, thereby developing learning and anticipation skills.

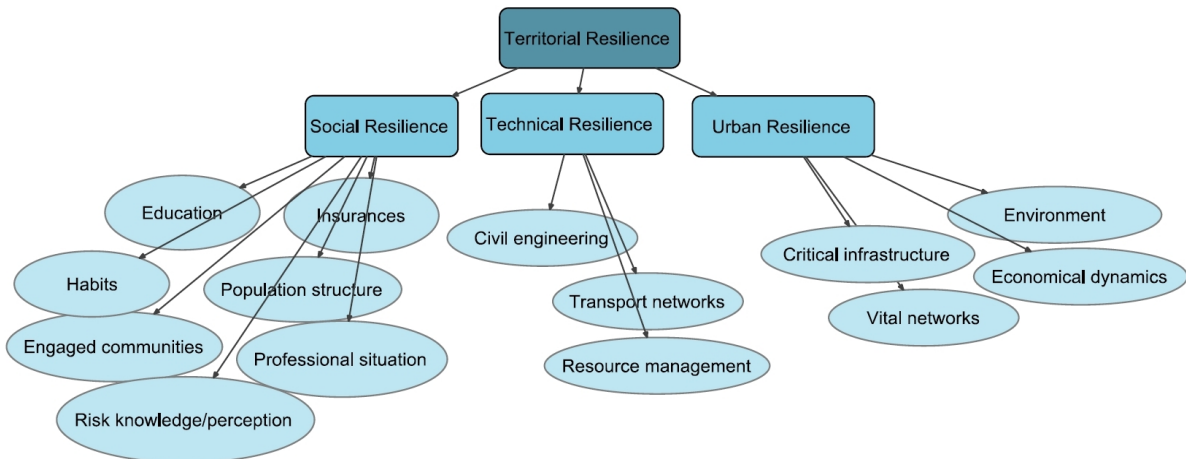


Figure 60: Resilient hierarchical index (Heinzlef et al., 2019).

In the methodology presented by Heinzlef et al. (2019), it is specified that social and urban resilience indicators are based on:

- social resilience variables such as population structure data (e. g., the age distribution of a population), professional situation, habits, and education level;
- urban resilience variables such as building characteristics (e. g., construction date), the location of critical infrastructures, and economic dynamics (including business creations and closures).

These quantitative variables were aggregated in order to map a social resilience indicator and an urban resilience indicator for a scenario « during crisis ». The local scale chosen, as well as this dissociation between variables and indicators, makes it possible to precisely analyze the components that accentuate or diminish resilience. This methodology was applied to the city of Avignon (France). Heinzlef et al. (2019) concluded that, in this city, social resilience is higher than urban resilience. This kind of results may lead to a change of mind, of consciousness of urban managers and policy makers and consequently to the definition of new strategic orientations.

Beyond the production of indicators, the interest of this research is mainly the extension of the investigations to many standardized socio-economic data, and the co-construction with urban managers of a tool that takes into account the needs at the community level, in addition to individual needs.

As a next step, the methodology presented by Heinzlef et al. (2019) could be transposed on a smaller scale, the scale of urban renewable projects, in order to guide decision-making. This future step would determine whether these new urban projects are contributing to the development of urban resilience, both at their own scale (the neighborhood level) and at the community level.

Risk assessment at the level of a protection system

Risk assessment approaches for protection systems are hybrid in nature. The diversity of natural structures and formations, as well as the diversity of the environments in which these components are placed, require the adoption of systemic approaches. However, the objectives of performance and rationalization of the resources employed, also force the adoption of analytical approaches. In particular, this is done in order to evaluate their reaction to various demands, or to determine quantitatively the human, financial, and material requirements for the management and adaptation of the protection system. Framing analytical approaches through systemic approaches is an ongoing challenge for managers of protection systems.

Among the components of these systems, levees are generally the most represented and most sensitive type of structure, particularly because of their considerable lengths and heterogeneity. This section will therefore focus on this type of work, without losing sight of the fact that protection systems potentially include other types of anthropogenic structures or natural features.

Risk assessment at the level of a protection system and at the level of the components of that system is critical to guide decision-making. Many research programs have been dedicated to risk assessment at the level of the protection system and at the level of the components of that system (CIRIA et al., 2013, chapter 5). Briefly, at the protection system level, risk assessment methods have two objectives:

- the evaluation in a leveed area of the residual risk associated with the levee system;
- the assignment of residual flood risk to levee segments in the leveed area, in particular to identify levee segments contributing most to flood risk.

At the scale of the structure, levee performance assessment is crucial since this process provides input for the evaluation of the residual risk in a leveed area. In addition, the results of the evaluation of the structures will determine, along with the results of the risk attribution at the scale of the system, the priorities for action: if the risk attributed to a structure is high, then the requirements on its structural state will also be high, which will give it a better ranking in the intervention priorities of the levee manager.

The main difficulty therefore lies in evaluating the performance of each component of the system. To meet this challenge, the concept of the fragility curve was explored. In the context of flood risk assessment, a fragility curve represents the probability of breaching of the defense given a set of loading conditions and therefore represents (along with the probability of overflowing and wave overtopping) part of the likelihood of water flowing from source to receptor in the SPRC model. This analytical approach can be either deterministic or probabilistic, as shown in figure 61. In the deterministic design, the assumption is made that the probability of failure is zero until the design load event is reached, at which point the probability switches to 1. In reality, as the load rises above the design condition, the probability of failure rises and only after considerable extra load has been applied does it actually approach 1. Similarly, there is a small but significant probability of failure at conditions below the design loading. This is what probabilistic approaches represent (Simm et al., 2008).

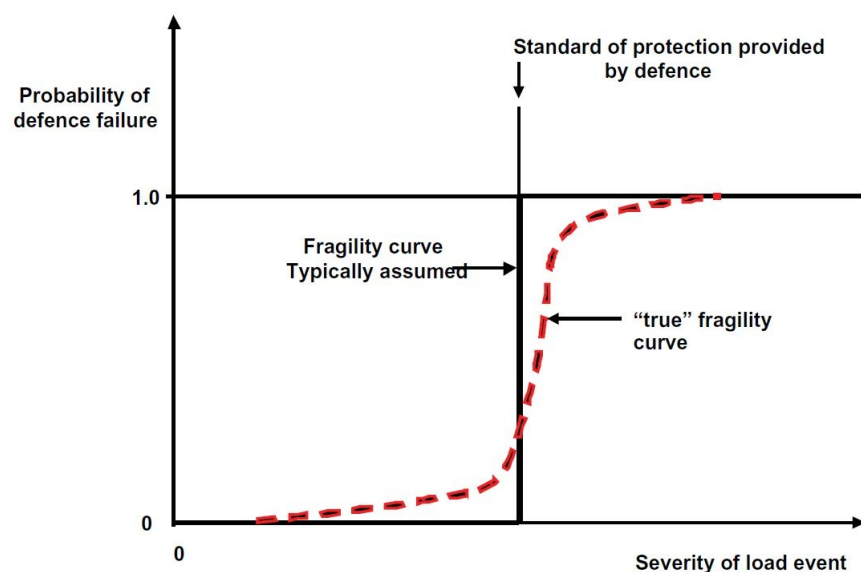


Figure 61: The true fragility curve compared with the deterministic design (Sayers and Meadowcroft, 2005).

While these modes of representation are interesting for understanding the complexity of levee behavior, the associated methods are difficult to apply due to the geotechnical heterogeneity, uncertainties about hydraulic loads, – even more so on coastlines exposed to waves –, and the multiple failure modes. In fact, since levees commonly extend over several tens or even hundreds of kilometers, their management can benefit from computer assistance in terms of data organization, management, and representation (spatial representation and evolution over time), but will always require expertise for their diagnosis. For example, the system designed by Serre et al. (2009) has two components:

- a geographic information system (GIS) application that allows collecting data necessary for managing a levee portfolio;
- a Spatial Decision Support System (SDSS) which uses performance indicators to assist levee managers in prioritizing maintenance activities.

This type of operating mode led Hathout et al. (2019) to question the validity of human judgment. These authors presented approaches of elicitation, calibration and aggregation of expert opinions to evaluate the reliability of river levees. Applying the proposed weighting and aggregation procedure reduces variability in the probability of failure estimate and provides a better probabilistic distribution of aggregated expert opinion than that of individual expert opinions.

This review of the state of the art shows that it is dangerous to seek « automation » of risk assessment at the level of a structure and, *a fortiori*, at the level of a protection system. The methods of evaluation which combine human expertise and the advantages of data management by computer means should indeed be sought. Since each structure is unique, monitoring its behavior over time is essential, especially during major events through feedback. However, it should be considered in the application of this principle that in a future affected by multiple changes, decisions based solely on past events will no longer necessarily be relevant and that more anticipation will be required in the application of risk analysis methods and also in the definition of adaptation strategies.

2.5 Methods for defining adaptation strategies for territories and their protection systems

As a follow-up to the study of methods for understanding risk, this section deals with methods for defining adaptation strategies for territories and their protection systems.

Drafting an adaptation policy requires thorough insight into the precise type and magnitude of future problems, the possibilities to counteract or reduce these in terms of strategic alternatives composed of physical measures and policy instruments. These strategic alternatives must be evaluated on performance, cost and side effects and opportunity criteria (Klijn et al., 2015).

The methods used to fulfill this objective may be based on the SES and CAS concepts applied to territories and their protection systems positioned within a hierarchy comprising, at the lower level, the components of a protection system, and at higher levels, the region and the planet. As such, scenario planning and the recent concept of Climate Resilient Development Pathways (CRDP) deserve to be highlighted because they represent methods of governance and management of SESs essential to operationalize the concepts of adaptability and transformability. This section is devoted to the study of these methods and their conditions of application.

In this section, if the territory and its protection system are considered as separate (though nested) SESs, they will no longer be treated separately since the definition of adaptation strategies generally requires joint consideration.

2.5.1 Scenario planning and pathways for building resilience to climate change

The definition of strategies for the adaptation and *a fortiori* the transformation of SESs can be based on the establishment of scenarios. Scenario planning is a systemic method for thinking creatively about possible complex and uncertain futures. The central idea of scenario planning is to consider a variety of possible futures that include many of the important uncertainties in the system rather than focusing on the accurate prediction of a single outcome (Peterson et al., 2003).

Scenarios can help overcome fundamental problems about transformation by organizing thinking in a coherent way. With so many changes happening simultaneously, the very complexity of the situation can become a barrier to understanding and action. The scenarios can organize information about transformation in a comprehensible way that facilitates discussion and action (Walker et al., 2004).

Peterson et al. (2003) stated that scenario planning is a process of envisioning plausible transformations and bringing them into social decision processes.

The definition of adaptation strategies largely depends on the dynamic nature of the SESs, which requires considering several time horizons and assessing uncertainties. The study of several scenarios helps to achieve these two objectives. To this end, it is possible to use general data, although transposition across territories is often difficult:

- for climate change scenarios, the use of climate model projections relative to RCPs (Moss et al., 2008; Moss et al., 2010; van Vuuren et al., 2011) is recommended. However, the further down the chain of effects, the larger the uncertainties about the degree of an effect (Haasnoot, 2013), and sometimes even about the direction. Moreover, when climate changes beyond the range historically observed, unforeseen shifts may occur that complicate the downscaling of global climate scenarios to the national or regional level (Klijn et al., 2015);
- for SSPs (O'Neill et al., 2017), Klijn et al. (2015) stated that the autonomous developments in the socio-economic subsystem are even more uncertain than climate change scenarios because of the global scale of economic developments and their dependency on very dynamic geo-political changes. Nevertheless, for demographic, economic, and land-use developments, a scenario approach may be applied.

The definition of scenarios must follow certain principles of robustness and flexibility in relation to environmental changes, including those of Van Rhee (2012), translated from the Dutch by Klijn et al. (2015), which are the following :

- short-term decisions should contribute to long-term objectives;
- the search for adaptation pathways should have successive decision points in time, rather than aim for a final situation at some point in the future to allow for adaptation over time;
- seek and value flexibility in individual measures and comprehensive strategies in order to allow for acceleration or deceleration and to prevent regret of underperformance or overinvestment;
- aim for synergies with goals and development initiatives by other public and private parties (for example, major players in industry and finance), which reduces the likelihood of regret because of the other benefits achieved.

The use of scenarios may also involve analytical techniques, including:

- the policy tipping points (Kwadijk et al., 2010). A tipping point is reached if the magnitude of change is such that the current management strategy can no longer meet its objectives. Beyond the tipping point, an alternative adaptive strategy is needed. By applying this approach, the following basic questions of decision makers are answered: *what* are the first issues that we will face as a result of climate change and *when* can we expect this? In the west of the Netherlands, the results show, for instance, that climate change and the RSL rise are more likely to cause a threat to the fresh water supply than flooding; and
- the adaptation pathways (Haasnoot et al., 2013). This method relates to an analytical approach for exploring and sequencing a set of possible actions based on alternative external developments over time. The authors tested this concept by producing an adaptive plan for long-term water management of the Rhine Delta in the Netherlands that takes into account the deep uncertainties about the future arising from social, political, technological, economic, and climate changes. Figure 62 provides a representation of this approach.

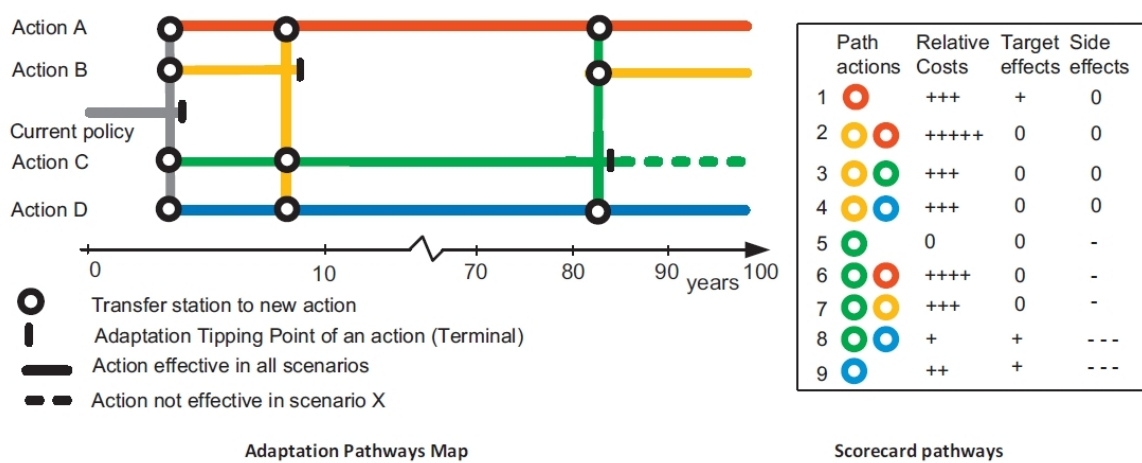


Figure 62: An example of an adaptation pathway map (left) and a scorecard presenting the costs and benefits of the 9 possible pathways presented in the map (right). The colors in the scorecard refer to the actions A (red), B (orange), C (green), and D (blue) (Haasnoot et al., 2013).

The following comments are useful to understand figure 62: In the map, starting from the current situation, the targets are no longer met after four years, yielding four options. Actions A and D (the red and blue lines, respectively) are projected to achieve the targets for the next 100 years in all climate scenarios. If Action B is chosen after the first four years, a tipping point is reached within about five years; a shift to one of the other three actions will then be needed to achieve the targets (follow the orange lines). If Action C is chosen after the first four years, a shift to Action A, B, or D will be needed in the case of Scenario X (follow the solid green lines). In all other scenarios, the targets will be achieved for the next 100 years (follow the dashed green line).

Both the policy tipping point approach and the adaptation pathways can be integrated into statutory land use or spatial planning provisions to formalize these decisions and enable effective implementation by relevant governing authorities (IPCC, 2019). For example, they are being applied in the Netherlands' Delta Programme, specifically for flood risk management and freshwater resources management (Klijn et al., 2015).

To address the major challenge of climate change adaptation and in order to take into account the Sustainable Development and Poverty Eradication Goals, it is also possible to use the concept of CRDP, represented in figure 63 (Kainuma et al., 2018; Roy et al., 2018).

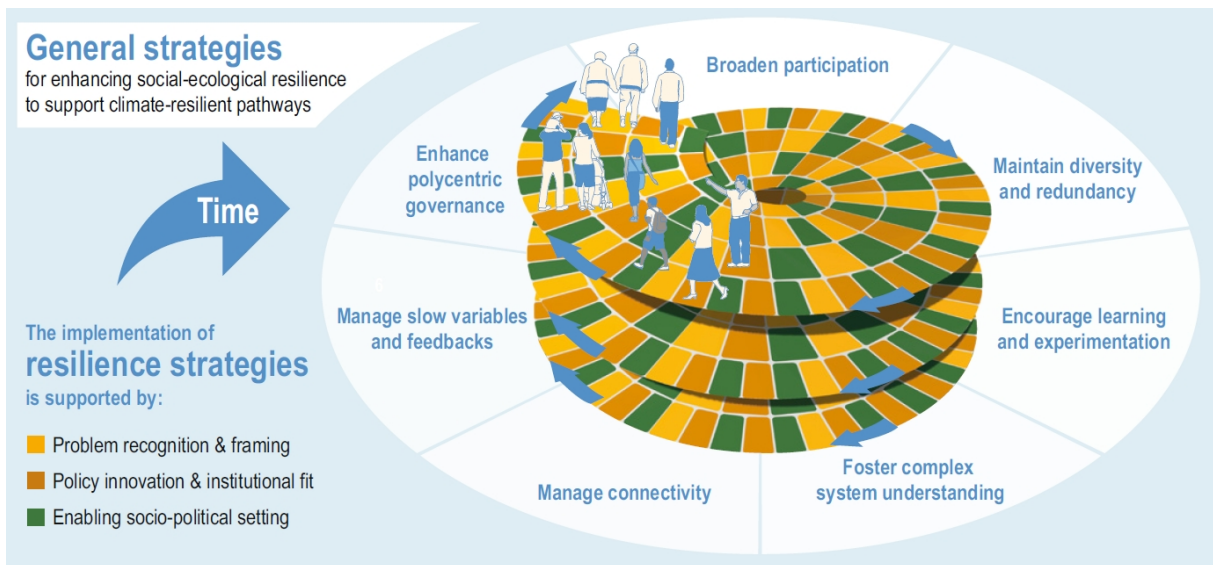


Figure 63: Climate-resilient development pathway. From Hock, R., G. Rasul, C. Adler, B. Cáceres, S. Gruber, Y. Hirabayashi, M. Jackson, A. Kääh, S. Kang, S. Kutuzov, Al. Milner, U. Molau, S. Morin, B. Orlove, and H. Steltzer. In: IPCC, 2019, figure CB2.2.

CRDPs are increasingly being explored as an approach for combining scientific assessments, stakeholder participation, and forward-looking development planning, acknowledging that pursuing CRDPs is not only a technical challenge of risk management but also a social and political process (Roy et al., 2018). This implies an organization of the process by the institutions in charge of the governance of the territories. CRDPs aim to establish narratives of hope and opportunity that can extend beyond risk reduction and coping – in particular integrating the fight against climate change (Amundsen et al., 2018) – and are critical in driving motivation, creative thinking and behavioral changes in response to climate change (Myers et al., 2012; Prescott and Logan, 2018).

The definition of the scenarios should be based on general strategies for enhancing social-ecological resilience. These principles, on which CRDPs are based, were the subject of an integrative presentation by Biggs et al. (2012) on the basis of a review of the scientific literature (see figure 64).

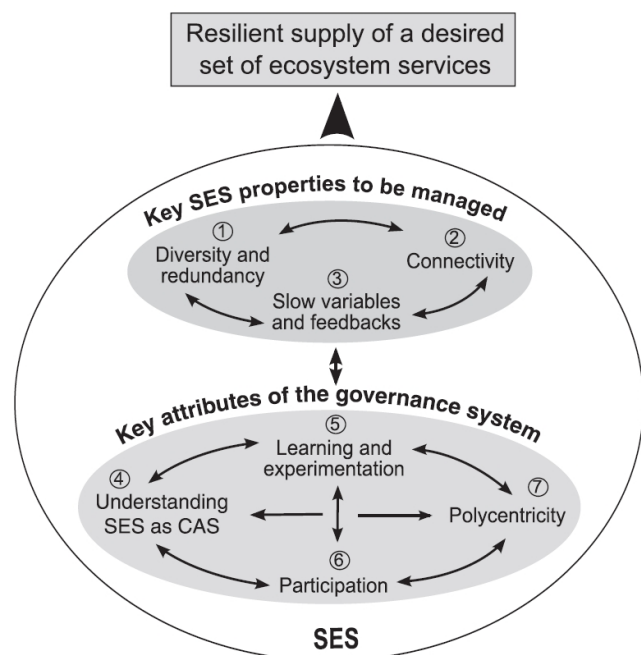


Figure 64: The seven principles for managing the resilience of an SES (Biggs et al., 2012).

The principles of resilience management fall into two levels:

- principles that relate to generic SES properties to be managed; and
- principles that relate to key attributes of SESs governance.

In this chapter, which deals with methods for defining strategies, the study will focus on the key attributes of SESs governance. In the next chapter, the study will focus more on the generic SES properties. There are nevertheless links between these two groups and a clear separation of the two areas is not realistic.

As a preliminary to a more detailed analysis, the four governance principles identified by Biggs et al. (2012) can be understood as follows:

- « understanding an SES as a CAS » involves a paradigm shift (which was already noticeable in the study of methods to understand risk). This paradigm shift in turn implies a change in the mode of governance;
- « Learning and Experimentation », « Participation » and « Polycentricity » are three principles often grouped under the same term « adaptive co-management » since the research of Ruitenbeek and Cartier (2001).

The methods associated with these governance principles will therefore be studied under these two headings. Since the question of the evolution of governance is decisive in the management of change, this point will be studied more extensively in the case of the transformation of a system.

2.5.2 Understanding an SES as a CAS

A territory subject to coastal flooding should be considered a CAS and the issue of protection against this risk can, as such, be dealt with in conjunction with other issues including freshwater management. In the context of adaptation to the effects of climate change, this is particularly relevant when one of the main threats to coastal territories is the salinization of freshwater bodies and soils.

Figure 65 shows how the evolution of mental perceptions and representations on this subject of fresh water, through the transition from an analytical to a systemic way of thinking, may result in a change in governance and improved flood resilience. The standard perception of freshwater management leads to inflexible, and often ineffective, command-and-control approaches, whereas accounting for ecological complexity opens avenues to adaptability, which builds better resilience to events such as flooding (Moberg and Galaz, 2005). One such pathway may be to assess the role of wetlands in flood mitigation and to anticipate across several scales (including those of the region and of the territory) increases in capacity that may be required in response to climate change (*e. g.*, changes in precipitation patterns and changes in thermal regulation by glaciers) and land-use changes (*e. g.*, increases in runoff caused by deforestation and urbanization).

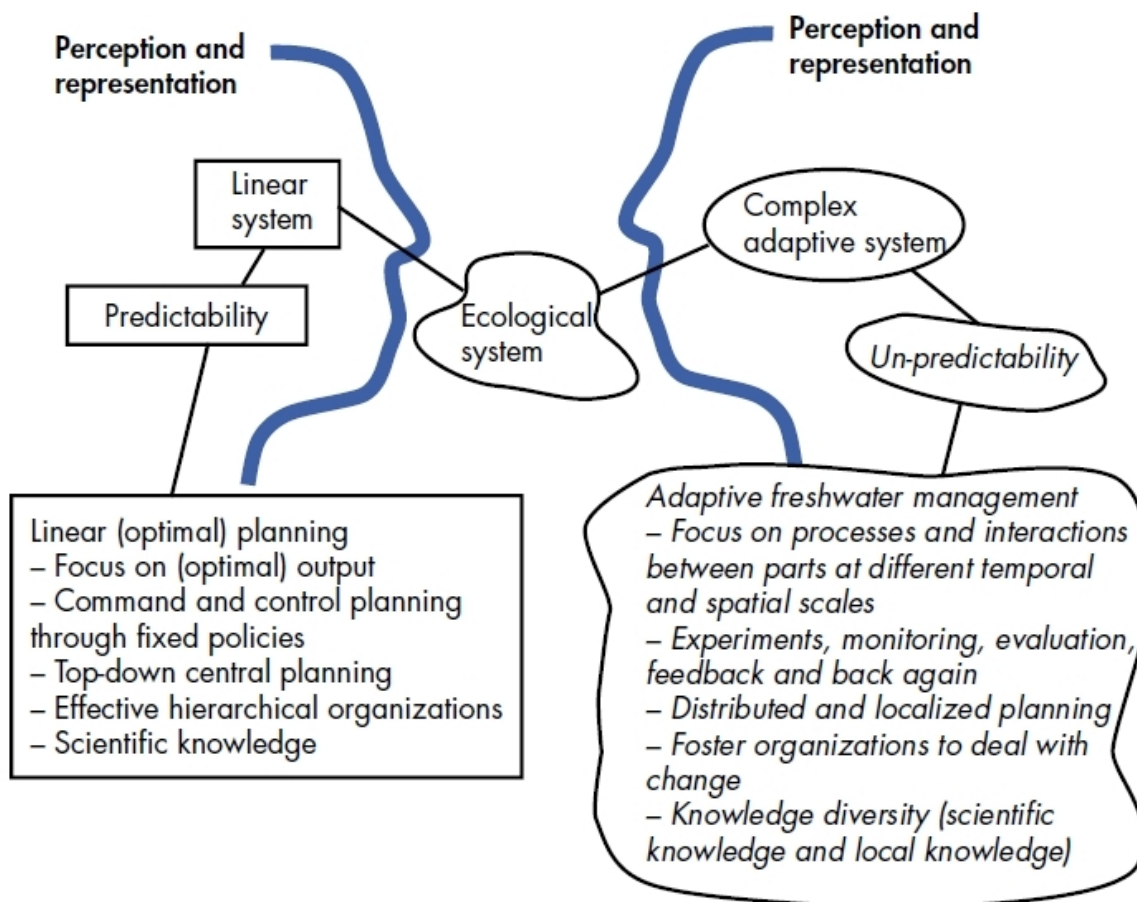


Figure 65: A comparison of analytical thinking and systemic thinking (Moberg and Galaz, 2005). Illustration by Henrik Ernstson.

The positions expressed by Moberg and Galaz (2005) show that the principles previously set out for understanding risk (e. g., analyses at several spatio-temporal scales, utilization of several scientific disciplines, combination of systemic and analytical approaches, etc.) are fundamental for defining strategies (the governance process) and their implementation (the management process). The additional principles recommended by these authors relate to planning arrangements and the evolution of governance arrangements.

The multidisciplinary study of coastal flood protection strategies shows that socio-economic constraints will limit the possibilities offered by the technique. The IPCC (2019) forecasts are as follows:

- technical limits to hard protection are expected to be reached under high emission scenarios (RCP8.5) beyond the year 2100 and biophysical limits (for example, increased temperature and ocean acidification for corals) to ecosystem-based adaptation may arise during the 21st century;
- but economic and social barriers arise well before the end of the century.

As an example of an integrated approach, in the Netherlands, the Delta Programme is being scientifically supported not only by dedicated studies, but also by the national research program « Knowledge for Climate (KfC) », which runs in parallel. This addresses the majority of adaptation challenges related to climate change, on both floods and droughts, for urban and countryside

environments and functions, and integrating various scientific fields, from climatology to decision support and governance (Klijn et al., 2015).

2.5.3 Applying the principles of adaptive co-management

Adaptive co-management intends to bridge two approaches (see figure 64):

- adaptive management, which focuses on « learning by doing » as a strategy to deal with uncertainty in CASs (which relates to the principle of « learning and experimentation » in the framework established by Biggs et al. (2012)); and
- co-management, which builds on the idea of participatory resource management and community–government linkages (which relates to the principles of « participation » and « polycentricity » in the framework established by Biggs et al. (2012)).

Hence, adaptive co-management combines « the iterative learning dimension of adaptive management and the linkage dimension of collaborative management in which rights and responsibilities are jointly shared » (Armitage et al., 2007).

Learning is the first principle of adaptive co-management and can be defined as the process of modifying existing or acquiring new knowledge, behaviors, skills, values, or preferences (Biggs et al., 2012). Although learning is inherently at the individual level, in the framework of risk prevention policies, it should also go beyond the individual to become situated within wider groups, organizations, or communities of practice, where it is referred to as « social learning » (Reed et al., 2010).

Participation is a key enabler of social learning (Biggs et al., 2012). By means of experiments and monitoring carried out on the right scale, the aim to gradually reach appropriate decisions can be achieved. In this process, the relations between the stakeholders are decisive, therefore, this process can only be undertaken in a climate of trust and if the community has sufficient social capital²⁶.

A positive feedback is reported by Sendzimir et al. (2007) in the river domain: the authors found that learning processes led to a paradigm shift in how to manage the Tisza River basin in Europe—from a conventional command-and-control paradigm to one based on living with water. This encompasses integrated solutions for a multifunctional landscape that combines flood protection with restoration of ecological conditions in rivers, which contrasts with earlier engineering-based approaches (see figure 66).

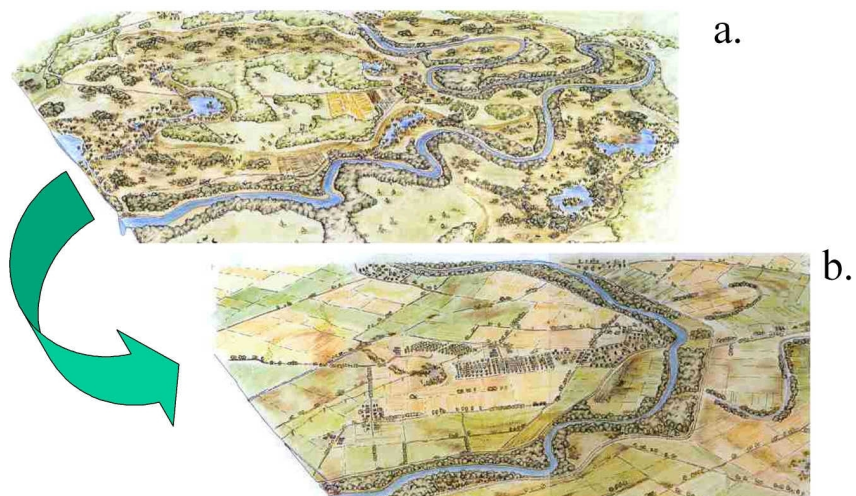


Figure 66: The artist's interpretation of different landscape mosaic patterns in the Tisza River floodplain both pre- (a) and post- (b) execution of the original Vasarhelyi River engineering plan in 1871 (from Siposs and Kiss, 2002, WWF Hungary).

²⁶ Bourdieu (1980) defines social capital as « the set of actual or potential resources that are linked to the possession of a durable network of more or less institutionalized relationships of inter-knowledge and inter-recognition or, in other words, to belonging to a group ».

Although experimentation and monitoring have often been carried out by specialist agencies and universities, there is growing recognition of the importance of broader participation in the learning process by all parties involved in SES governance and management (Danielsen et al., 2005). The participatory nature of adaptive co-management enables sharing and reflecting on experiences, ideas, and values with others, which builds trust and relationships and facilitates social learning as well as collective action (Olsson et al., 2004). Participatory learning processes can help actors learn about each other's mental models, which builds social capital, in turn supporting institutional change and conflict resolution (Biggs et al., 2011).

For « coastal territory » SESs, the utilization of an expanded circle of actors can be sought in different ways, for example:

- in the definition of town planning rules, a consultation phase may involve all stakeholders in the decision-making process. Perherin (2017) described in detail how the debate between the actors can be organized around the production of hazard maps carried out as part of the elaboration of coastal risk prevention plans. Greater openness to multiple stakeholders would allow not only a better appropriation of knowledge on hazards by the community at that stage, but it would also promote the integration of the issue of protection against coastal risks into territorial public action;
- citizen participation in data collection and analysis can reduce the vulnerability of urban areas to rainfall flooding, as shown by the European FloodCitiSense research program (McCrorry and Veeckman, 2017), which had study sites at Birmingham, Brussels, and Rotterdam. The mission of this program was to develop an urban pluvial flood warning service, which was co-created with and for citizens and city authorities. The project aimed to integrate crowd-sourced hydrological data of local stakeholders through a citizen science approach, making use of low-cost sensors and web-based technologies. It proposed an integrated and co-operative approach where citizens are no longer considered passive, potential victims of flooding, but are engaged and active contributors in the process of flood monitoring and mapping. This project followed the guidelines of the European Flood Risk Directive (Directive 2007/60/EC) that encourages participation of local stakeholders in the development of flood risk management plans, in which citizens are expected to take active responsibility at the beginning of the process, rather than passively receiving a service;
- in urban flood management strategies, the use of flood risk as a design parameter for spatial planning increases flood risk awareness and improves the development of practical strategies to cope with and communicate the residual risk. Following this principle, an applied scientific research project was executed by a learning network nested across multiple scale levels, from the national level to the local planning and street/building level in the city of Dordrecht (Netherlands). Local, regional, and national authorities, a water board, a developer, a housing corporation, and two research institutes participated in the project. The methods and multiple benefits of this project are further presented by Zevenbergen et al. (2008).

Methods are therefore available to involve stakeholders more broadly in the definition and implementation of strategies at the territorial level. In any case, this involves setting up tools and locations for sharing knowledge and projects (Cerema, 2019a).

However, care must be taken when it comes to the protection structures themselves, since their management requires very specific skills at each stage of their life cycle. Recommendations on the management of SESs cannot therefore be applied to levee systems without discernment. As Stringer et al. (2006) pointed out, participants and their contributions are context-specific and need to be continually revised throughout the policy process or adaptive management cycle. A nuanced understanding of who participates, under what conditions participation is appropriate, and how participation takes place is therefore essential.

2.5.4 Implications of transformational objectives on governance modes

The evolution of modes of governance is a necessary condition for change when a profound transformation is envisaged. This can be supported by three examples:

- in China, addressing the issue of urban pluvial flooding and managing urban stormwater, Jiang et al. (2018) concluded that the « Sponge cities » initiative can be an effective approach only if the country commits to appropriate technical, governance, financial, and organizational measures to effectively address the challenges for policy implementation;
- in Australia, by studying urban planning processes that have led to adaptation to sea-level rise in Lakes Entrance in Victoria, Hurlimann et al. (2014) concluded that to be sustainable, urban planning needs to (i) facilitate local ownership of adaptation responses, (ii) build collective action within local communities and between local communities, as well as between different branches and levels of government, and (iii) be fair in its application in space and time. The authors added that addressing these social dimensions of adaptation takes time, but they are a *sine qua non* of sustainable adaptation to RSL rise;
- in Italy, the need to accompany the paradigm shift of a change in governance is also pointed out in the case study of the Lambro river basin (in the metropolitan city of Milan) by Vitale et al. (2020). In this territory, whereas the discourse of engineering resilience emphasizes the use of flood protection infrastructures, the discourses of social-ecological resilience advocate river restoration and spatial strategies to reduce flood risk. Whereas bottom-up initiatives try to foster social-ecological resilience, the authors demonstrated that the engineering resilience discourse still dominates because national policies and funds are geared towards hard infrastructure measures.

In the three cases, it appears that the change in governance should also be accompanied by institutional changes and administrative reorganization. The evolution of financial channels is also explicit in the conclusions for two of these three case studies.

The governance implications of the adaptive co-management principles should therefore be well understood methodologically. Olsson et al. (2004) showed that the self-organizing process of adaptive co-management development, facilitated by rules and incentives of higher levels, has the potential to expand desirable stability domains of a region and make SESs more resistant to change. The European Flood Risk Directive (Directive 2007/60/EC) is in line with this principle by encouraging the participation of local stakeholders in the development of flood risk management plans. Its application has indeed led to an institutional and administrative restructuring of governance, by developing more integrated visions of land use planning by combining the issues of risk prevention and management of aquatic environments. The refocusing of institutions on the geographical perimeters of emerging risk (e. g., river basins) is another notable advance (Cerema, 2020). The advantages (and potential disadvantages) of this type of polycentric system, as well as the positive (and potentially negative) effects that can be induced by the redundancy and diversity of decision centres and the connectivity between them, are described in more detail by Biggs et al. (2012).

While a review of the modes of governance can be initiated by a top-down process as is the case for the implementation of the European directive, which can lead to real progress, this observation should not, however, obscure two aspects:

- all regions of the world do not benefit from a national or supra-national organization that encourages changes in the modes of governance. It is therefore necessary to clarify how governance can be improved through bottom-up initiatives and how this change can be initiated. To initiate a change in governance, Temeer et al. (2017) proposed a methodological framework. Beyond the dichotomy of « transformational change » and « incremental change », they conceptualized « continuous transformational change ». Resulting intervention strategies include (i) providing basic conditions for enabling small in-depth wins; (ii) amplifying small wins

through sensemaking, coupling, and integrating; and (iii) unblocking stagnations by confronting social and cognitive fixations with counterintuitive interventions. These interventions necessitate a modest leadership;

- an evolution of SES governance towards adaptive co-management should be accompanied by an assessment of the effectiveness of the change and the efficiency of the new mode of governance, in particular to justify the resources invested to achieve this change. To this end, Cundill and Fabricius (2010) identified system attributes and key variables that could form the basis for monitoring the governance dimension of adaptive co-management : social capital, adaptive capacity, self-organization, and operational conditions for adaptive governance (access to information, conflict-resolution mechanisms, effective rule compliance and enforcement, sufficient infrastructure, people and organizations prepared for change). Their results suggest that creating the conditions that facilitate self-organization, and particularly cross-scale institutional linkages, is the major challenge facing attempts to initiate adaptive co-management (as suggested by Olsson et al. (2004)). Factors requiring greater attention include access to long-term funding for adaptive decision making, and access to reliable information about changes in natural resources and legal options for the formation of decision-making bodies. Although their work focuses on the management of natural resources, their conclusions nevertheless appear to be broadly consistent with the recommendations previously identified in the field of flood protection.

2.6 Synthesis and conclusion

The adaptation of protection systems through the development of their resilience is considered with significantly different approaches depending on the type of actor :

- levee system specialists apply the concept of resilience directly to the protection system considered as a technical system with the main objective of maintaining protection performance through monitoring actions, preservation, or reinforcement of the components' state. Maintenance (monitoring and maintenance) or investment (reinforcement and rehabilitation) activities are integrated into short cycles, on the order of a year and a decade, respectively. The corresponding strategies are defined with reference to time horizons which therefore do not cover the long-term developments;
- planning specialists apply the concept of resilience to the territory (considered as an SES with a levee system as a subsystem) with the objectives of fostering sustainable development and reducing disaster risk. Planning activities are conducive to the development of longer-term strategies that incorporate changes related to climate change or coastal urbanization. However, without sufficient knowledge of the field of protection systems, planning activities may overestimate the protection opportunities offered by these systems and underestimate the risks associated with their use.

To address these differences, a common conceptual framework is proposed: territories and their protection systems are considered to be nested social-ecological systems. The evolutions of these systems and the interactions existing between them can be studied using models of basins of attraction and adaptive cycles.

This conceptual framework provides an opportunity to put into perspective methods for understanding risk (SES observation and analysis) and for defining adaptation strategies, thus seeking convergence between approaches relative to territories and approaches relative to protection systems.

From the study of the methods, it appears that the observation and analysis of SESs should be carried out first as part of a systemic approach taking into account the possibility of multiple risks. After this global analysis, which integrates the multiple issues of the territory and is inclusive with regard to its actors, analytical approaches can be led, dedicated to specific points relating to quantitative evaluations and dimensioning.

Understanding the risks in a territory provides a basis on which adaptation scenarios can be built. Analytical techniques exist to decide over time between the different options offered by these scenarios. Furthermore, the idea that improving resilience increases the chances of sustainable development in a changing and uncertain environment is reflected in the relatively recent concept of the CRDP. With this perspective, risk management should not be seen as a constraint only, but also as an opportunity for sustainable development.

Regardless of the projection technique chosen (scenario planning or CRDP), the SESs should be considered as CASs which should lead to the emphasis on the substantial uncertainties surrounding these systems, and therefore, the need to continually learn and experiment, and adaptively manage uncertainty, disturbance, and surprise rather than attempt to eliminate them. This principle, coupled with that of participatory and inclusive management, forms the basis of a recommended mode of governance, which includes engaging transformational forms of adaptation: adaptive co-management. The transition to this mode of governance requires institutional, administrative, and financial changes. This transition is adapted depending on whether a structured organization exists at regional, national, or supra-national levels, or whether it is limited to the local level alone. Top-down or bottom-up change methodologies have been developed to cover the different scenarios. Nevertheless, in relation to the study of methods to understand risk, it appears that risk management results from two complementary processes:

- the definition of risk prevention policies results in laws and regulations whose formalism corresponds mainly to analytical approaches because of the impossibility to assess the specifics of each situation;
- the behavior of the actors on site who identify the real situation and react appropriately through their ability to adapt. These modes of risk protection correspond mainly to systemic approaches.

Safety on site is thus ultimately ensured first by a general framework and second by reactions to particular situations, the study of the latter by feedback from experience being essential to adjust the general framework. This justifies the importance of participatory and collaborative approaches grouped under the term adaptive co-management.

Adaptive co-management is a mode of governance that can allow bringing together the community that benefits from the protection systems and the managers of those systems. However, since protection systems require specialized expertise, their roles are not interchangeable: the decision-making processes must precisely identify the contributions of each actor.

3 STRATEGIES FOR ADAPTING PROTECTION SYSTEMS

Coastal territories and their flood protection systems face multiple pressures from climate change (rising sea levels, increasing extreme meteo-oceanic events, changing precipitation, and stream hydrological regimes) and other local anthropogenic disturbances (deterioration or destruction of natural features and ecosystems contributing to the protection and extraction of water or hydrocarbons causing subsidence, modification of sedimentary transit, etc.). The scientific literature presents many recommendations on adaptation strategies, a good synthesis of which is provided by the IPCC report (2019). The purpose of this chapter is to produce a critical analysis of these recommendations by focusing on the coastal flood protection system, considered as an SES embedded within a higher-level SES (the territory). In this context, a system of protection evolves under the double constraint of a natural environment and a built environment (as social and institutional constraints have been addressed in the strategy definition methods, they will not be treated specifically, but will be treated in a related manner).

However, because on the one hand, the increase in sea level triggers multiple adverse effects and often appears, rightly or wrongly, as the most important factor in the appearance of risk and on the other hand, the monitoring of a single parameter has a practical advantage for the establishment and implementation of a strategy, the adaptation options in response to this factor alone have a high visibility in the scientific literature. It is therefore necessary to examine how these adaptation options – corresponding to an analytical approach, since the consequences produced by a single factor are sought –, can be articulated with a systemic approach considering territories and their protection systems as CASs. The objective of this « scoping » is to identify the benefits that the analytical approach is likely to provide, while at the same time warning against errors that it may produce.

In order to carry out this study, a critical analysis of the literature is undertaken through the following steps:

- a first section identifies studies of the evolution of coastal flooding stakes and risks on a global scale, as well as opportunities to protect against these risks. Although at this macroscopic scale it is impossible to consider the singularity and complexity of the territories, certain lessons can be drawn from these studies, in particular with regard to the identification of the vulnerable stakes and the benefits that would result from protection in cases where protection could be implemented;
- a second section looks at how to apply the principles of managing CASs facing multiple changes in a territory subject to the risk of coastal flooding. Considering that a protection system is an SES embedded in a territorial level SES, this section also clarifies the relationship of a protection system with the natural environment and the built environment;
- a third section sets out, in a comprehensive approach, the adaptation options corresponding to both the objectives of combating climate change and protecting against its effects and the effects of other environmental disturbances;
- a fourth section presents the modes of adaptation resulting from simplified approaches based on taking into account mainly the increase of the RSL, and identifies the benefits as well as the biases induced by these approaches;
- a fifth section provides a complementary analysis to the global and simplified approaches, focusing on key aspects of the adaptation of protection systems, such as the assessment of their performance, and estimation of their long-term costs and the risk of maladaptation;
- a final section summarizes some recommendations for articulating global systemic approaches and simplified approaches based on the complementary insights provided at the end of the chapter.

3.1 Stakes and adaptation strategies on a global scale

Determining risk management strategies, in particular when deciding whether to set up or maintain a protection system, requires a great deal of decisive information, which covers both hazards, the territory, and the populations living there. While global studies cannot consider all of these characteristics, they can nevertheless shed some light on the territories exposed and the demographic and economic issues involved. It is thus possible to assess the overall economic and social risks, as well as the expected benefits of the protection strategies.

3.1.1 Overview

The studies of the stakes at risk of coastal flooding are based on the assumption that risk evolves mainly as a result of increases in the RSL. Considering low-lying coastal areas categorized as the low elevation coastal zone (LECZ, defined by McGranahan et al. (2007), using elevation data from National Geophysical Data Center (1999)), the IPCC (2019) established a comprehensive census by distinguishing:

- islands with a maximum elevation of 10 m above sea level (Weigelt et al., 2013);
- small Island Developing States (SIDS);
- coastal megacities (cities with more than 10 million inhabitants, within 100 km from the coast, and with a maximum of 50 m above sea level; Pelling and Blackburn, 2013; UN-DESA, 2018); and
- deltas (Tessler et al., 2015).

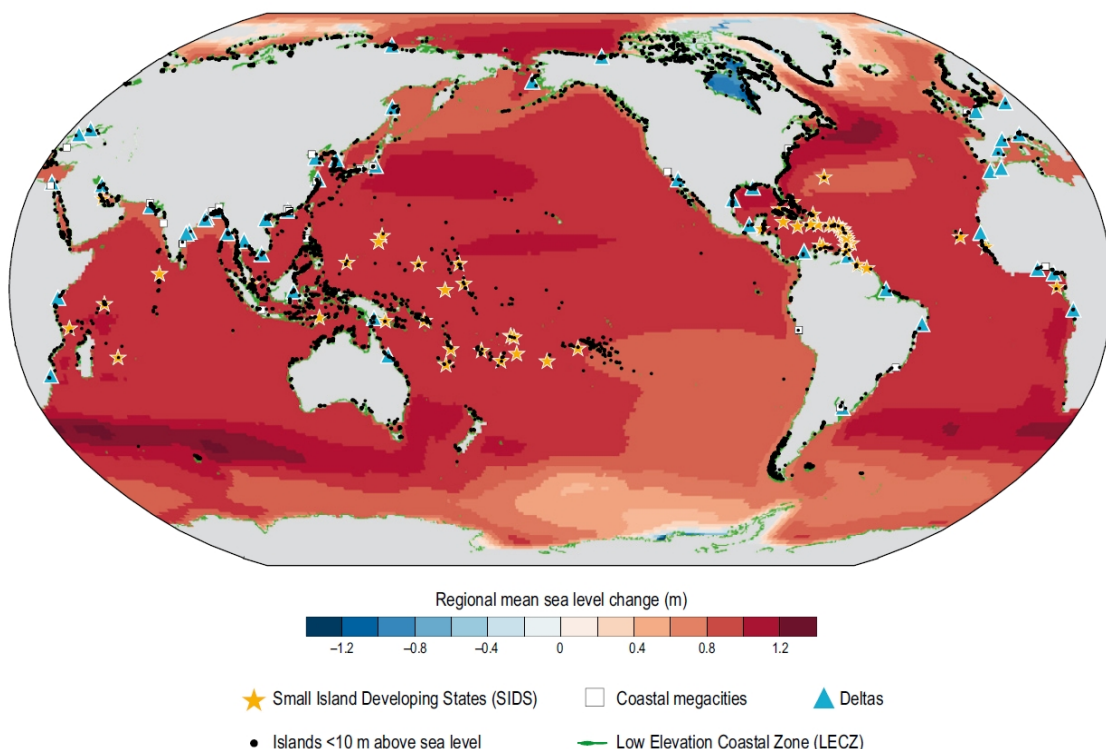


Figure 67: The global distribution of low-lying islands and coasts particularly at risk from sea level rise. Regional sea level changes refer to projections under RCP8.5 (2081–2100). From Magnan, A.K., M. Garschagen, J.-P. Gattuso, J.E. Hay, N. Hilmi, E. Holland, F. Isla, G. Kofinas, I.J. Losada, J. Petzold, B. Ratter, T. Schuur, T. Tabe, and R. van de Wal. In: IPCC, 2019, Cross-Chapter Box 9, Figure CB9.1.

These areas are shown in figure 67. Regional sea level changes refer to projections under RCP8.5 (2081–2100). This panorama shows that special attention must be paid to deltas, which are both the locations of most coastal megacities (and therefore represent the territories with the highest stakes) and the main deployment sites of levee systems (and thus also represent the territories where the greatest challenges of adaptation of these systems exist).

It should also be noted that climate change will certainly result in an almost generalized increase in the frequency of ESL events, but with strong regional disparities in the evolution of marine submersion hazards over the 21st century, as illustrated in figure 68 for three RCPs. These disparities arise from the non-uniform variation in RSL (see section 1.1.1), as well as from the local variability in ESL events (see section 1.2.4).

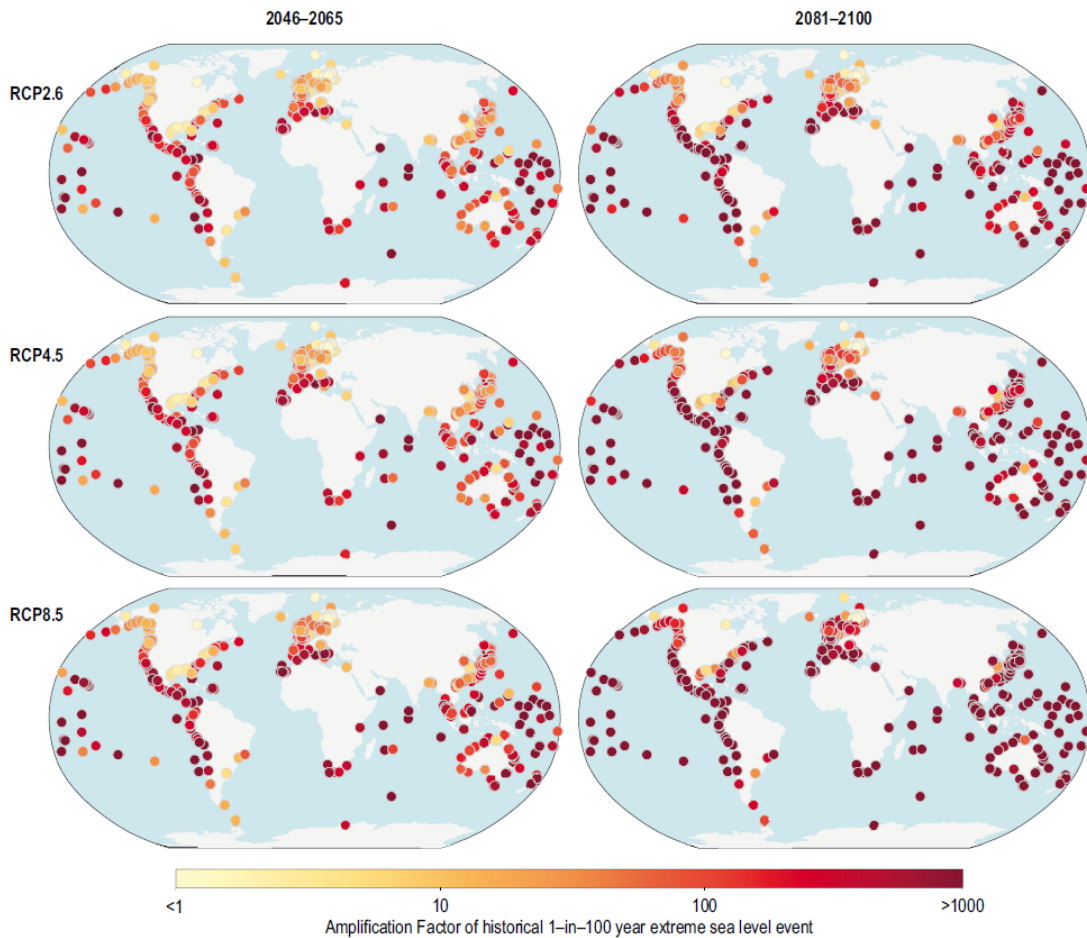


Figure 68: The colors of the dots express the factor by which the frequency of ESL increases in the future for events that historically have a return period of 100 years. Hence a value of 50 means that what is currently a 1-in-100 year event will become a 1-in-2 year event due to a rise in RSL. Results are shown for three RCP scenarios and two future time slices as median values. From Oppenheimer, M., B.C. Glavovic, J. Hinkel, R. van de Wal, A.K. Magnan, A. Abd-Elgawad, R. Cai, M. Cifuentes-Jara, R.M. De Conto, T. Ghosh, J. Hay, F. Isla, B. Marzeion, B. Meyssignac, and Z. Sebesvari. In: IPCC, 2019: Sea Level Rise and Implications for Low-Lying Islands, Coasts and Communities, figure 4.12.

3.1.2 Evolution of stakes exposed to the risk of marine flooding

A necessary condition for the socio-economic justification of protection systems is the exposure of sufficiently important vulnerable stakes. In fact, on the global scale, vulnerable stakes are very high:

- low-lying islands and coasts contain around 11% of the global population (Neumann et al., 2015), and generate about 14% of the global gross domestic product (GDP) (Kummu et al., 2016); in addition, 1.3% of the global population is estimated to be exposed to a 1-in-100-year flood (Muis et al., 2016);
- for the year 2000, the low elevation coastal zones (with a highest elevation up to 10 m above sea level) were estimated to be home to around 625 million people (Lichter et al., 2011; Neumann et al., 2015), with the vast majority (517 million) living in non-developed conditions.

Evidence indicates that exposure of persons and assets in all countries has increased faster than vulnerability has decreased, thus generating new risks and a steady rise in disaster-related losses (UNISDR, 2015). This diagnosis is valid for coastal flood hazards: global coastal flood risk is also expected to increase in the future as a result of increasing exposure due to growth in population and wealth, and increased economic activities in flood-prone areas (Tiggeloven, 2020).

Demographic and economic studies have been conducted on the evolution of stakes in the 21st century. The main conclusions are presented below.

Assessment of stakes at risk in demographic terms

The evolution of the exposure of stakes at risk of coastal flooding was studied by Neumann (2015) on the basis of climatic and socio-economic scenarios projected to occur by 2030 and 2060. At these time horizons, the number of people living in a low-elevation coastal zone, as well as the number of people exposed to flooding from 1-in-100 year storm surge events is highest in Asia. China, India, Bangladesh, Indonesia, and Vietnam are estimated to have the highest total coastal population exposure in the baseline year, and this ranking is expected to remain largely unchanged in the future. However, Africa is expected to experience the highest rates of population growth and urbanization in the coastal zone, particularly in Egypt and sub-Saharan countries in Western and Eastern Africa. These results highlight countries and regions with a high degree of exposure to coastal flooding and help identify regions where policies and adaptive planning for building resilient coastal communities are not only desirable but essential.

It should be recalled here that if the Greenland and Antarctic ice sheets melt faster, Bamber et al. (2019) recommend, for planning purposes, the use of a scenario where the GMSL increase exceeds 2 m in the 21st century (this scenario is outside the scope of the IPCC scenarios). This could lead to land losses of 1.79 million km², including land important for agricultural production, and the displacement of 187 million people.

While the latter hypothesis of a 2 m GMSL rise is not included in the most likely scenarios adopted by the IPCC for the end of the 21st century, 2 m is a median value by 2300 (with values between 0.6 and 5.4 m considering the two scenarios RCP2.6 and RCP8.5 based on IPCC (2019)). Since population projections for coastal areas are strongly upwards in the 21st century, Bamber et al. (2019) therefore provided an insight into the stakes at risk over the next two or three centuries.

Assessment of stakes at risk in economic terms

Hallegatte et al. (2013) assessed the effects of climate change and subsidence on the cost of coastal hazards: average global flood losses in 2005 were estimated to be approximately 6 billion USD per year, increasing to 52 billion USD by 2050 with projected socio-economic changes alone. In response to the effects of climate change and subsidence, the present protection will need to be upgraded to avoid unacceptable losses of 1 trillion USD or more per year.

Hallegatte et al. (2013) assessed economic average annual losses (AAL) in 136 coastal port cities. Their analysis takes into account infrastructure-based adaptation (for example, levees) and the vulnerability of populations and assets. Cities were ranked according to relative vulnerability, namely the ratio of AAL to the city's gross domestic product (GDP). This value can be understood as the share of the city's economic output that should be saved annually to pay for future flood losses. The 20 cities most vulnerable according to this indicator are presented in figure 69.

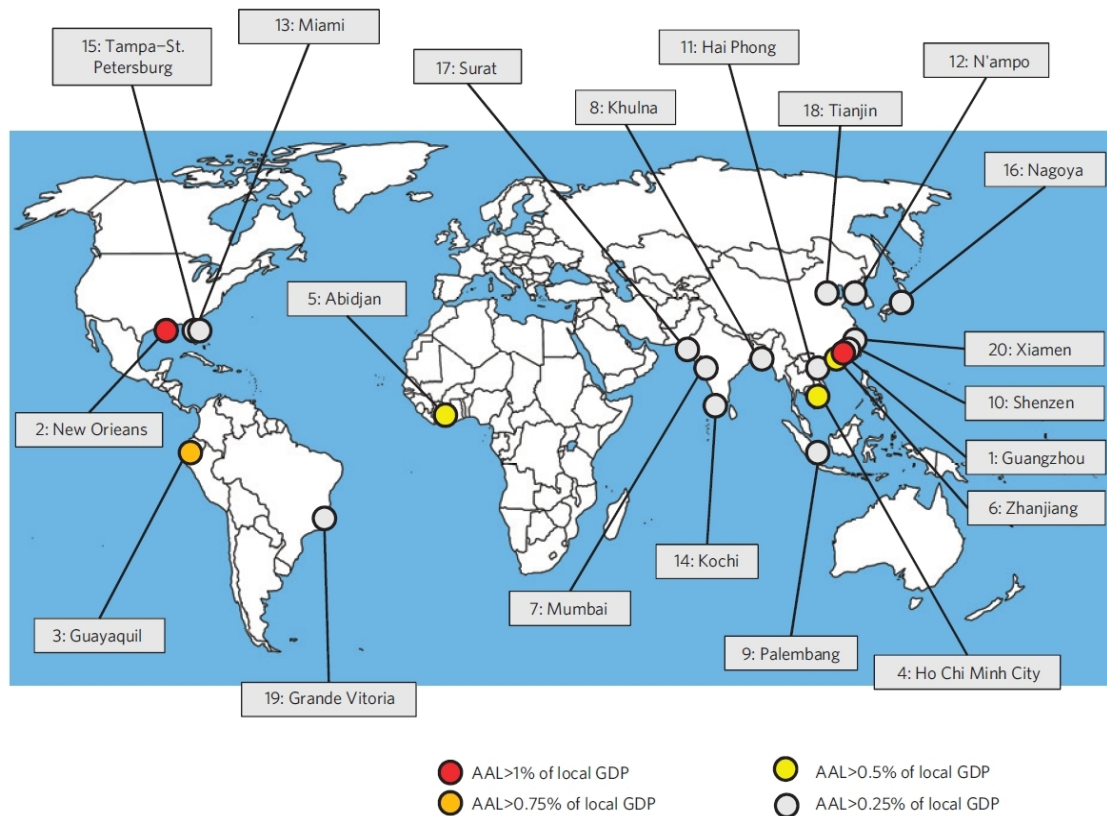


Figure 69: The 20 cities where the ratio of AAL with respect to local GDP (*i. e.*, relative risk) was the largest in 2005 (Hallegatte et al., 2013).

Considering an alternative scenario to those identified by the IPCC as most likely, Pycroft et al. (2016) investigated the world-wide economic cost of rapid sea-level rise that could be caused by accelerated ice flow from the West Antarctic and/or the Greenland ice sheets. The extreme scenario chosen was described by Bamber et al. (2019) and considers an elevation of the GMSL of 2 m during the 21st century. Such an event would have direct impacts on economic activities located near the coastline and indirect impacts further inland. Considering a sea-level rise scenario that corresponds to 1.75 m by the 2080s, the loss of GDP worldwide is estimated to be 0.5%, with a loss of welfare (due to current consumption costs and forced migration) of almost 2% world-wide. Beyond this overall assessment, there are large regional disparities, with the Central Northern Europe region and parts of South-East Asia and South Asia being especially prone to high costs (with welfare losses in the range of 4–12%). This analysis assumes that there is no adaptation at the community level, which would substantially lower the costs.

As indicated above for demographic stakes, although the IPCC does not consider this scenario of a rapid rise in sea level to be the most likely, it nevertheless calls for better anticipation, over a time horizon greater than a century, in protection strategies.

3.1.3 Expected benefits of protection strategies

Climate change provides new incentives for the need to plan for and anticipate extreme events and trends. The adaptation to climate should start now to prevent costly « emergency » interventions in the future. This means that flood risk management strategies must meet present needs, while providing a path for adjustment for the future (Zevenbergen et al., 2008). And so for example, in the Netherlands, the leading ideology of the Delta Programme is that the country should anticipate, rather than react to a disaster afterwards (Klijn et al., 2015). Hurricane Katrina, which caused between 100 and 125 billion USD in direct damage (NatCatSERVICE, Munich RE, 2013), showed how a lack of anticipation can aggravate the consequences of such an event.

These views are largely supported by studies conducted on a global scale.

Thus, Lincke and Hinkel (2018) assessed the cost-effectiveness of structural protection measures against RSL rise and population growth using the DIVA model²⁷. They concluded that it was economically justified to invest in structural adaptation measures for 92 500 km of the world's coastline. While these 92 500 km cover only 13% of the global coastline, they account for 90% of the population and for 96% of assets in the global coastal floodplain. On the contrary, for 451 000 km of the global coastline (65%) covering 0.2% of the coastal floodplain population and representing 0.2% of coastal floodplain assets globally, it is economically robust not to invest in protection. These results were established for multiple scenarios over the 21st century: with GMSL rise between 0.3 m and 2.0 m, five Shared Socio-economic Pathways, and discount rates²⁸ from 0 to 6%. However, these results do not take into account subsidence, which can be a key parameter for deltas, where the highest stakes are located. Indeed, the 100-year projections of subsidence rates (Bangkok: 2 m, Ho Chi Minh: 3 m, Manila: 4 m, and Jakarta: 5 m) far exceed the IPCC GMSL forecasts.

Hallegatte et al. (2013), considered socio-economic changes (e. g., urban population growth) and environmental changes (e. g., subsidence and RSL rise), and concluded that with no adaptation, the projected increase in average losses by 2050 is unacceptable, with aggregate losses for the 126 most vulnerable coastal cities increasing to more than 1 trillion USD per year. Even if adaptation investments maintain a constant probability of occurrence for flooding events, subsidence and RSL rise will increase global flood losses from US\$6 billion to 60–63 billion USD per year in 2050 : since a larger share of existing assets is protected by these defenses, annual losses will rise relative to local GDP. Figure 70 shows the 20 cities where the increase in average annual losses between 2005 and 2050 is the greatest in relative terms. The most vulnerable cities are distributed throughout the world, with a concentration in the Mediterranean Basin, the Gulf of Mexico and East Asia. Even though absolute levels of risk are sometimes low in these cities, they can be considered as hot spots for adaptation, as these are the places where vulnerability will increase most rapidly.

²⁷ DIVA is an integrated research modeling framework for coastal systems that assesses biophysical and socio-economic consequences of sea-level rise and socio-economic development. It takes into account coastal erosion (both direct and indirect), coastal flooding (including river mouths), wetland change, and salinity intrusion into deltas and estuaries. Adaptation and associated cost is a crucial part of the model (see <http://diva.globalclimateforum.org/>).

²⁸ Discounting is the usual method used to compare the future value to a present value. The discount rate is a key parameter for evaluating the socio-economic impact of public investment projects decades in the future (<https://www.strategie.gouv.fr/english-articles/discount-rate-evaluation-public-investment-project>).

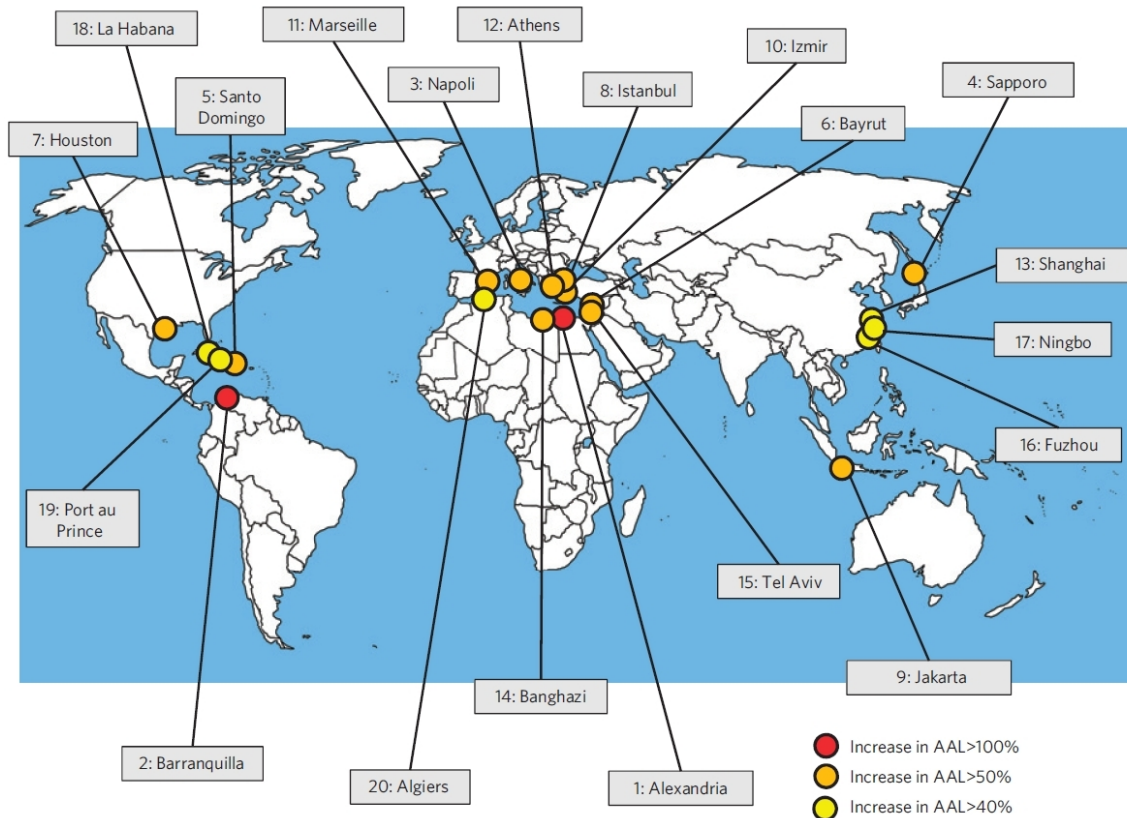


Figure 70: The 20 cities where average annual losses (AAL) are projected to increase most (in relative terms of the year 2050 compared to 2005) in the case of optimistic RSL rise (20 cm), and if adaptation only maintains the present defense standards or flood probability (Hallegatte et al., 2013).

Hallegatte et al. (2013) provided valuable insight on the vulnerability of coastal megacities, making a clear distinction between economic damages and social vulnerability (although ideally, the analysis from this point of view could still be completed by taking into account the solidarity mechanisms). On the other hand, the performance and risk of structural failure are assessed in the prospective scenarios without taking into account the dynamic effects: even if the rise of the RSL in 2050 on most coastlines will be in the order of 0.20 to 0.40 m, values which seem low if one considers the static levels, these increases in the water level will already significantly favor the propagation of waves, and therefore overtopping and the impacts on structures. This study therefore underestimates the risk of failure and overestimates the performance of protection systems.

In a complementary manner, Tiggeloven et al. (2020) presented a global-scale cost-benefit analysis of coastal flood adaptation to different flood risk drivers (namely RSL rise, subsidence, and socioeconomic change) using structural measures. The overall methodological framework is summarized in figure 71 and consists of four main steps: (1) flood risk estimation, (2) adaptation cost estimation, (3) cost-benefit analysis for four adaptation objectives, and (4) attribution of the total costs to the different drivers.

Expected annual damage (EAD) is calculated for different scenarios with and without adaptation, with the difference between these two representing the benefits. For this analysis, levees are positioned arbitrarily 100 m from the shoreline. The costs are calculated by estimating the dimensions of the required levees (height and length) and multiplying these by their unit costs. Maintenance costs are also included in the cost model. A cost-benefit analysis is performed for four adaptation objectives, and finally the costs of adaptation are attributed to several risk drivers.

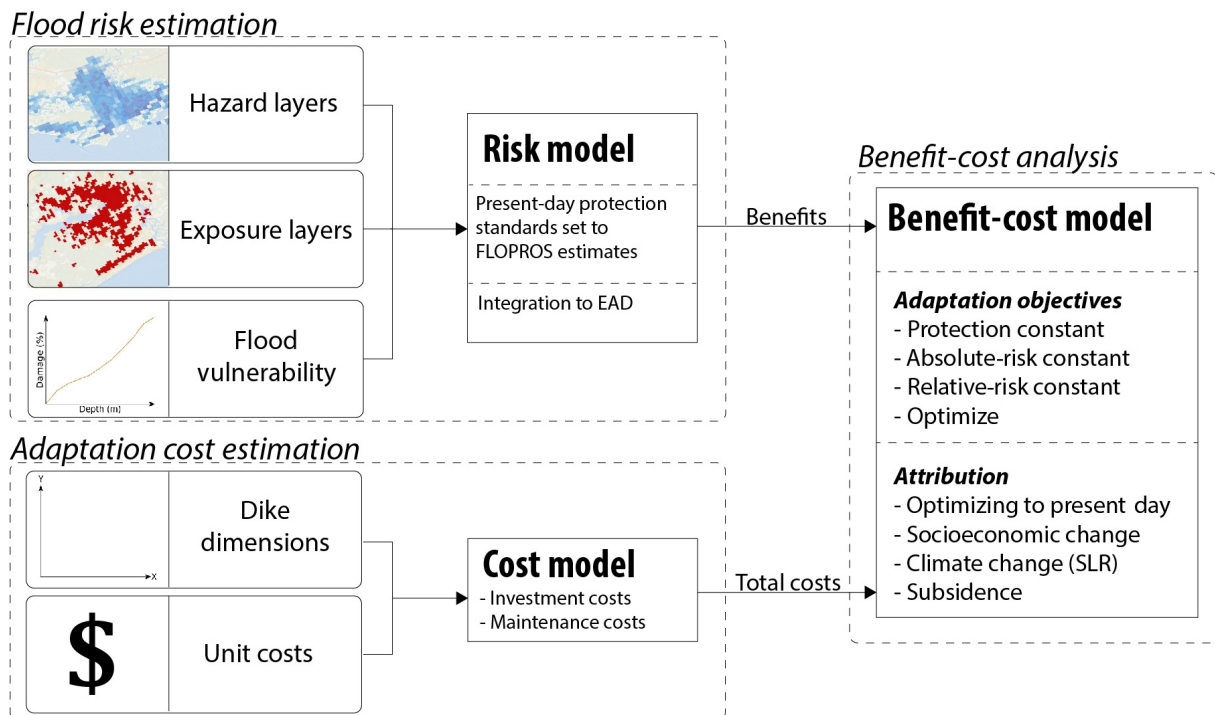


Figure 71: Overview of models and data layers for assessing flood risk, costs of adaptation, and attribution of different drivers (Tiggeloven et al., 2020).

The study by Tiggeloven et al. (2020) concludes on two main points:

- if we assume that no adaptation takes place, it appears that the estimated expected annual damage (EAD) will increase by a factor of 150 between 2010 and 2080 in the scenario RCP4.5–SSP2 : US\$3 trillion per year globally (and US\$6.8 trillion for the scenario RCP8.5–SSP5). China, Bangladesh, and India have the highest flood risks in absolute terms for the year 2010. In 2080, these three countries remain in the top four if no adaptation takes place and are joined by the Netherlands;
- protection by levee systems could cost-effectively reduce (future) coastal flood risks at the global scale in 2080. RSL rise contributes the most to the total costs of adaptation. However, the other factors also play an important role.

The risk assessment model in the scenario with no adaptation appears robust for the representation of hazard, exposure, and vulnerability. The quality of the risk model lies in considering multiple reference events to represent risk, accounting for inland flow dynamics, and in the assessment of damage along the five shared economic paths (O'Neill et al., 2017). The results are consistent with those obtained previously by Hallegatte et al. (2013) on a closer horizon (1 USD trillion per year of damage in 2050 without adaptation).

However, the assessment of adaptation costs does not appear to be as fair or as precise as the assessment of risk without changes in protection systems. Firstly, the definition of adaptation measures is too rudimentary: it is based only on the construction or the raising of levees, and considers this type of work as relevant in all territories with sufficient stakes, whereas the appropriateness and feasibility of this solution should be determined on a case-by-case basis. Secondly, certain biases appear for the sizing of these structures and the estimation of their cost:

- levees should not be uniformly positioned 100 m away from shore: the adaptation of levee systems should be determined on the basis of an inventory of existing structures and should make the best use of the topography for the possible implantation of new structures and take

into account the multiple conditions imposed by the natural environment and the built environment;

- in order to calculate future levee heights, RSL rise is used in the calculation of the crest height for different return periods. This is done by adding sea-level rise directly to the crest height. This does not take into account the fact that the elevation of the RSL by an increase in the water depth in front of the structures will promote wave propagation, which will generate higher hydraulic forces on structures. However, this phenomenon will require a more radical review of the dimensioning of structures to ensure their resistance and hydraulic performance, particularly with regard to wave overtopping and overflowing. It should also be noted that on land subject to subsidence, the raising of the embankments causes subsidence from the additional weight, which can make this solution partially or totally inoperative;
- levee raising costs are described as a linear function of the height of the structure. The cost of raising is at least proportional to the square of the height, if only taking into account the quantity of materials to be used. In addition, considering higher structures require special arrangements both for design and for monitoring to reduce the risk of failure. The study therefore underestimates the cost of adapting the structures, especially in cases where they reach great heights;
- maintenance costs are represented as a percent of investment costs and are set to 1%. This percentage is the minimum value adopted for levees by authors such as Jonkman et al. (2013). Under relatively stable conditions such as those experienced in the 20th century, it was already more prudent to adopt a minimum value of 2% (Cerema, 2018). In the context of climate change, given the considerable increase in the frequency of stresses on these structures and the extreme events of greater intensity that they will experience, in the absence of reinforcement operations to resize the structures to accommodate new hydraulic loads, the cost of maintenance on the structures will increase as new hydraulic conditions deteriorate the structures more rapidly. Moreover, the discount rate used in the study is high (5%), which, in the calculation of the global cost, leads to a significant reduction in maintenance expenses compared to what would be achieved by applying, for example, the discount rates set by the Quinet Commission (2013): 2.5% until 2070 and 1.5% thereafter for risk management investments.

In conclusion, global studies provide orders of magnitude of information on the value of the stakes exposed and the damage they are likely to suffer in the absence of adaptation. This is in part because scenarios provide a framework for changes in climatic and socio-economic parameters, and modeling tools are sufficiently reliable to correctly represent flood phenomena on land whose topography can be fairly accurately known. However, adaptation costs cannot be defined by considering a default protection strategy. The development of a protection strategy requires complete technical and economic analyses at the level of the site whose protection is envisaged and also considering other external elements. From an economic point of view, the result of cost-benefit analyses is very sensitive to maintenance costs (which are generally higher than the investment cost over the duration of the protection project) and discount rates. Sensitivity analyses on these two parameters should therefore be carried out in order to determine the cost-effectiveness of the protection projects. Such analyses were carried out by Tiggeoven et al. (2020), but with assumptions of discount rates that remain very high and maintenance rates that remain very low.

Finally, protection strategies cannot be defined independent of the long-term developments of the territories and the vulnerable issues that are implanted there. The focus must therefore be on time horizons beyond the 21st century, in addition to shorter-term approaches. In the event that a strategy such as maintaining, adapting, or implementing a containment system would appear relevant on a site until 2100, the same analysis conducted over the longer term (on economic and safety criteria of the works) could eventually lead to foregoing it for the benefit of other strategies.

These considerations lead to further investigations of adaptation strategies of coastal flood protection systems at the territorial level.

3.2 Principles of adaptation for protection systems within territories

Despite immense technological progress and urbanization, human society still depends on the capacity of ecosystems to produce goods (like timber, crops, and medicines) and services (like flood control, shoreline protection and water purification) that support and sustain social and economic development. The days of living with resilient, predictable, and self-repairing ecosystems that « bounce back » from stresses and disturbances (such as storms, fires and pollution) are over (Moberg et Galaz, 2005). It is challenging to define strategies for the adaptation of territories and their protection systems on all coastlines, because the nature and scale of the changes are difficult to grasp, as well as the timelines by which the measures are to be implemented, and finally, because each site behaves differently as a CAS.

In order to address the adaptation or transformation of a coastal territory and its protection system, the territory and its protection system will be considered as CASs producing a « bundle » of ESs, including flood protection. Under this prism, the sustainable development of a territory corresponds to the development of its resilience, that is to say its capacity to sustain a desired set of ESs in the face of disturbance and ongoing evolution and change (Biggs et al., 2012).

Building on the CAS governance principles presented in chapter 2, the CAS generic property principles will be utilized. Since these principles provide a framework covering all the ESs, this section will look more specifically at the principles likely to maintain or improve the ES for protection against coastal flooding.

Secondly, the changing conditions of coastal flood protection systems in relation to the natural environment and the built environment will be studied in more detail. To this end, the following assumptions are made:

- a territory is a city or other space with vulnerable issues and for which a protection system exists;
- this territory and its protection system evolve under the double constraint of the natural environment and the built environment, whose perimeters are not necessarily the same. Since social and institutional constraints have already been studied in chapter 2, they will only be addressed marginally in this chapter.

3.2.1 Principles relative to generic properties of CAS

The three principles corresponding to the generic properties of SES are, based on the framework established by Biggs et al. (2012), the following:

- Maintain diversity and redundancy;
- Manage connectivity;
- Manage slow variables and feedbacks.

By considering a territory and its protection system as two nested SESs, it is therefore necessary to assess how these principles can be applied, in particular for protection against coastal flooding.

Maintaining diversity and redundancy

The basic elements set out in the first chapter highlight:

- a real diversity in the modes of protection. This diversity appears in the very definition of protection systems that can be composed not only of various structures, but also of natural formations. This range of protection methods could be further expanded by taking into account certain measures for the development of areas to be protected. For example, prohibiting construction in a low zone can be both a protection measure (the retention basin thus created can be considered as an integral part of the protection system) and a measure to reduce vulnerability (through avoiding exposing buildings to the most unfavorable conditions). Note that the first interpretation of this measure concerns the protection system, while the second relates to the territory;
- forms of redundancy in protection systems. The most obvious examples are systems consisting of levees installed in multiple rows, which both provide staggered barriers to the progression of water, but also, between their rows, provide retention basins. In the case of a system with a front and a rear defense (e. g., a storm surge barrier and levees), the front defense can improve the reliability of the rear defense by reducing the load on this rear defense (Dupuits et al., 2017). Other examples, detailed below also show the effectiveness of hybrid solutions combining the effects of natural formations (for example, coral reefs or mangroves) with a land-based structure (for example, a levee). As before, these modes of protection combining several natural or anthropogenic structures reveal how difficult it is to distinguish formally between the protection system and the territory in which it is located.

More generally, redundancy and diversity can result from multiple lines of defense (possibly linking anthropogenic structures with natural formations), as well as from complementary technologies for retention devices and those of piping, storage, infiltration, and evacuation of water. Ultimately, the principle of maintaining diversity and redundancy applies well to coastal flood protection. It should be noted that, depending on whether redundancy or diversity is preferred, there may be opposing logics for adaptation: redundancy will favor the preservation of the system (the development of a form of engineering resilience), while diversity will favor innovation, thus further transforming the system (via the development of a form of social-ecological resilience).

Managing connectivity

Managing connectivity for coastal flood protection involves three key issues that affect both the natural and urban environments:

- water flow and sediment displacement. This is a major issue in many contexts, such as:
 - in deltas, reduced freshwater and sediment inputs from the river basins are critical factors that determine their sustainability (Renaud et al., 2013; Day et al., 2016). In these territories, where engineering operations have often constrained flows by channelling them, it is necessary to restore, in the long term and at the scale of the watershed, larger natural flows of water and sediment through the system. This involves improved river-floodplain connectivity, if necessary by the removal of levees (Brakenridge et al., 2017);
 - on coastlines, where the protection consists of sedimentary formations (beaches, dunes, mangroves, salt marshes, etc.), the disruption of sediment transit by groynes or the degradation of vegetation that holds these sediments increases the vulnerability of these areas to coastal risks. These risks may be exacerbated by sea walls reflecting waves, which can lead to sediment loss. As this phenomenon favors a lowering of the beach and thus a better propagation of waves towards the structure, a feedback process develops which can lead to the ruin of the structure by scouring its foundations (MEEDDM, 2010; Cerema, 2015);

- the preservation of ecosystems. The ability of coastal SESs to cope with and adapt to RSL rise depends on coastal ecosystem habitat connectivity and ecosystem health conditions (IPCC, 2019). The importance of connectivity to the resilience of SESs and the ESs they produce underlies many conservation initiatives, such as:
 - conservation actions on levees, which are often the last green corridor in urbanized areas;
 - the design of networks of protected areas, *e. g.*, the Great Barrier Reef Marine Protected Area network (McCook et al., 2010). Maintaining connections to areas that serve as refuges can accelerate the restoration of disturbed areas and associated ESs (Nyström and Folke, 2001);
- the management of critical infrastructure including telecommunications, transport services, power, emergency services, water, agriculture, and health care (Hammond et al., 2015). In the event of a flood, these critical infrastructure systems must be preserved so that a community can continue to function normally. This task is challenging if critical infrastructures are highly interconnected, as this increases vulnerability by rapidly propagating failures and interruptions from one infrastructure system to another (Pescaroli and Alexander, 2015). Limiting the interdependence of infrastructure networks, while promoting their redundancy, is one way to reduce this vulnerability.

It should be noted that in France, the two first issues are addressed jointly through a common policy for flood risk prevention and management of aquatic environments. The restoration of flows in the floodplains is one of the emblematic actions.

Managing slow variables and feedbacks

Slow ecological variables are often linked to regulating ESs, *e. g.*, climate regulation and flood regulation (Millenn. Ecosyst. Assess., 2003). Concerning the coastal flood protection ES, the rate of soil sealing, the RSL, sedimentary transit, and other processes influencing erosion phenomena (sea states, including wave climate and marine currents) are slow variables whose monitoring is necessary to understand the system evolution and the associated risks. Thus, one important response for preparing for RSL rise is to improve observational systems (including tide gauges, wave buoys, and remote sensing techniques), because in many places around the world, current frequencies and intensities of ESL events are not well understood due to a lack of observational data (IPCC, 2019).

Feedbacks occur when a change in a particular variable, process, or signal either reinforces (positive feedback) or dampens (negative feedback) subsequent changes of the same type (Biggs et al., 2012). Changes in slow variables and feedbacks can lead to nonlinear changes or regime shifts in the SES if certain thresholds are exceeded, with substantial impacts on the set of ESs produced by the SES (Scheffer et al., 2001). The absence of monitoring information on changes in slow variables and feedbacks is often an important contributor to environmental degradation and loss of resilience (Biggs et al., 2012).

Feedbacks between human interventions and delta morpho-sedimentary response have been studied by Welch et al. (2017): engineered interventions interact with the morphological evolution of the delta, reducing or removing sedimentation, which accelerates subsidence, increasing the consequences of flooding, and requiring further adaptation. These interventions also encourage further development, reinforcing this feedback. This example illustrates that management interventions that weaken stabilizing feedbacks that underlie coastal flood protection can erode the resilience of the SESs.

Conversely, strengthening the stabilizing feedbacks in a system can help maintain a particular SES regime and associated ESs in the face of external stresses, *e. g.*, climate change (Thrush et al., 2009). For example, coral reefs can shift between regimes dominated by hard corals that provide ES (including coast flood protection) and regimes dominated by seaweed. The resilience of the hard-coral regime can be enhanced by promoting the abundance of herbivores (*e. g.*, parrot fish that graze on

seaweed), as it reduces the possibility for seaweed to become established after shocks such as coral-bleaching events (Mumby and Hastings, 2008). The authors also showed that the proximity of a mangrove to coral is a necessary condition for the action of parrot fish on corals since these fish need both habitats. Therefore, the destruction of the mangrove leads not only to a weakening of the protection on land against submersions, but also may lead to a degradation of the defense provided at sea by the coral reefs.

3.2.2 Dealing with the natural environment

Mangroves, salt marshes, and coral reefs occur along about 40–50% of the world's coastlines (Burke, 2011; Giri et al., 2011; Mcowen et al., 2017; IPCC, 2019). These ecosystems provide important ESs including coastal protection by wave attenuation and shoreline stabilization. Recently, a global meta-analysis of 69 studies demonstrated that, on average, these ecosystems together reduced wave heights between 35–71% at the delimited locations considered (Narayan et al., 2016), with coral reefs, salt marshes, mangroves, and seagrass/kelp beds reducing wave heights by 54–81%, 62–79%, 25–37% and 25–45% respectively.

Moreover, sandy beaches and dunes occur at all latitudes covering approximately 34% of the world's coastlines (Hardisty, 1994). The protection offered by these natural formations can be considered close to 100% for a robust dune belt in the absence of a major disturbance disrupting the hydrosedimentary cell functioning.

The preservation of these ecosystems therefore appears to be a priority in the protection strategies against coastal hazards.

All of these ecosystems have a varying capacity to build vertically and expand laterally in response to RSL rise. Nevertheless, drivers other than RSL rise are expected to contribute more to the biophysical limits of their adaptation to future changes. For corals, limits may be reached during this century due to ocean acidification and ocean warming, and for tidal wetlands, due to pollution and infrastructure limiting their inland migration. The natural capacity of ecosystems to adapt to climate impacts may also be limited by human activities that fragment wetland habitats.

Gattuso et al. (2015) stated that ocean warming, acidification, sea-level rise, and the expansion of oxygen minimum zones will continue to have distinct impacts on marine communities and ecosystems. CO₂ emissions will largely determine the severity of the impacts on coastal ecosystems, particularly for corals. These emissions will also determine the effectiveness of human interventions to protect, adapt, or repair ecosystems. Figure 72 presents the effects of climate change on selected species, as well as ecosystem services under scenarios RCP2.6 and RCP8.5. It is clear that in 2100, in the absence of a net change in CO₂ emissions, the degradation of corals, sea grasses, and, to a lesser extent, mangroves, will lead to a decrease in protection against marine flooding, and consequently a sharp increase in this risk. Maintaining high emissions would greatly reduce the potential for adaptation: for most species, protection and repair strategies are only feasible in a low-emissions scenario.

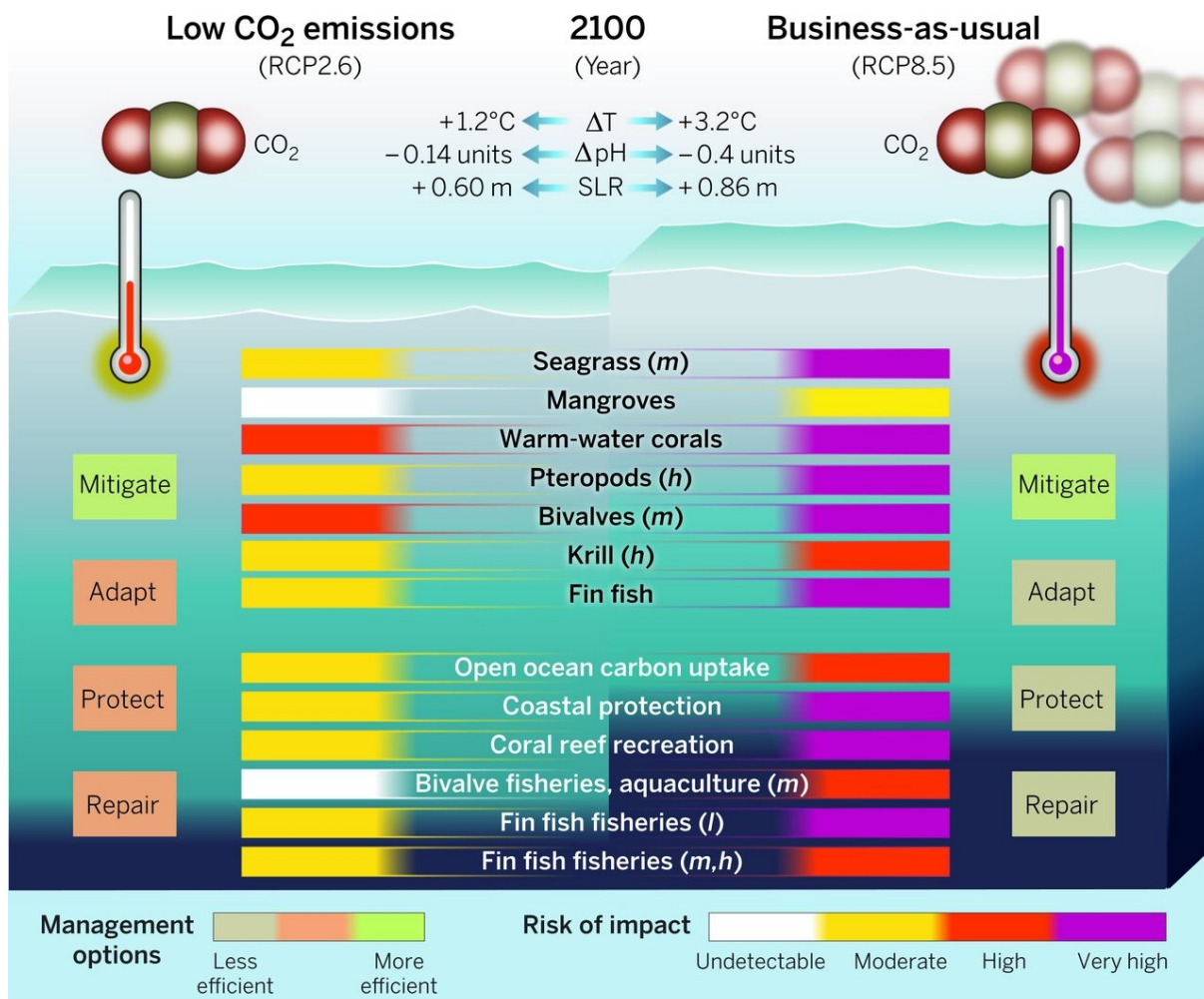


Figure 72: Changes in ocean physics and chemistry and impacts on organisms and ESs according to low (RCP2.6) and high « business-as-usual » (RCP8.5) CO₂ emissions scenarios (Gattuso et al., 2015). l, m, h: low, mid-, and high latitudes, respectively.

Provided they do not disturb ecosystems, anthropogenic structures can complement the protection provided by these natural features. Below are the protection mechanisms associated with coastal wetlands, coral reefs, and dunes, that could exist in harmony with anthropogenic structures. Considering all modes of protection and their possible combinations, the « Maintain diversity and redundancy » recommendation in the framework established by Biggs et al. (2012), seems to be essential for defining the relationship between a protection system and its natural environment.

Coastal wetlands

Salt Marshes, seagrass meadows, and mangrove forests will be collectively referred to as « coastal wetlands ». Figure 73 shows an example of a salt marsh in the Bay of Somme. This space contributes to the protection of inhabited land by the extension of civil engineering works on the seafront.



Figure 73: Aerial view of the Bay of Somme. Credit: Joel Balcaen, Cerema.

Among the coastal wetlands, mangroves and salt marshes are the most ecologically important. Mangroves are mainly distributed along tropical muddy coasts, with a total area of 150 000 km², while salt marshes dominate the muddy coasts from subtropical, temperate to sub-polar, and arctic zones, with a total area of 45 000 km² (Scott et al., 2014).

One of the most important eco-morphodynamic feedbacks that allows for relatively stable morphology under RSL rise is the ability of coastal wetland systems to enhance the trapping of sediment, which in turn allows tidal wetlands to grow and increase the production and accumulation of organic material (Kirwan and Megonigal, 2013). When ecosystem health is maintained and a sufficient sediment supply exists to support their growth, this particular feedback has generally allowed marshes and mangrove systems to build vertically at rates equal to or greater than RSL rise up to the present day (Kirwan et al., 2016). It should be noted that in the context of many tropical deltas that experience deep subsidence, which augments RSL rise, the persistence of mangroves implies an ability to cope with moderately high rates of this parameter (Woodroffe et al., 2016).

For coastal flood protection purposes, vegetated foreshores can be created or restored in front of a levee or any other structure that forms an obstacle to flow progression. These human interventions can reduce the risk of flooding under present conditions and anticipate the effects of climate change and other anthropogenic disturbances. Vuik et al. (2019) summarized several strategies, including strategies that involve human intervention on the foreshore (see figure 74).

The construction of brushwood dams is often a relevant solution: at exposed coasts, strong waves and currents may impede the settling of fine sediments and the establishment of salt marsh vegetation or mangroves (Winterwerp et al., 2013). Construction of a system with brushwood dams (see figure 75) creates shelter, facilitates sedimentation, and prevents erosion. Combining these dams with drainage ditches improves consolidation of the settled sediment. This method has successfully been applied for centuries, and has led to artificial salt marshes along 450 km of the Dutch, German, and Danish Wadden Sea coastline (Bakker et al., 2002; Hofstede, 2003).

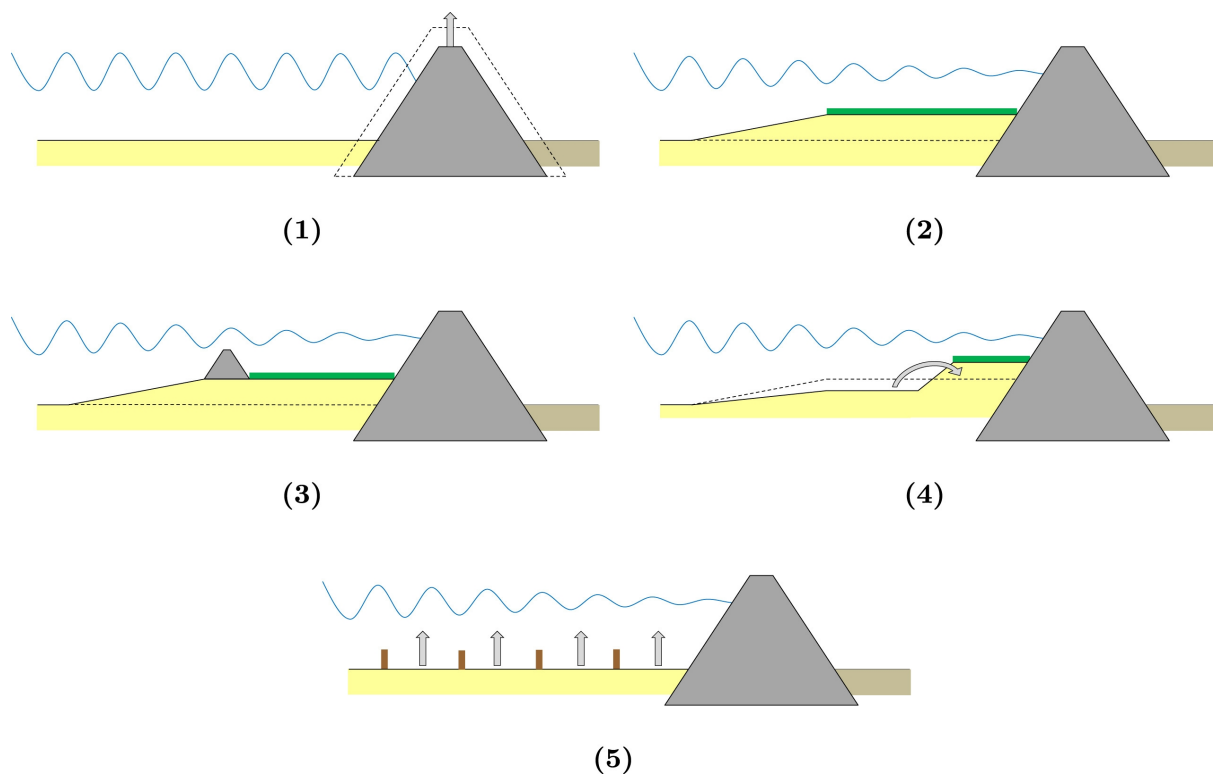


Figure 74: Strategies for reducing flood risk via levee heightening, or via human interventions on the foreshore. (1) levee heightening, (2) salt marsh construction, (3) salt marsh with detached structure, (4) marsh rejuvenation and high zone, (5) brushwood dams and sediment accretion (Vuik et al., 2019).



Figure 75: Brushwood dams in the Dutch Wadden Sea, which create artificial shelter for salt marsh vegetation from waves and currents. The levee is visible in the background. Credit: V. Vuik.

In addition, Vuik et al. (2018) assessed the failure probability of a hybrid flood defense (such as a levee in combination with foreshores such as salt marshes and/or mangrove forests), taking into account the relatively strong temporal and spatial variations in shape and vegetation characteristics (e. g., stem height and density), which cause uncertainties with regards to their protective value under extreme storm conditions. Results show that vegetated foreshores cause a reduction in failure probability for both mechanisms : (i) wave overtopping and (ii) wave impacts on revetments. This effect is more pronounced for wave impacts on revetments than for wave overtopping, since revetment failure occurs at relatively low water levels.

Beaches and dunes

Dissipative coasts that are subject to energetic waves provide the best conditions for the development of a strong dune belt (Dronkers, 2021). This also means that in the event of the deterioration of a dune, the stakes behind it may be exposed to severe hydraulic phenomena.

Schematically, a coastal dune system is composed of three compartments (see figure 76): the shoreface (subtidal beach), the beach (intertidal and supratidal), and the dune. Since these three compartments permanently exchange sediments, they must be considered as a whole. Similarly to coastal wetlands, vegetation is necessary to trap sand for dune growth, and also to stabilize the soil (Heurtefeux et al., 2021). But unlike wetlands, sand dunes are aeolian landforms (*i. e.*, shaped by the wind).

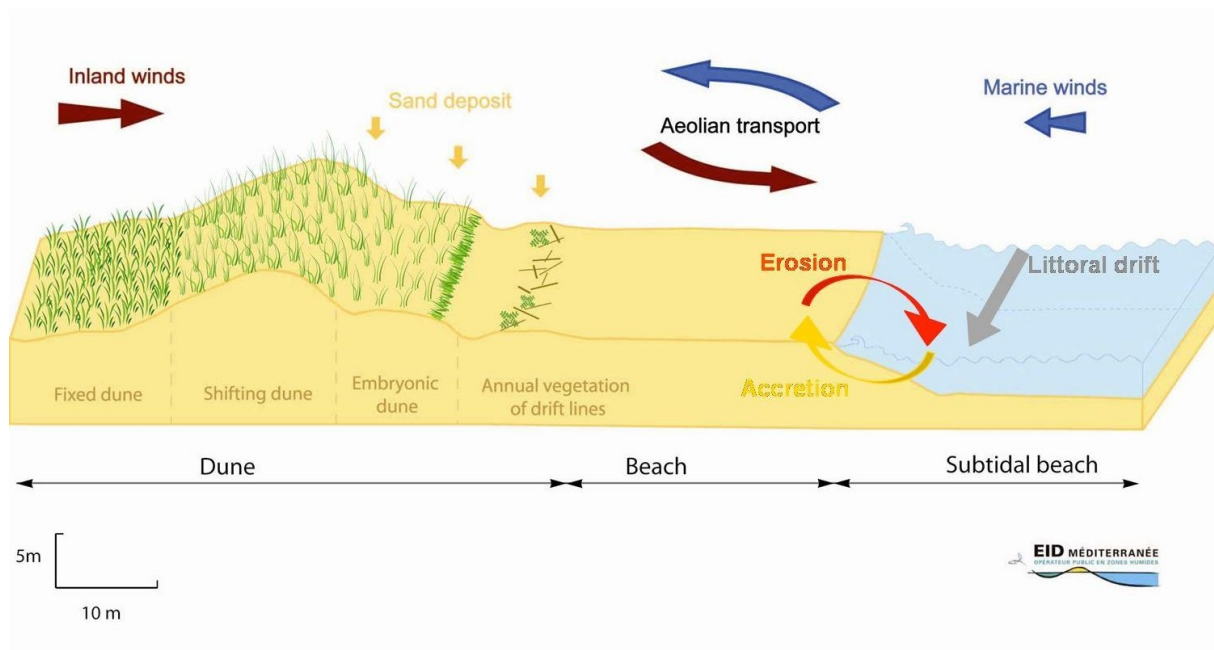


Figure 76: Dune cross-section. Credit : EID Méditerranée.

The evolution of the dune-beach system depends on the functioning of a larger system, the hydro-sedimentary cell, which can experience various natural and anthropogenic constraints (see figure 77). Thus, many factors determine dune formation, in particular: sediment supply, beach morphology, wind regime, wave climate, storms, grain size, aeolian sand transport, vegetation, and overwash (Dronkers, 2021). Each of these factors can be influenced by the effects of climate change (including changes in weather parameters and RSL rise) and the disturbance of water and sediment fluxes resulting from civil engineering works on rivers or along the coast, and from offshore activities and changes in land use.

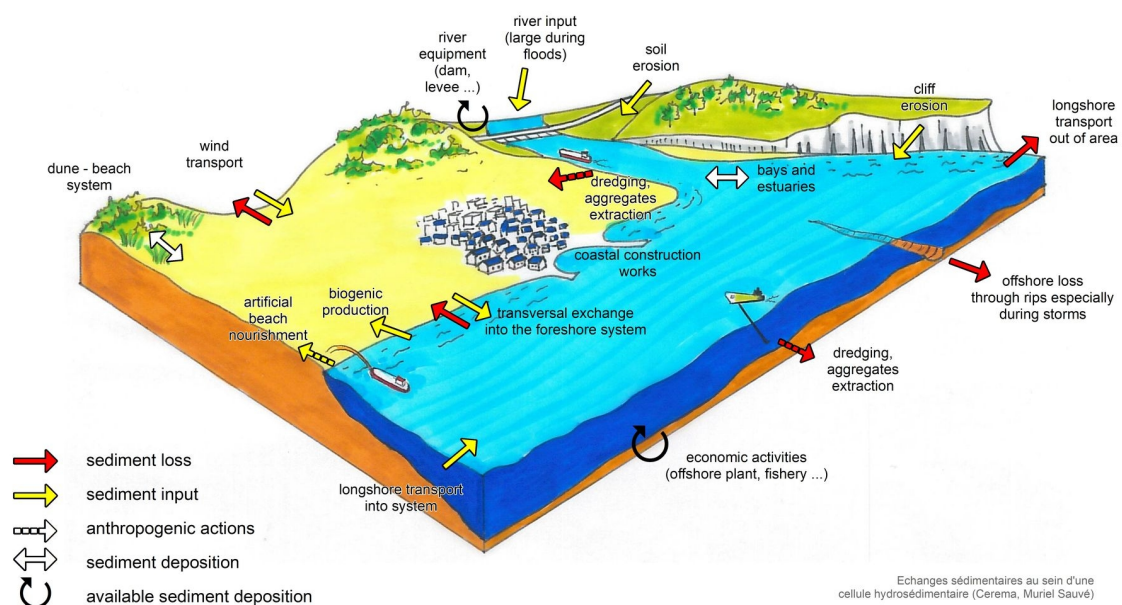


Figure 77: Sedimentary exchanges within a hydro-sedimentary cell (MEDDE, Cerema, 2015). Credit : Muriel Sauvé, Cerema.

The majority of shorelines worldwide experience erosion and this is expected to accelerate under climate change and subsequent RSL rise. Like in the Netherlands, a negative sand balance and inland migration of the beach-dune system can be counteracted by sand nourishment (a.k.a., beach filling) operations. Important preconditions that make this strategy possible are: a readily available sand resource, a reliable monitoring system supported by solid science, political consensus, and a good institutional structure to implement the strategy (Keijzers et al., 2014).

Given the importance of vegetation for dune formation and soil stabilization, the sensitivity of these natural formations to the effects of climate change should be emphasized. Plant communities of coastal dunes are distributed along a characteristic sea-inland gradient (Ciccarelli, 2015). There is a typical vegetation zonation, ranging from the upper beach, to embryonic dunes, mobile dunes, transition dunes, and finally, backdunes. Each coastline, however, shows particular adaptations. Changes in wind, rain, and temperature patterns, in addition to disrupting wind transport, also alter the moisture and salinity of the substrate on which vegetation develops. In this context, Prisco et al. (2013) highlighted the importance of using species' responses to climate change for modeling coastal dune habitat adaptation.

Coral reefs

Coral reefs are considered to be the marine ecosystem most threatened by climate-related ocean change, in particular from the ocean warming and acidification, even under RCP2.6 scenario (Albright et al., 2018; Hoegh-Guldberg et al., 2018). Another concern is that locally, even minimal SLR can increase turbidity on fringing reefs, reducing light and therefore photosynthesis and calcification (Field et al., 2011).

Figure 78 shows the main anthropogenic stressors affecting coral reefs.

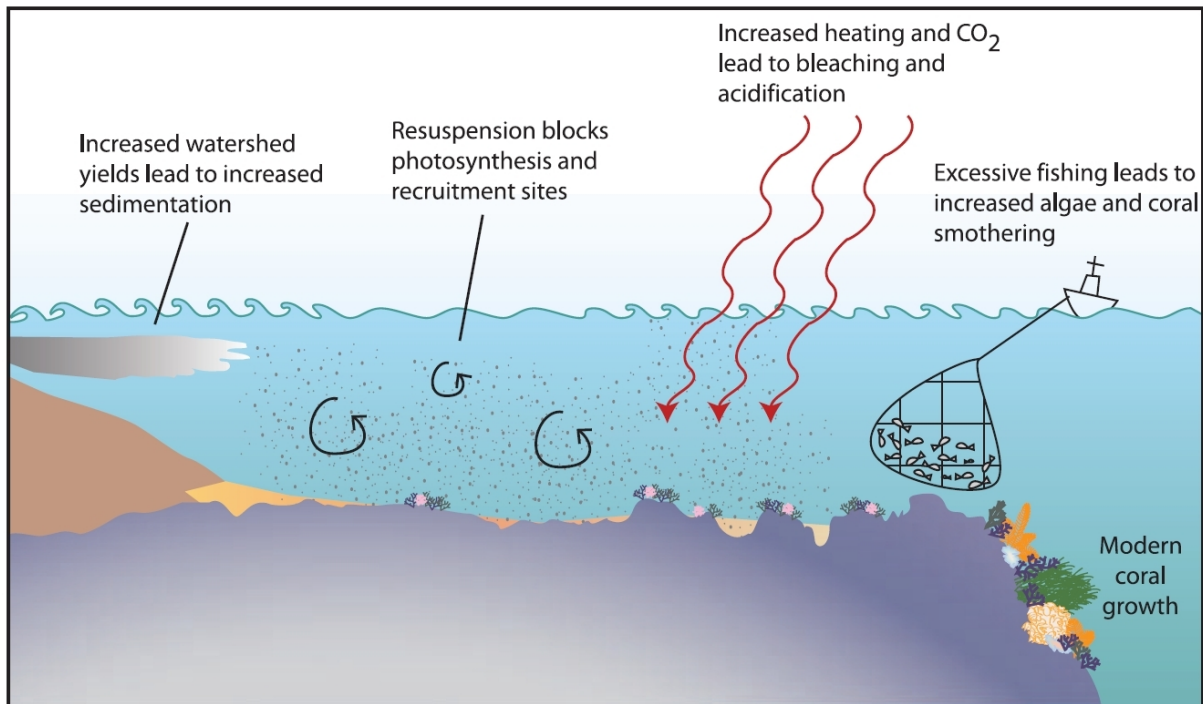


Figure 78: A diagram of a fringing coral reef showing major anthropogenic stressors that affect the health and sustainability of reef habitats (Field et al., 2011).

Such prospects contribute to the concerns about the future ability of atoll islands to adapt naturally to RSL rise and persist (IPCC, 2019). At least 150 000 km of coastline in over 100 countries benefit from the presence of coral reefs. It is estimated that they protect more than 100 million people from coastal flooding (Burke, 2011). Ferrario et al. (2014) stated that coral reefs can provide comparable wave attenuation benefits to artificial defenses such as breakwaters, and that coastal hazard defense by reefs can be enhanced in a cost-effective manner. To obtain this result, the costs of building breakwaters were compared with the costs of restoration of coral reef structures. The authors focused on breakwaters and reefs built in tropical environments, as construction costs are often different between temperate and tropical or island environments. For coral reefs, the used projects concerned restored structures (for example, with reef rubble or concrete blocks) as opposed to projects that only restored coral species (for example, by transplanting corals).

3.2.3 Dealing with the built environment

Coastal flooding can be of marine, river, rain, or underground origin, with the combination of phenomena often generating the most dangerous situations. Protection against these phenomena involves many elements of the territory. The previous section on the natural environment showed the importance of coral reefs, wetlands and mangroves, beaches and dunes. By resisting the rising water and action of waves, they strongly contribute to reducing water inflows into the vulnerable areas. The fact remains, however, that flooding can occur, either by overflowing or overtopping of sea water, by overflowing from a river or runoff on impervious surfaces, or by the rising of a water table. In all these cases, whether the water is salty, fresh, or brackish, clear or turbid, and whatever its temperature – sometimes even in the presence of ice –, the protection system must, in relation to the built environment, reduce the risks generated by these phenomena. As the protection system is nested in the territory, proactive actions are required at the level of the community. Thus, the adaptation of coastal flood protection systems depends closely on the modalities of:

- reduction of hazard exposure by controlling urbanization: water management primarily involves the management of space and in particular, the liberation of low-lying areas where water could be oriented without negative consequences;
- reduction of the infrastructure, buildings, and other assets vulnerability. On this point, it is more of a question of coordinating actions over time.

Where the increase in risk is significant, restructuring and urban transformation operations may be necessary. In this case, it is not a question of adapting the existing system, but of arriving at a new system.

The search for nature-based solutions must also be encouraged in flood protection. The other ESs to which these solutions are likely to contribute to (in particular water purification, climate regulation, and reduction of air pollution) can thus be integrated into the review.

On all these points, the control of water circulation and the preservation of exchanges of all kinds (including humans and other living species, materials, energy, and information) in the urban environment are essential. In reference to the framework established by Biggs et al. (2012), the relationship between protection systems and the built environment are mainly driven by the same recommendation: « manage connectivity ».

The reduction of exposure to hazards by controlling urbanization

Coastal cities are among the most developed cities in the history of civilizations. In modern times, the vast majority of the most populated urban areas in the world have a seafront: Tokyo (42.8 million inhabitants), Jakarta (31.7 million), Seoul (25.4 million), Bombay (24.3 million), Shanghai (24.2 million), Manila (24.2 million), New York (23.7 million), and Lagos (21.7 million). Only Delhi (26.5 million inhabitants) and Cairo (22.9 million) are truly inland cities (Cerema, 2019a). This situation results notably from the development of international trade by sea and the concentration of activity at the level of port towns.

Beyond the case of megacities and coasts, the proportion of the world population in urban areas has increased from 10% in the 1990s to 50% in only two decades (Meerow et al., 2016). From lack of available land space, the population settles in areas at risk (Barroca et al., 2006). New neighborhoods are emerging with no adequate equipment in flood-prone, polluted, or unhealthy areas (Heinzlef et al., 2019).

The study of the dynamics and underlying processes of global urban expansion (Angel et al., 2005) revealed that the spatial distribution of urban populations is, by and large, not the result of intentional planning. Cities are complex systems, for which planning and management by public authorities are only one factor in their evolution. This is particularly true in emerging countries, where the fragility of statistical tools, the sometimes inextricable nature of governance problems, demographic and social pressure, the lack of resources and the difficulty in bringing together public and private players in development explain the essentially unplanned development of the urban fabric (Cerema, 2019a).

However, cities should plan early and much more carefully to accommodate and disperse the impact of over-concentrations of people and economic activities in order to avoid large-scale catastrophes (Zevenbergen et al., 2008). During the planning process, the coordination of flood protection measures and land use planning should be ensured regardless of the time horizon considered. But the system formed by all the protection structures imposes strong spatial constraints:

- although civil engineering works, such as concrete or steel walls, can be used at sites where land prices are very high, the most technically and economically suitable works are generally levees made of earth. However, these low-slope structures have a significant footprint;
- a protection system can only function properly if perfect continuity is ensured between the structures providing retention functions. Continuity constraints also exist on the drainage network.

Enabling the development of protection systems therefore requires well-defined and well-respected planning schemes. One way to promote the implementation of these measures in a context evolving at the scale of a few decades is to shorten the lifetime cycles of buildings and infrastructure, a practice already common in many flood-prone areas around the world, but not in Western countries where buildings have life cycles of 40 years or more (Zevenbergen et al., 2008).

Reducing the vulnerability of urbanized areas

Reduction of exposure to hazards is an essential orientation that should be extended by reducing the vulnerability of developed areas. Vulnerability reduction measures are generally referred to as « accommodation measures ». The major co-benefit of accommodation is improved resilience of *in situ* communities without retreat or use of land and resources for the construction of protection structures (Zhu et al., 2010). This is an interesting option if urbanization has not been sufficiently controlled. Measures may aim to:

- protect critical infrastructure. When infrastructure is affected, the consequences can indeed be dramatic. For example, in 2012 Hurricane Sandy significantly impacted coastal communities across New Jersey and New York with a devastating storm surge that triggered a series of unanticipated failures in the critical infrastructure systems including transportation and power networks (Hatzikyriakou and Lin, 2018). In the south part of Manhattan, many types of infrastructure, such as the subway system, tunnels under the river, and an electric substation, were damaged due to flooding of underground facilities (Mikami et al., 2015). Critical infrastructure must therefore be positioned at sufficient altitude or have special means of protection such as watertight closures or drainage devices adapted to these exceptional situations. These special provisions must be fully integrated into the crisis management system, for example, by prohibiting access to flood-prone infrastructure, including underground infrastructure. These measures therefore require institutions capable of operating in highly degraded situations. The protection strategy is therefore very dependent on the context of the situation. This was shown, for example, by Singh et al. (2021). By examining flood resilience institutions, strategies, and outcomes in three selected cities – New York (U.S.), Tokyo (Japan), and Rotterdam (Netherlands), and their impacts on the transportation network, these authors highlighted differences in approaches to developing system resilience, related to geographic, cultural, and institutional factors, and linked to the transportation network performance in flood events. Duy et al. (2019) provided similar recommendations for emerging-coastal cities (resilient transport systems to reduce urban vulnerability to floods). These recommendations were illustrated by the case study of Ho Chi Minh City (Vietnam);
- individual protection of buildings by impermeabilization « flood proofing », or by reducing their vulnerability inside « wet proofing », or by using floating houses or stilt houses. These measures help prevent the demolition or relocation of structures and are often an affordable and cost effective approach to reducing flood risk (Zhu et al., 2010). For example, in Ho Chi Minh City, in areas at high risk, elevating and retrofitting buildings have a cost-benefit ratio of 15 considering an SLR of 1,80 m and a discount rate of 5% during the 21st century (Scussolini et al., 2017).

Accommodation measures also include alert and evacuation systems. Success stories include the case of Bangladesh, where an improved early warning system, combined with the construction of shelters, and development of evacuation plans, helped to reduce fatalities derived from flooding and cyclones (Haque et al., 2012).

Thus accommodation measures can be very effective for current conditions and a relatively low sea level rise. In regard to the problem of adapting coastal flood protection systems, they « buy time » to prepare for more severe conditions. However, in general, flood protection costs increase with flood height. A long-term strategy must therefore be defined, incorporating, if necessary, other directions such as the restructuring of the urban environment or the relocation of people and activities.

It's important to note that accommodation – depending on the measures implemented – has the potential to maintain landscape connectivity, allowing access to the ocean as well as landward migration of ecosystems to a certain degree. Moreover, accommodation can also contribute to maintain flood dynamics and the related benefits of flooding such as sediment re-distribution (FEMA, 2014). This can be achieved, for example, by promoting stilt houses that leave space for the floodwater. These measures can therefore in some cases do more than « buy time ». They can also enable ecosystems to adapt to change and become part of sustainable land management.

Restructuring and transforming the urban environment

Faced with numerous changes underway, risk management should become a structuring element of territorial projects for many coastlines. In this case, it is necessary to move from a mode of reaction to a mode of anticipation to better adapt. In the most exposed areas, the effects of climate change will be severe, even violent. Adaptation projects will also undoubtedly involve some violence for the population, but this violence can be mitigated by mastering the transformation process over time. Another condition for the success of an adaptation project is the ability to identify the principles of long-term protection. On this subject, it should be noted that « long term » cannot be defined for all territories using the time frame of a single duration (50 years, 100 years or several centuries), as this depends on the context and projections for the territory. The long term must therefore be defined in a « tipping point » approach (see section 2.5.1). The evolution of slow variables leads to a change of protection strategy at a certain threshold.

If we consider the urban environment in isolation, the use of levees does not really correspond to an adaptation measure, since their presence serves, on the contrary, as a pretext for not modifying the existing state. Liao (2012) highlighted that flood protection by means of levees, dams, and channelization neglects inherent uncertainties arising from human–nature couplings, and fails to address the extreme events that are expected to increase with climate change, and is thereby not a reliable approach to long-term flood safety.

Depending on the site, in the long term, other orientations should therefore be preferred to protection structures for the development of areas exposed to coastal hazards. Adaptability to change requires more lightness, hydraulic transparency, and reversibility in the design modes. In particular, at sites whose topography has a sufficient slope, a gradation could be sought with the following orientations:

- leave more room for water;
- construct fewer buildings near the coast;
- avoid points of resistance in the territories that would hinder their evolution;
- redeploy urbanization inwards.

It should be noted that these guidelines are well suited to territories where there is available space, but may be thwarted at sites where coastal compression has reduced the possibilities for adaptation. For example, in France, this strategy is easier to implement in the Camargue delta than in the city of La Rochelle (Bellouin, 2021).

In all cases, when restructuring is required:

- the approach must be transdisciplinary (*i. e.*, it needs to associate several disciplines, science and practice, and multiple actors). The rules must be defined at the community level to ensure that specific initiatives are well integrated in the land use project. The same applies to levee system revision projects that should be integrated into a comprehensive territorial transformation scheme;
- the difficulty of predicting temporal changes, while accounting for variation and unpredictability, should not be overlooked. The collegial dimension is necessary to support strategies and projection techniques (scenario planning or VDRC).

Finally, the measures to reduce exposure and vulnerability presented above should not be opposed to long-term measures. In this regard, Beillouin and Pecquet-Caumeil (2019) showed the benefits of focusing action on short-term issues to achieve the long-term objectives of spatial recomposition.

These authors also showed that, in addition to putting an end to dangerous situations, it is possible to produce a consensus by focusing on public facilities, such as schools or nurseries.

Finally, urban transformation can also provide opportunities, as indicated by Zevenbergen et al. (2008), in particular to:

- implement additional flood mitigation measures. In this regard, individual flood resilience measures adopted at the street and building level could make a particularly important contribution to urban planning objectives such as reviving the urban waterfront;
- deliver simultaneous short-term societal benefits (e. g., the high amenity value of attractive waterfronts);
- provide additional economic benefits through dual-use options, such as a theatre that also serves as a dry refuge, an elevated road that also provides safe access and escape route, a watertight parking garage that also provides flood storage, or dual land use by means of floating spaces.

On the latter point, if it is necessary to look for ways of escaping the spatial dichotomy between « areas dedicated to the protection » and « areas whose protection is sought », dual use is a questionable option when it comes to structures that have a water retention role, such as levees and walls (as opposed to structures that store water). Indeed, structures whose design is relatively simple and whose sole function is water retention may already experience multiple failure modes and, because their lengths are very important, their management is delicate (CIRIA et al., 2013). Searching for forms of multi-functionality for these structures complicates their design and monitoring, and may also involve transitions with other structures, transitions often corresponding to points of fragility (Simm et al., 2019). Yet some authors suggested the construction of this type of work when space is limited (e. g., in an urban setting), and considered that co-benefits can be generated through multi-functional hard flood defenses, which combine flood protection with other urban functions, such as car parks, buildings, roads, or recreational spaces (Stalenberg, 2013; van Loon-Steensma and Vellinga, 2014). This type of solution can only be adopted on a case-by-case basis, and extensive studies should support decision-making. In the project shown in figure 79, the multiple uses are justified by the reinforcement of an existing levee, with the uses likely to harm the levee only encroaching on the part corresponding to its reinforcement. However, the modification of protection structures is subject to caution. For example, permitting the development of high vegetation exposes the structure to wind forces on trees and the transmission of forces in the ground, which are not easily quantifiable. Regular monitoring is required to ensure that vegetation remains consistent with safety objectives.

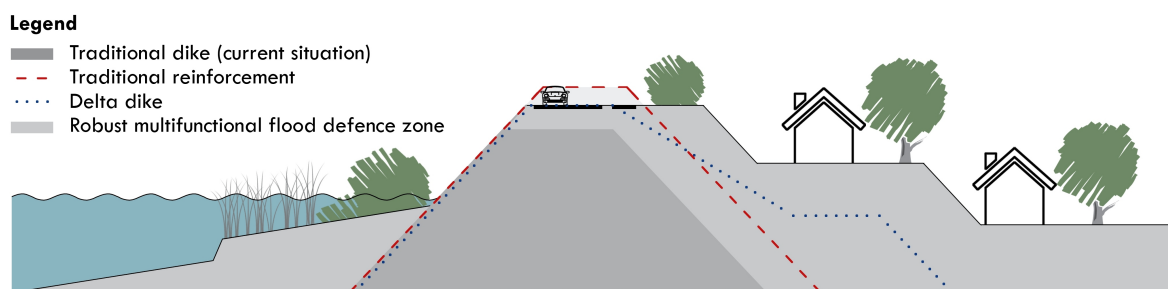


Figure 79: Cross-sectional profiles of a current levee, a traditional reinforcement, a Delta levee, and a multifunctional flood defence considered as unbreachable (van Loon-Steensma and Vellinga, 2014 adapted from Silva and Van Velzen, 2008 and Stowa, 2013).

Conversely, the simple widening of coastal levees does have undeniable advantages: greater ease of doing repairs, increased adaptability, and enhanced spatial quality compared to a traditional levee (van Loon-Steensma and Schelfhout, 2017).

Nature-based solutions and green infrastructure

Nature-based solutions can be used both in the natural environment and in anthropogenic areas to protect against coastal flooding. In the section on the natural environment, ways of preserving or improving protection against such hazards at the edges of built environments were presented (for example, by measures to preserve or rehabilitate dunes, mangroves, or other natural features). In this section, the principles for the application of these solutions in developed areas, particularly in urban areas, will be set out. The term for these solutions in this context is « green infrastructure ». The following definition, while generic, is interesting, as it emphasizes the systemic nature that must be sought:

« The interconnected set of natural and constructed ecological systems, green spaces, and other landscape features. It includes planted and indigenous trees, wetlands, parks, green open spaces, and original grasslands and woodlands, as well as possible building- and street-level design interventions that incorporate vegetation. Green infrastructure provides services and functions in the same way as conventional infrastructure (Culwick and Bobbins, 2016) ».

To protect against coastal flooding, the following types of green infrastructure can be specifically utilized: wetlands, ponds, porous pavements, and greenways. Green infrastructure can integrate the functions of water storage and infiltration and be another emerging sustainable solution that plays a crucial role in the restoration of natural patterns and processes in infrastructure to reduce flood inundation (United States Environmental Protection Agency [US EPA], 2020).

Green infrastructure consists of a network of multifunctional green spaces that have the potential to build resilience using limited resources (Alves et al., 2020). Green infrastructure appears to be a complementary tool to conventional flood risk management solutions such as drains, pumping stations, levees, and dams. This infrastructure should, to varying extents, replace conventional structures as these ecology-based flood protections offer more advantages compared to traditional hard structures, including cost-effectiveness, less raw materials consumption, improved system adaptability, and a functioning ecosystem (McPhillips et al., 2020; van der Nat et al., 2016). Nevertheless, this is a challenge since urban drainage systems are complex structures. Focusing on stormwater infrastructure planning, Alves et al. (2020) showed that, in decision making, to consider co-benefits (such as aesthetic value and biodiversity) enhancement as an objective boosts the selection of green infrastructure. However, flood mitigation effectiveness can be diminished when extra benefits are pursued. Finally, combining traditional and ecological measures is particularly relevant in urban spaces when several benefits are sought simultaneously.

More generally, systemic approaches to water management in large cities are developing, and flood risk is increasingly being taken into account using a resilience-building approach, alongside other objectives such as: the prevention of water pollution from runoff, water resource maintenance, alleviation of excessive heat, and increased liveability of urban environments (Gersonius et al., 2016).

3.3 Comprehensive approach: strategies in territories considered as CASs

The adaptation or transformation of coastal territories and their coastal flood protection systems can be undertaken based on the methods of risk understanding and strategies outlined in chapter 2. These methods should be applied by considering these systems as CASs and should incorporate elements belonging to the natural environment and the built environment. To this end, this section provides concrete elements to better inform decision-making, including:

- a typology of adaptation options referring to climate change objectives and adaptation objectives for climate change and other effects;
- spatial landmarks to address the multiple themes involved;
- indications, including time indications, to guide action for adaptation or transformation.

3.3.1 Adaptation options referring to multiple changes

To avoid maladaptation risks, adaptation strategies should be integrated into a comprehensive scheme (IPCC, 2019), as represented in figure 80. This scheme comprises:

- mitigation, which refers to human actions to limit climate change by reducing emissions and enhancing the sinks of greenhouse gases;
- adaptation, which refers to processes of adjustment by natural or human systems to actual or expected climate and its effects, intended to moderate harm or exploit beneficial opportunities.

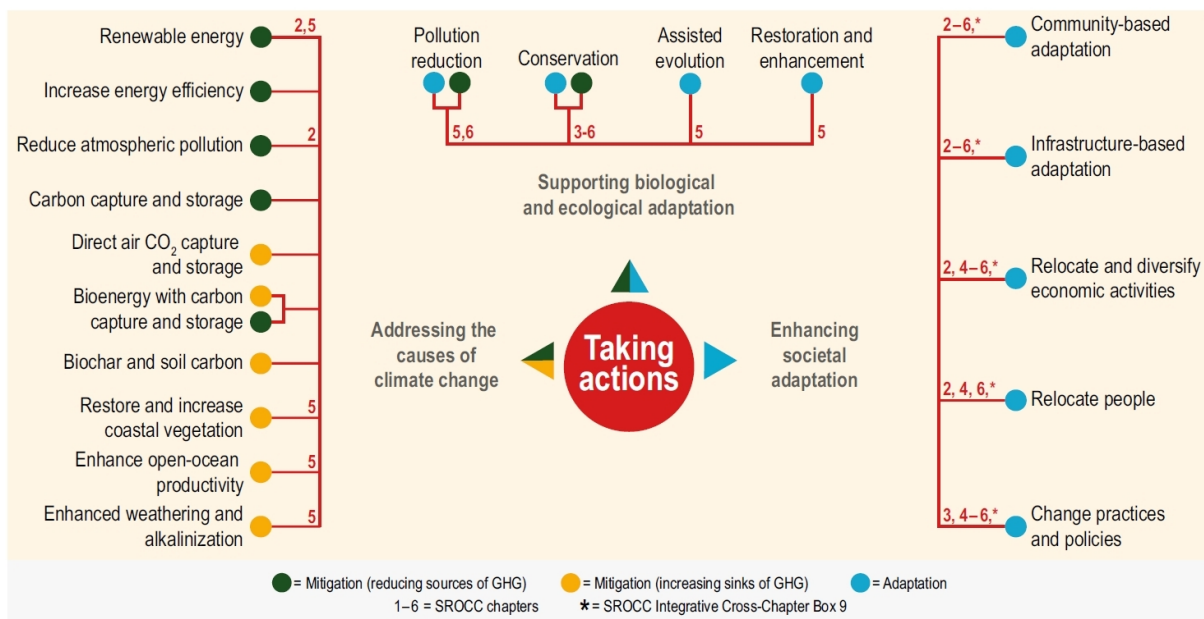


Figure 80: Overview of the main mitigation and adaptation measures (from Abram, N., J.-P. Gattuso, A. Prakash, L. Cheng, M.P. Chidichimo, S. Crate, H. Enomoto, M. Garschagen, N. Gruber, S. Harper, E. Holland, R.M. Kudela, J. Rice, K. Steffen, and K. von Schuckmann. In: IPCC, 2019, Framing and Context of the Report, figure 1.2).

Synergies can be developed between climate action, risk prevention, and sustainability (Hackmann et al., 2014). Climate change impacts on the ocean and cryosphere can also present opportunities, in at least the near- and medium-term future. To benefit from new opportunities while also avoiding or mitigating hazards, it is necessary to be aware of the trade-offs between risks and benefits (IPCC, 2019).

3.3.2 Plan adaptation in relevant frames of reference

The implementation of mitigation and adaptation measures should be undertaken in frames of reference that are consistent with the main processes being implemented. Schematically, these processes correspond to several spatial scales, which should logically also correspond to the scales at which the actions should be carried out, namely:

- the planet, for reducing greenhouse gas emissions (using mitigation measures);
- the catchment (or the delta), whose process management contributes to limiting rapid increases in exposure and vulnerability to coastal flood risk. These processes have direct impacts on the coastline, particularly in terms of water and sediment budgets;
- the coastal territory, where the interactions between the natural and the built environment should be considered. The measures most directly related to coastal flood protection systems should be defined at this level. The coastal fringe and the urban environment can be considered as subsets of this territory.

Three examples of country, city, and neighborhood adaptations are given below:

- in the Netherlands, on the deltas of the Rhine, the Meuse and the Scheldt, an integrated strategy for multiple issues (including flood protection, water resource management, and sanitation), defined at the national level, is implemented locally;
- in Dublin, Ireland, the development of the city's resilience to floods is undertaken on the basis of a diagnosis considering the interrelationships of technical networks and the impact of their malfunctions on vital services;
- in a neighborhood in Beira, Mozambique, an action program integrates civil engineering operations, nature-based solutions, and warning and evacuation measures.

A case study of adaptation in the Netherland

The Netherlands Delta Program can be characterized as a comprehensive adaptation strategy for the Netherlands, as it aims to integrate climate adaptation into flood risk management, freshwater resource management, and spatial planning (Klijn et al., 2015).

Five overarching decisions form the basis of the work that the Netherlands will perform over the next 35 years (with a planning horizon of 2100). The decisions concern new water safety standards, sustainable fresh water provisions, climate-resilient design and construction of urban and rural areas across the Netherlands, and structuring choices for flood risk management and freshwater supply in the IJsselmeer region and the Rhine-Meuse delta (Bloemen et al., 2018).

Formally, two plans form the basis of the regional strategies: the Delta Plan for flood risk management and the Delta Plan for freshwater. Strategies were defined using the adaption pathways method. The proposal sent to parliament in September 2014 contained a total of 14 pathways, developed with a planning horizon until 2100. Figure 81 illustrates the pathway developed for the Rotterdam area.

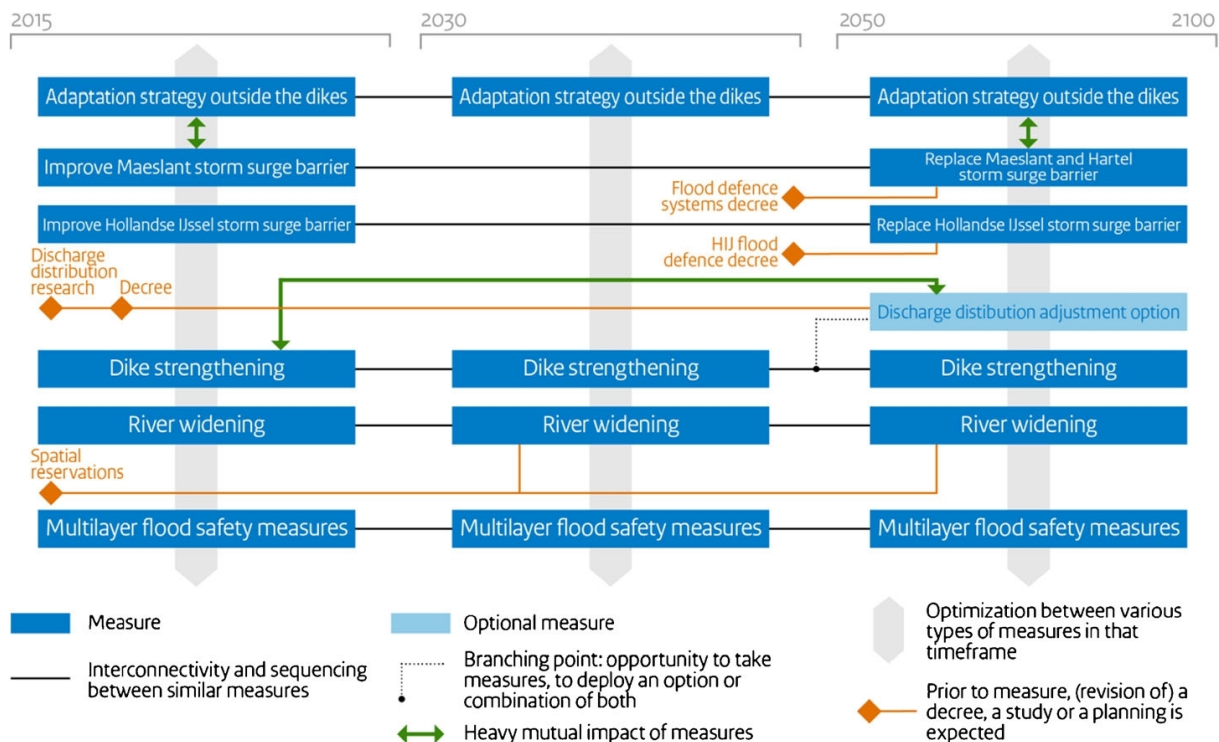


Figure 81: Adaptation pathway map for flood risk management in the Rotterdam area (Delta Programme Commissioner, 2014).

The following comments, taken from Bloemen et al. (2018)²⁹ are useful to understand this figure:

- dark blue boxes indicate measures that are considered in the three consecutive time periods: 2015–2030, 2030–2050, and 2050–2100;
- light blue boxes indicate long-term options, like the modification of the discharge distribution among the Rhine branches;
- the orange diamonds indicate preparatory actions. Examples are spatial reservations, especially necessary for river widening, and research on the costs, benefits, and technical feasibility of modifying the discharge distribution among the Rhine branches;
- green arrows highlight measures that heavily influence the effectiveness of other measures. If for instance the research on the possibilities of modifying the discharge distribution leads to a decree that this measure will be implemented, then dike strengthening projects will need to include the effects of this modification in their planning and design.

²⁹ Bloemen et al. (2018) also presented lessons learned from applying the adaptation pathways method in flood risk management for the Thames Estuary (United Kingdom).

Case study of adaptation of a city (Dublin, Ireland)

The city of Dublin is prone to floods derived from river, coastal, and rainwater origins and is characterized by continuous urban development that exerts an important land pressure on flood-prone areas.

Lhomme et al. (2019) studied Dublin's technical networks reaction in the face of a 200-year coastal flood (probability of 1/200 to occur each year) by analyzing the physical infrastructure, its functioning, and its recovery, while taking into account the interdependencies existing between sewerage and electricity networks³⁰.

Given its good meshing and geographical position of the source substations, the electricity network does not suffer from major malfunctions. They are limited to parts that can be cut preventively. However, the situation is much more worrying for the sewerage network (see figure 82) that can be disrupted by the sewerage network. For example, lifting pumps located near the Ringsend treatment plant are threatened by disturbances in the electricity grid. However, an important part of the sewerage network depends on the operation of these pumps.

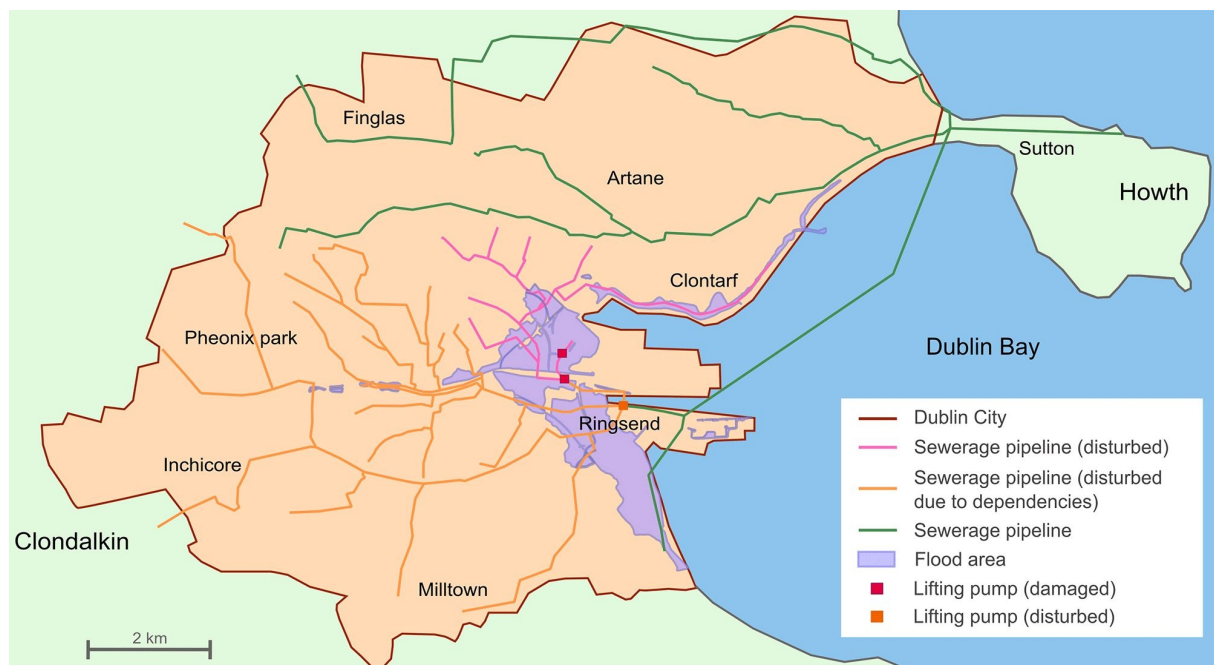


Figure 82: Despite rather favorable assumptions regarding the resilience of the sewerage network, the network remains severely disrupted (Lhomme et al., 2019).

While almost all the major stakes (e. g., hospitals, fire stations, ministries, and embassies) are located outside the flood zones, it is apparent that these major stakes will be very much affected by the malfunctions of the sanitation network. Figure 83 shows the possible impacts of the sanitation network disruption on the hospitals.

This example shows that the development of the city's resilience to flooding must be supported by a thorough study of the relationships between the components of this system. An approach limited to controlling hazard or reducing the vulnerability of each component taken separately is ineffective.

³⁰ This study was carried out within the framework of the FloodResilienCity European project.

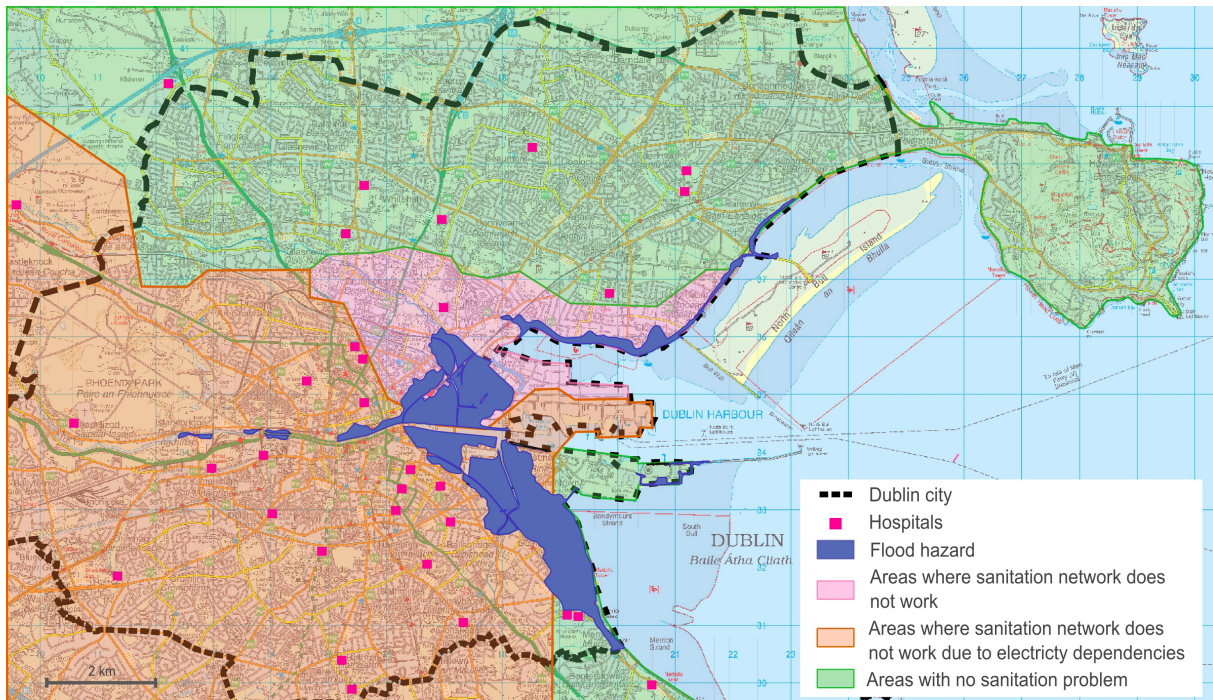


Figure 83: Hospital distribution and sanitation network operation (Lhomme et al., 2019).

A case study of the adaptation of a neighborhood in Beira (Mozambique)

A flood risk management strategy has been defined for the coastal city of Beira (Mozambique), particularly for a neighborhood in the immediate vicinity of the coast. Considering the impact of many storms and comparing multiple strategies and scenarios, Van Berchum et al. (2020) demonstrated that expansion of the drainage capacity and strengthening of its coastal protection in the southwest are crucial components of any effective flood risk management strategy for Beira. Figure 84 shows a few examples of flood risk reduction measures implemented in this territory.

This program of measures has the advantage of exploiting the possibilities offered by the natural environment (e. g., the reinforcement of the dune-beach system) and the built environment (e. g., the road network and the sewerage network). In regard to the urban environment, the measures adopted aim to improve several services simultaneously: flood protection, transport, and sanitation. Specific provisions for crisis management are also included in the plan, with the establishment of an early warning service and the improvement of infrastructure identified as essential in the event of evacuation.

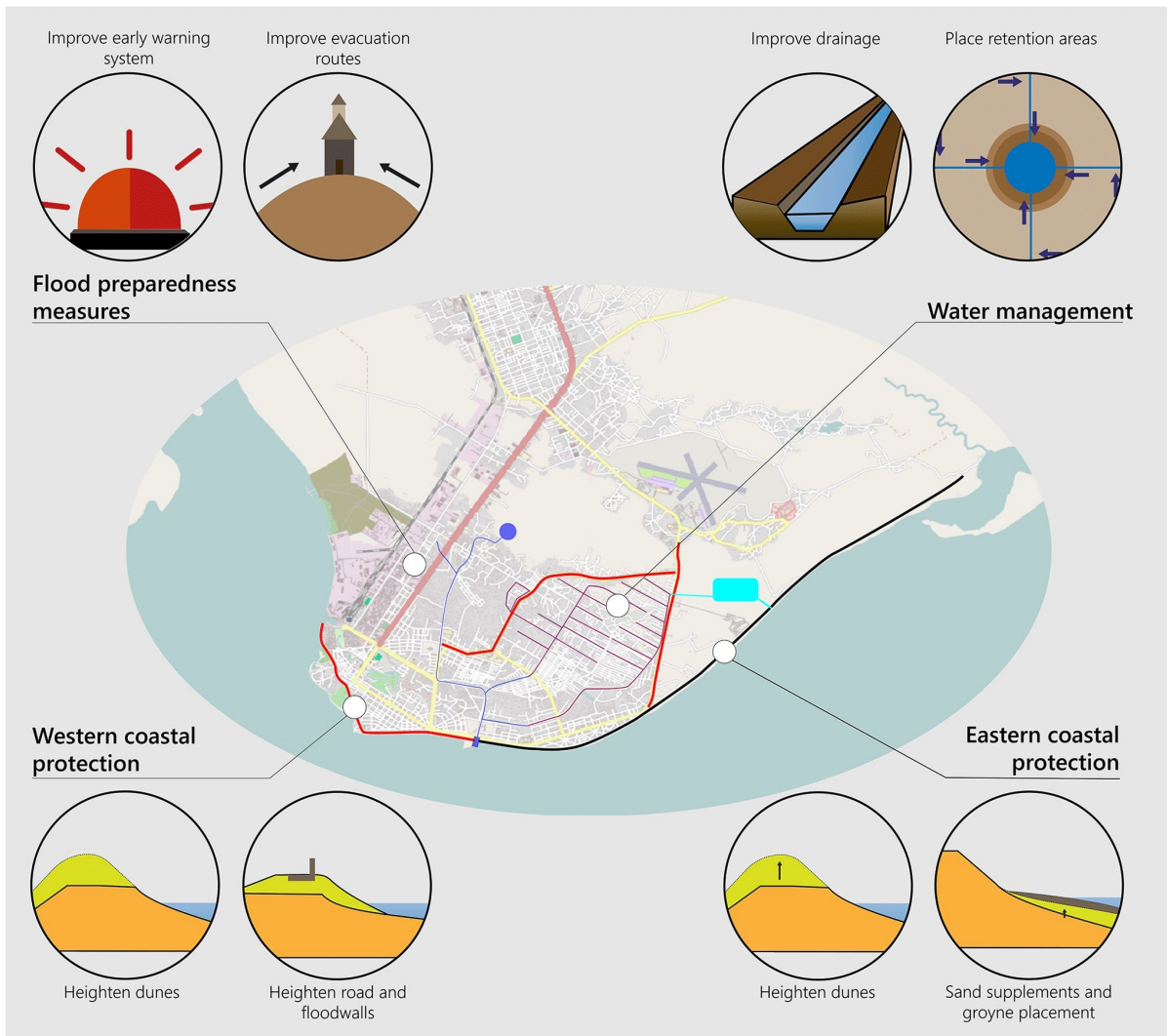


Figure 84: Map of Beira, Mozambique. Denoted are a few examples of flood risk reduction measures (Van Berchum et al., 2020).

3.3.3 Manage a transformation

Transformation becomes particularly relevant when existing mitigation and adaptation practices cannot reduce risks and impacts to an acceptable level (IPCC, 2019).

At a conceptual level, knowing if, when, and how to initiate transformative change, before it is too late to escape a seriously undesirable basin of attraction, is at the heart of SES transformability (Walker et al., 2004). It should be noted that in the context of population growth, land use changes, and climate change, the possibility of returning to a desirable regime that would have been left behind is certainly very limited, since slow evolutions that underpin the regime change, continue and accelerate (such as population growth, deforestation, rising sea levels, ocean acidification, and rising water temperatures).

Therefore, the main challenge is to control the conditions of the transformation to avoid the disastrous consequences of a sudden change, for example, initiated by a large-scale marine submersion. Walker et al. (2004)'s theoretical insights on this issue are also useful for understanding better the types of situations the territories are facing and how change should be « negotiated »: « A tension will exist between maintaining the resilience of a desired current configuration in the face of known (and some

unknown) shocks, and simultaneously building a capacity for transformability, should it be needed. How can we foster or maintain the flexibility that will be required to cope with unforeseen challenges? »

The answer to this type of question can no doubt be provided only gradually, through an adaptive approach, by seeking throughout the process:

- to preserve the chances of remaining in the original regime, for example, by ensuring the redundancy of the protection ecosystem service is maintained; and
- to prepare for a transformation that cannot be avoided, which includes ensuring that the diversity of protection modes is maintained, considering that this diversity will foster innovation.

Unfortunately, in practice, the process of transformation is generally undertaken under the constraint of difficulties which may arise on a daily basis (for example, due to a large subsidence or the rise of the RSL leading to a marine transgression), or during a major meteo-oceanic event. In response to the latter case, the Build Back Better initiative (Clinton, 2006) has been promoted in post-disaster recovery to encourage communities and stakeholders to rebuild beyond the pre-disaster state for safer, more sustainable and resilient communities. « Building Back Better (BBB) » is an approach to post-disaster recovery that reduces vulnerability to future disasters and builds community resilience to address physical, social, environmental, and economic vulnerabilities and shocks (World Bank/GFDRR, 2021). This concept was first introduced in 2006 by the United Nations Secretary-General's Special Envoy for 2004 Indian Ocean Tsunami Recovery, former US President William (« Bill ») Clinton (Fernandez and Ahmed, 2019), and it was adopted by UN member states as one of four priorities in the Sendai Framework (UNISDR, 2015). This approach applies the following recommendations, particularly to flood risk:

- designing buildings or raised-floor elevation in flood-prone areas;
- introducing and enforcing appropriate land-use planning regulations, which curtail reconstruction in high-risk areas;
- reconstructing improved hazard-control infrastructure, such as flood embankments.

As with adaptation strategies, examples of transformation strategies provide a more accurate and concrete representation of measures to be implemented in response to complex situations. To better cover the diversity of cases, these examples will again be chosen from both rich and emerging countries. As the strategies can be very different in rural and urban contexts, we distinguish these two cases, respectively through the following examples:

- the Mekong Delta, Vietnam. This territory represents an example of transformation in the rural context which is characterized by an evolution of economic activities. The smaller spatial constraints in the rural environment allow significant processing capacities;
- New Orleans, U.S.A. This example shows the significant transformation challenge for coastal megacities facing subsidence, disturbance of sedimentary fluxes, and the effects of climate change.

Example of transformation in a rural area (Mekong Delta, Vietnam)

The concept of transformation may involve, as a response to coastal flooding, shifting from a paradigm of protection reliant on seawalls to living with saltwater.

For example, coastal areas of the Mekong Delta in Vietnam increasingly experience salinity intrusion in freshwater systems, in part due to sea level rise, that compromises agricultural production and

domestic water supply. Faced with this threat, the development of engineered infrastructure is favored by national authorities, whereas complementary or alternative solutions to increase the resilience of SESs with respect to salinity intrusion exist. These include regeneration of coastal ecosystems (in particular, mangroves and other forests), agronomic measures, upstream flow control, and shifts in agro-ecosystems (Renaud et al., 2015)

In this context, farmers of the Mekong Delta of Vietnam seized the opportunity to diversify their land use, switching, for instance, from permanent rice to alternating rice-shrimp systems, or even changing completely to permanent shrimp systems (Kruse et al., 2020).

Nevertheless in Vietnam, as in the rest of the world, large parts of the remaining mangrove forest are lost due to the expansion of shrimp farming in coastal areas. Even if shrimp farmers may well be able to plant, protect and manage mangroves, they have not enough rights and responsibilities over forests, and thus are not able to benefit from the production of mangroves as much as from shrimp farms (Ha et al., 2012).

In conclusion, the Mekong Delta has undergone a transformation that has resulted in changes in economic activity. These activities are now much less vulnerable to flood risk and salinization. However, an evolution of the mode of governance is essential, so that this transformation also ensures better preservation of the environment.

Example of transformation in an urban area (New Orleans, United States)

Transformation in an urban environment is much more difficult than in a rural setting. It is marked by an opposition between the need to ensure protection in the short term (on this time scale, the use of civil engineering works seems indispensable) and the equally compelling need, although it can only be satisfied in the long-term, to strengthen the protection provided by the natural environment.

In the case of New Orleans and the coasts of Louisiana after Hurricane Katrina, Constanza et al. (2006) demonstrated how the restoration of wetlands could provide an important and sustainable buffer against storm surges and wave action generated by tropical storms and hurricanes. The authors also proposed replacing parts of New Orleans that are well below sea level with :

- wetlands to trap sediments and rebuild the land (wetlands inside the levees can help clean waters, store short-term flood waters, provide habitat for wildlife, and become an amenity for the city); or
- buildings that are adapted to occasional flooding (*i. e.*, on pilings or floats or with non-essential items on lower levels).

Unfortunately, this type of action, as relevant as it is, is only beneficial over decades and centuries. However, after such a disaster, a rapid restoration of some form of protection is required. The first priority is therefore to re-establish a protection system based on civil engineering techniques. For this reason, in New Orleans, investments in the order of 15 billion USD, including a major storm surge barrier, followed Hurricane Katrina in 2005 (Fischetti, 2015).

The Louisiana Master plan for the coast, however, reconciles the two approaches as shown in figure 85.

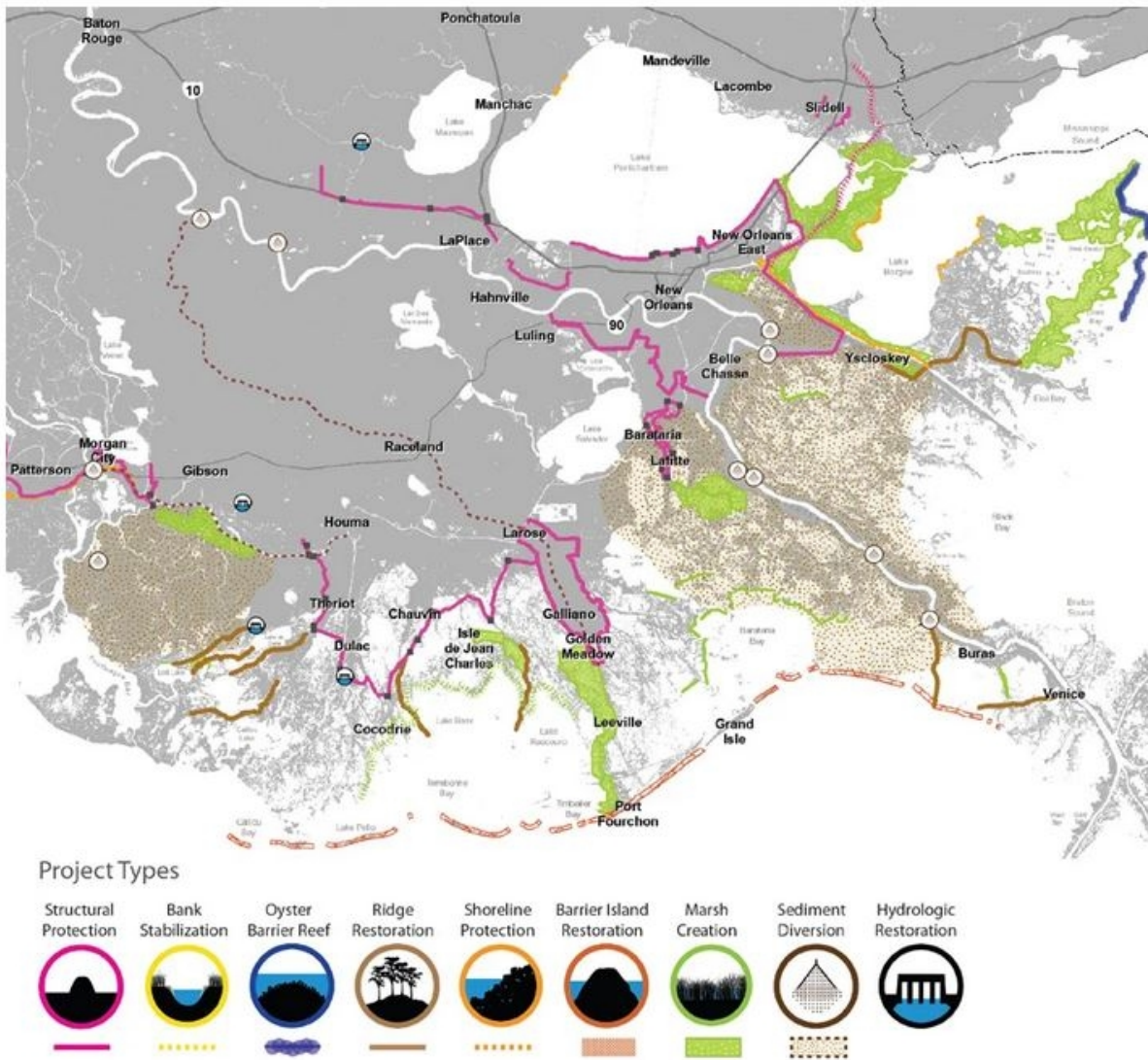


Figure 85: A detailed map from Louisiana's Comprehensive Master Plan for a Sustainable Coast. Credit: Coastal Protection and Restoration Authority of Louisiana. Baton Rouge, LA. 2012.

The following comments are helpful in understanding figure 85:

« Many projects (noted in the key) would be needed to rebuild vast but tattered wetlands (brown area) that would help protect New Orleans from surges of floodwater driven in by hurricanes. Chief among them are sediment diversions (brown circles), cuts in levees along the Mississippi River (winding white line), with gates that would open to allow nourishing sediment and freshwater to flow into the wetlands, revitalizing them. A 2.9-kilometer wall with gates to block surges from entering inner-city navigation channels has also been built (orange triangle just under the label « New Orleans East »). »

In conclusion, this example shows that projects to transform a territory can be undertaken in the long term. It is remarkable, however, in the case of New Orleans, that the transformation is intended to return the local environment to a pre-anthropogenic state.

3.4 A simplified approach: strategies in reference to sea level rise

Although the systemic approaches that consider territories and their protection systems as CASs should be preferred (at least to define the scope of the studies), adaptation recommendations often use, generally implicitly, another reading key for a simplified approach: assuming that sea level rise is the main threat, the main parameter guiding the strategies is the variation of the RSL.

To best account for this type of approach, the following points will be presented successively:

- projections of sea level rise and its effects;
- issues related to the monitoring of this parameter, both globally and locally; and
- adaptation options with reference to RSL rise.

Finally, a critical analysis of the simplified approach will be proposed.

3.4.1 Sea level rise and its effects

Variations at the global scale of the GMSL and at local scales of the RSL are phenomena that are the subject of numerous studies, and despite uncertainties about their magnitudes and speeds, some knowledge is well established. The projections for the coming decades and centuries and the expected effects are presented here on the basis of the synthesis elements of the Special Report on the Ocean and Cryosphere in a Changing Climate (IPCC, 2019).

Projections of sea level rise

The future rise in GMSL caused by thermal expansion of ocean, melting of glaciers and ice sheets, and land water storage changes, is strongly dependent on which RCP is followed:

- GMSL rise at the end of the century is projected to be faster under all scenarios, including those compatible with achieving the long-term temperature goal set out in the Paris Agreement. GMSL is expected to rise between 0.43 m (0.29–0.59 m, likely range; RCP2.6) and 0.84 m (0.61–1.10 m, likely range; RCP8.5) by 2100 relative to 1986–2005;
- ESL events that are historically rare are predicted to become common by 2100 under all emission scenarios, leading to severe flooding in the absence of ambitious adaptation efforts. Following both RCP2.6 and RCP8.5 emission scenarios, many low-lying coastal areas at all latitudes are expected to experience such events annually by 2050;
- beyond 2100, the GMSL is predicted to continue to rise for centuries due to continuing deep ocean heat uptake and mass loss of the Greenland and Antarctic ice sheets, and is predicted to remain elevated for thousands of years; Under RCP8.5 the few available studies indicate a likely range of 2.3–5.4 m in 2300. With strong mitigation efforts (RCP2.6), GMSL rise could be kept to a likely range of 0.6–1.1 m.

Sea level rise is not globally uniform and varies regionally. Thermal expansion, ocean dynamics, and land ice loss contributions will generate regional differences of about $\pm 30\%$ of GMSL rise. Deviations from the global mean can be greater than 30% in areas of rapid vertical land movements, including those caused by local anthropogenic factors such as groundwater extraction.

The effects of sea level rise

The rise of the RSL triggers numerous cascading effects, as shown in figure 86. In particular, rising sea levels, by increasing water depths, promote the propagation of waves to the coast and contribute greatly to the increase in the frequency of extreme events as well as to the weakening of coastlines, especially by erosion. The rise of RSL can also lead to other effects that could damage the habitability of a territory, including impeding drainage of inland waters and the salinization of soils and freshwater bodies. RSL rise and its physical impacts, such as flooding or salinization, also increase ecosystem vulnerability and decrease the ecosystem's ability to protect the coasts (IPCC, 2019). However, other phenomena, including local anthropogenic changes, also contribute significantly to the emergence of risks.

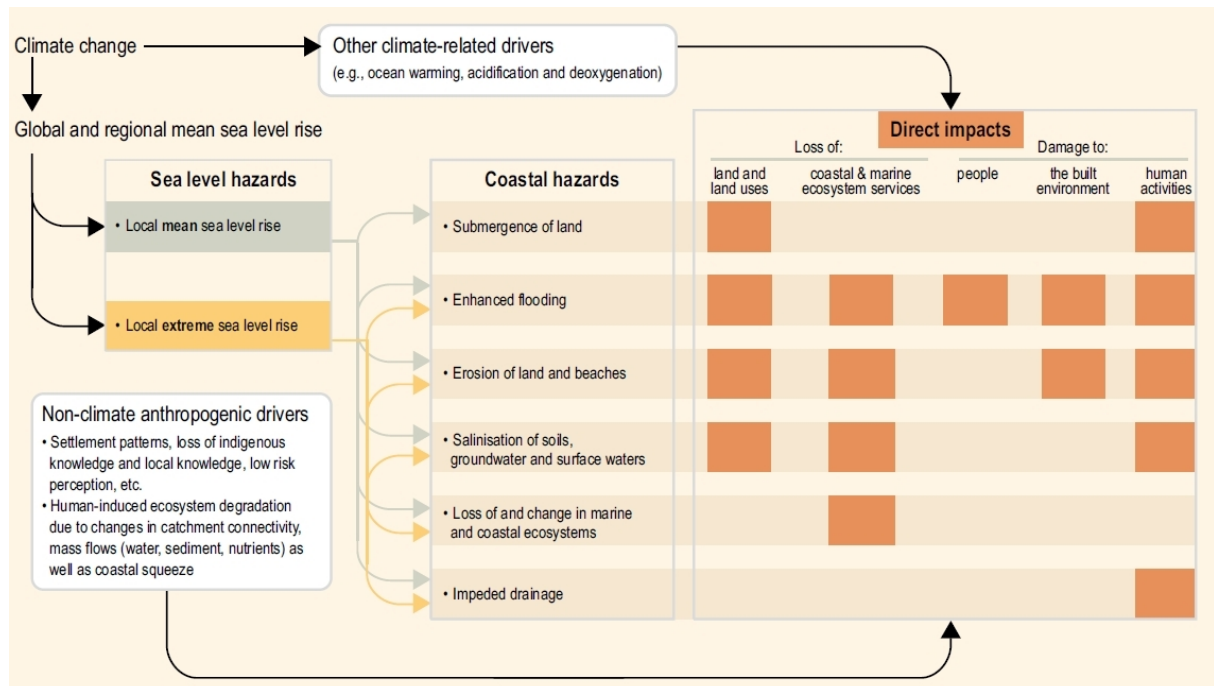


Figure 86: Overview of the main cascading effects of sea level rise. From Oppenheimer, M., B.C. Glavovic, J. Hinkel, R. van de Wal, A.K. Magnan, A. Abd-Elgawad, R. Cai, M. Cifuentes-Jara, R.M. DeConto, T. Ghosh, J. Hay, F. Isla, B. Marzeion, B. Meyssignac, and Z. Sebesvari. In: IPCC, 2019: Sea Level Rise and Implications for Low-Lying Islands, Coasts and Communities, figure 4.13.

3.4.2 Use of GMSL and RSL parameters

Monitoring the change in GMSL or local RSL and projections according to RCP scenarios have distinct interests depending on whether we consider:

- the planet: the objective is to assess the global consequences of GMSL rise and local variations of the RSL and thus contribute to the identification of stakes concerned by climate change and the actions to counter it;
- the territory: the objective requires planning for local adaptation. The RSL variation can be used to guide decision-making.

Assessment of stakes at the global level

At the planet level, assessing the consequences of the rise of the RSL by establishing a direct link in the projections between variations in RSL rise and greenhouse gas emissions, provides information on the benefits of measures taken to limit emissions. These benefits could, as part of a simplified approach, be compared with the cost of adapting territories to sea-level rise in order to determine whether efforts should be directed towards the fight against climate change, or rather towards measures to adapt to its effects. However, it is more relevant to address this issue as part of a comprehensive systemic approach that incorporates concerns other than coastal flood protection. Therefore, this point will not be further developed here.

To refine the estimates of SLR impacts on territories, the report (IPCC, 2019) provides a risk assessment for specific geographies: resource-rich coastal cities, urban atoll islands, large tropical agricultural deltas, and the selected Arctic communities far from regions of rapid GIA. As risk also depends on the effectiveness of coastal societies' responses to both extreme events and slow onset changes, to capture the response dimension, four metrics have been considered that refer to: (i) the implementation of adequately calibrated hard engineered coastal defenses; (ii) the restoration of degraded ecosystems or the creation of new natural buffer areas; (iii) planned and local-scale relocation; and (iv) measures to limit human-induced subsidence. On this basis, two contrasting adaptation scenarios were considered (see figure 87):

- the first scenario is called the 'No-to-moderate response' (see left bars in figure 87) and represents a business-as-usual scenario where no major additional adaptation efforts compared to today are implemented. That is, neither substantial intensification of current actions nor new types of actions, *e. g.*, only moderate raising of existing protections in high-density areas, sporadic episodes of relocation, or beach nourishment where large-scale efforts are not already underway;
- the second scenario, called the « Maximum potential response » (see right bars in figure 87), refers to an ambitious combination of both incremental and transformational adaptation (*i. e.*, significantly scaled up efforts); for example, relocation of entire districts, raised protections in some cities, or the creation/restoration of beach-dune systems at a significant scale, including indigenous vegetation.

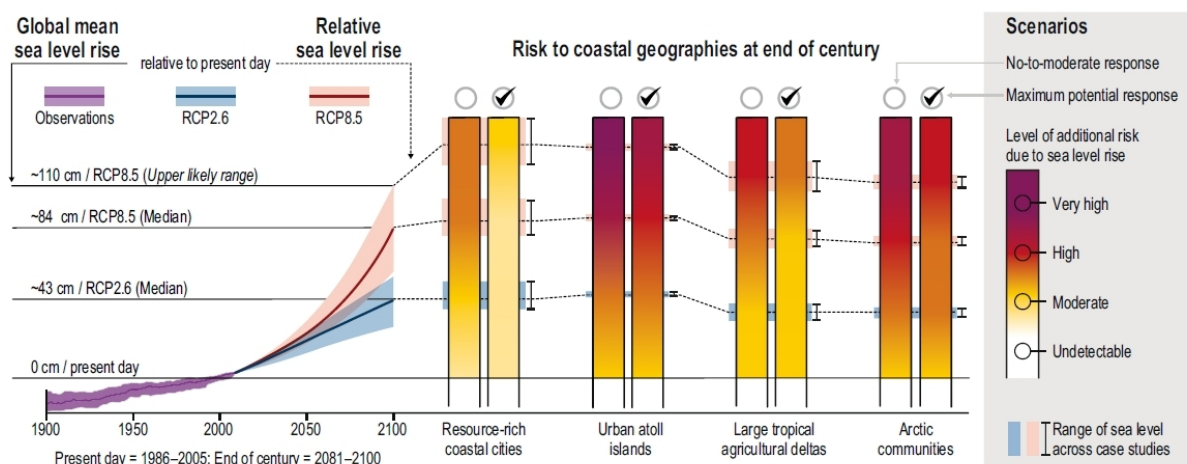


Figure 87: Additional risk related to sea level rise (SLR) for low-lying coastal areas by the end of the 21st century. From Oppenheimer, M., B.C. Glavovic, J. Hinkel, R. van de Wal, A.K. Magnan, A. Abd-Elgawad, R. Cai, M. Cifuentes-Jara, R.M. DeConto, T. Ghosh, J. Hay, F. Isla, B. Marzeion, B. Meyssignac, and Z. Sebesvari. In: IPCC, 2019: Sea Level Rise and Implications for Low-Lying Islands, Coasts and Communities, figure 4.3.

The findings of the IPCC (2019) report on this analysis by geographic category are as follows:

« The assessment shows that benefits in terms of risk reduction over this century are to be expected from ambitious adaptation efforts:

- for resource-rich coastal cities, adequately engineered hard protection can virtually eliminate the risk of flooding for the median value of the RCP8.5 scenario in 2100 (84 cm), except for the residual risk of structural failure;
- in other contexts, such as atoll islands, for example, while engineered protection structures will reduce the risk of flooding, they will not necessarily prevent seawater infiltration due to the permeable nature of the island substratum. So even coastal protection would not eliminate risk;
- in large tropical agricultural deltas and the selected Arctic communities, ambitious adaptation efforts mixing adequate coastal defenses, the restoration and creation of buffering ecosystems, and a moderate amount of relocation are expected to reduce risk. »

From this analysis, it appears that the use of coastal flood protection systems should be an option to study in priority in the context of coastal cities and deltas, but that other problems (*e. g.*, erosion and salinization), as well as more limited resources, lead to the adoption of other strategies (including relocation) in the context of small islands and Arctic communities.

These findings are questionable with respect to coastal flood protection systems. The fundamental issues of adaptation, transformation, or forced abandonment of levee systems on the most threatened coastlines, and the risks of maladaptation will be discussed in the next section.

Adaptation planning at the local level

Local monitoring of changes in RSL is based on the essential idea that « at some point », especially at the sites most exposed to coastal hazards, it will be necessary to make choices. The prospect of acceleration of RSL rise and the continuation of this phenomenon over several centuries raises the question of how long the habitability of a territory or of certain parts of that territory can be maintained. Under the assumption (too approximate on some coastlines but fairly accurate on the majority of them) that the variation of the RSL is of the same order of magnitude as the variation of the GMSL, the outlook is as follows:

- up to the year 2050, uncertainty in climate change-driven future sea level rise is relatively small, which provides a robust basis for short-term (30 years) adaptation planning: GMSL will rise between 0.24 m (with a 0.17–0.32 m likely range) under RCP2.6 and 0.32 m (with a 0.23–0.40 m likely range) under RCP8.5;
- beyond 2050, uncertainty in climate change induced GMSL rise increases substantially due to uncertainties in emission scenarios and the associated climate changes, and the response of the Antarctic ice sheet in a warmer world: GMSL is projected to rise between 0.43 m (with a 0.29–0.59 m likely range) under RCP 2.6 and 0.84 m (with a 0.61–1.10 m likely range) under RCP 8.5 by 2100.

Despite the large uncertainties about post-2050 SLR, adaptation decisions can be made now, facilitated by decision analysis methods specifically designed to address uncertainty, as presented in chapter 2.

The range of RSL rise to be considered in decision making also depends on the risk tolerance. Stakeholders with a low risk tolerance (*e. g.*, those planning for coastal safety in cities and long term investment in critical infrastructure) may also consider RSL rise above this range, because there is a 17% chance that GMSL will exceed 0.59 m under RCP2.6 and 1.10 m under RCP8.5 in 2100 (IPCC, 2019).

3.4.3 Adaptation options related to sea level rise

Building on previous research (Wong et al., 2014), the IPCC report (2019) describes, in addition to the option of no response, five main modes of adaptation to mean and extreme sea level rise: advance, protect, retreat, accommodate, and ecosystem-based adaptation³¹. These options are shown in figure 88.

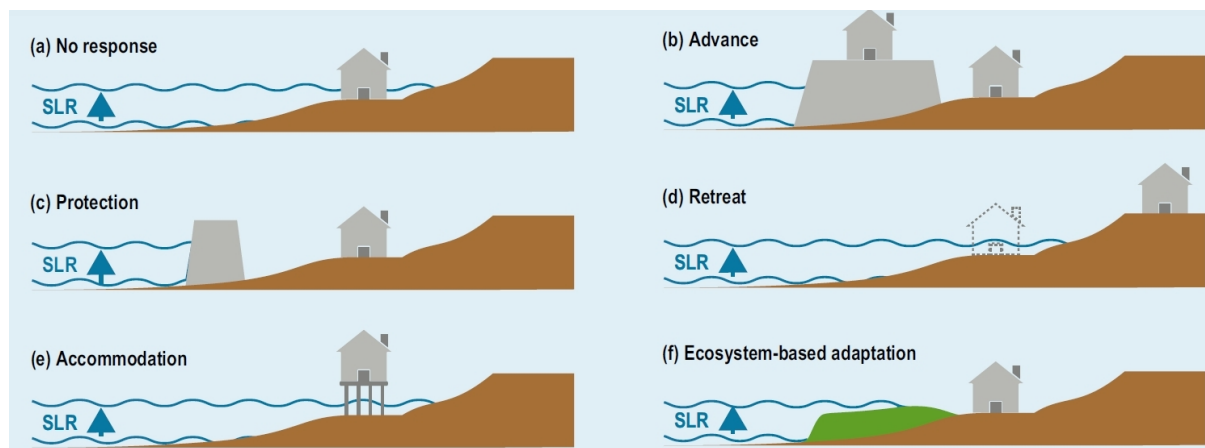


Figure 88: Different types of responses to coastal risks and sea level rise. From Oppenheimer, M., B.C. Glavovic, J. Hinkel, R. van de Wal, A.K. Magnan, A. Abd-Elgawad, R. Cai, M. Cifuentes-Jara, R.M. DeConto, T. Ghosh, J. Hay, F. Isla, B. Marzeion, B. Meyssignac, and Z. Sebesvari. In: IPCC, 2019: Sea Level Rise and Implications for Low-Lying Islands, Coasts and Communities, Box 4.3, Figure 1.

Chapter 4 of the IPCC report (2019) provides a comprehensive analysis for each of these options based on six criteria: observed responses, projected responses, cost of responses, effectiveness of responses, co-benefits and drawbacks of responses, governance challenges (or barriers), and economic efficiency.

While there may be some reservations about this approach based on the distinct options, the precise analysis of the IPCC (2019) report on each option provides credibility to its overall conclusions. These qualitative conclusions, moreover, focus only on the least debatable elements:

« All types of responses to SLR, including protection, accommodation, ecosystem-based adaptation, advance, and retreat have important and synergistic roles to play in an integrated and sequential response to SLR. Hard protection and advance are economically efficient in most urban contexts facing land scarcity, but can lead to increased exposure in the long term. Where sufficient space is available, ecosystem-based adaptation can both reduce coastal risks and provide multiple other benefits. Accommodation such as flood proofing buildings and early warning system for ESL events are often both low-cost and highly cost-efficient in all contexts. Where coastal risks are already high, and population size and density are low, or in the aftermath of a coastal disaster, retreat may be especially effective, albeit socially, culturally, and politically challenging (IPCC, 2019). »

While these conclusions cannot be disputed, their purpose is to shed light on the possibilities for adaptation emerging at the global level. However, this in no way constitutes strategic guidelines for building an adaptation project in a particular territory.

³¹ It should be noted that this typology presents a slight discrepancy with the typology of response options to sea level rise presented above: it does not take into account the fight against subsidence and consider the conquest of land on the sea.

3.4.4 A critical analysis of the simplified approach

The simplified approaches described above may be criticized, particularly when determining the strategies of adaptation for a particular territory. Simplification lies in two aspects:

- the monitoring of a single parameter: the RSL;
- choice making based mainly on a typology of actions defined in relation to this parameter.

Criticism of the choice of a single parameter

If, in the context of the establishment of strategies for the adaptation of a territory, questions are raised as to the reasons that lead to a preferential consideration of RSL rise in relation to other parameters, these reasons are generally not sufficient:

- RSL rise certainly triggers numerous cascading effects and can therefore represent an important parameter, however, other parameters related to ecosystem degradation and increased exposure in hazardous areas may be just as or even more important;
- defining an adaptation strategy certainly requires time benchmarks. The rise of the water level, despite uncertainties about its evolution, can be understood locally through long-term scenarios on the basis of a single parameter: the RSL. However, if other changes in the environment or exposure to hazards do not offer the same possibilities or the same projection facilities, they should still be taken into account.

The monitoring of sea levels cannot therefore be questioned: it helps to satisfy the CAS management principle of managing slow variables and feedback. However, in order to respond correctly to this principle, it is necessary to follow other variables, potentially equally as important, and not limit the study to the effects of sea level rise. Instead, it is crucial to extend the investigation into feedbacks that may occur in the systems studied.

Criticism of a decision-making method based on a typology of simplified options

The typology of adaptation options with reference to sea level rise is based on strong implicit assumptions that are not justified in many cases. Thus, the options described are only applicable if the following assumptions are, either completely or partially, verified:

- the coastal strip must have a significant slope, and therefore the possibility of reducing the exposure of the stakes by providing a zone for retreat at a short distance from the coast. The reality of territories is often quite different: the deltas are very flat areas and many small islands do not have an area allowing for retreat;
- the territory must have a topography maintained at a sufficient altitude over time. In many territories (such as deltas, small islands, and arctic territories), the observed phenomena and long-term projections indicate that this topography is likely to vary under the effects of subsidence or erosion of coastal features;
- the territory must have sufficient environmental stability. Most territories experience major disturbances in their natural environment (*e. g.*, acidification, rising ocean temperatures, and the degradation of wetlands) and the built environment (particularly as a result of population growth).

In addition, the simplified approaches consider the issues separately and propose adaptation solutions for each of them. However, these issues belong to a territory, *i. e.*, an SES that should be considered

as a CAS, and solutions should be defined at the level of the system in order to take into account the interrelationships between its components.

In conclusion, decisions for a territory cannot be made by considering the issues separately and by seeking solutions only modifying the coastline, as might be suggested by the simplified schemes presenting adaptation options. On the contrary, the issues should be considered globally and should take into account the physical, human, and biological dynamics of the territory envisaged in its three spatial dimensions. The use of methods that make it possible to understand these developments is therefore necessary to give meaning to decision-making. Ultimately, if simplified approaches are not devoid of interest, they are analytical approaches that should be preceded by comprehensive systemic approaches.

3.5 Complementary analyses to global and simplified approaches

The adaptation, transformation, or forced abandonment of protection systems can determine the habitability of territories, especially for the most exposed sites. As simplified approaches may generate some bias in assessment, this section provides additional insight into what can be referred to as « shadow zones ». These investigations are undertaken by considering the different levels of the panarchy identified in chapter 2. Thus, adaptation strategies are addressed:

- at the level of the protection system, pointing out two particular difficulties:
 - the ecological, technical, and social challenge of maintaining a coastal flood protection capacity;
 - the assessment of the economic cost of such protection;
- at higher levels (*i. e.*, the territory, region and planet), to avoid maladaptations that generate one or more adverse effects, including:
 - increased reliance on technology;
 - unsustainable management of resources.

In conclusion, a general view on adaptation strategies is given, taking into account the ecological, technical, economic and social aspects at the different levels of the panarchy. This view is complementary to those derived from global and simplified approaches.

3.5.1 Adaptation strategies at the level of protection systems

The adaptation of protection systems must be decided by means of an analysis that makes it possible to balance benefits and costs at different scales. However, the state of the art shows a strong tendency to:

- overestimate benefits by overestimating the system's ability to meet protection objectives;
- underestimate costs by too approximate estimates of project expenditures.

The conditions for obtaining a better appreciation of costs and benefits will therefore be sought here.

Overestimation of protection structure performance

The representation of a protection system as an SES warrants paying as much attention to ecological and social aspects as to the technical aspects. Indeed, for a system composed of multiple natural and anthropogenic structures to actually provide protection, it requires meeting many conditions: technical (condition of the structures), ecological (condition of the ecosystems in which the components of the protection system are situated), and social (capacity of the human organization to carry out maintenance, restoration, and adaptation operations) conditions. Failure to meet any of these conditions can significantly weaken or even destroy the protection capability of the system. However, the scientific literature, as summarized in the IPCC report (2019), does not address these multiple conditions jointly: their juxtaposed presentation does not allow for a correct assessment of the combined and cascading effects of the difficulties encountered for each of the components. Some of these effects are identified below, addressing technical constraints in relation to:

- biophysical constraints. In the relatively stable context preceding the first effects of climate change, the nominal operating conditions of the systems were determined by levee system managers on the basis of historical reference events. However, in the rapidly evolving context of the 21st century, the IPCC's (2019) prognosis is too optimistic: « For resource-rich coastal cities, adequately engineered hard protection can virtually eliminate risk of flooding for the median value of scenario RCP8.5 in 2100 (84 cm) except for residual risk of structural failure. ». In the face of an intensification of hydraulic actions generated in particular by the RSL rise and the degradation of ecosystems, the residual risk of structural failure is a significant risk that does not allow for such a strong assertion of protective capabilities (the New Orleans flood clearly showed that the resource wealth of a city is not a sufficient condition for its protection);
- socio-economic constraints. In addition to capital investment, the development of appropriate institutions and governance mechanisms to deliver maintenance, as well as the necessary funding streams, are essential for a protection-based adaptation strategy to be effective (Nicholls et al., 2019). The occurrence of a disastrous event, such as the Xynthia storm that impacted the central part of the French Atlantic coast, affects multiple systems of protection against coastal flooding and for the restoration of the systems and their adaptation, requires the sustained multi-year engagement of jurisdictions and organizations with technical expertise (where this capacity is not available, it needs to be developed, requiring even more time). The ability to adapt, or more simply to maintain a form of protection in the face of a sharp increase in events that are deteriorating systems, will most certainly be limited by the ability of societies to develop adaptation plans that are:
 - acceptable to the community as a whole – sometimes this consists of only a few dozen people, but in other cases hundreds, thousands, or even millions of people. Regardless of the number, differences may arise and conflicts erupt; and
 - achievable within a short period of time with the resources available, while respecting the principles of sustainable management of these resources.

Regardless of the analyses undertaken and the disciplines involved, it is important not to lose sight of the significant changes underway or anticipated. While feedback remains useful, in the reality of rapidly changing environmental conditions, it is unfortunately not sufficient. Thus, it is not relevant to transpose to all sites historical cases of successful control of flood risks such as that of the Netherlands: in this country, the protection has been put in place over a period of about a thousand years, promoted by the abundance of resources and during a relatively stable period for sea level. The necessary adaptation in many territories will take place in the context of rapid and accelerating sea-level rise, and increases in extreme phenomena, often in combination with subsidence phenomena, sedimentary erosion, and environmental degradation. Therefore, specific studies should be carried out to assess the cumulative and cascading effects that often constitute the workings of disasters. Further steps must be taken to ensure that natural disasters are not aggravated by industrial disasters, when sensitive sites are

positioned in submersible areas, which is frequently the case at industrial-port sites, and nuclear power stations in particular. Thus the analysis reported by the IPCC (2019) does not seem to give a realistic or accurate report when stating that:

« There is high confidence that well designed and maintained hard and sediment-based protection is very effective in reducing risk to the impacts of sea level rise (SLR) and extreme sea level (ESL) (Horikawa, 1978; USACE, 2002; CIRIA, 2007). This includes situations in which coastal megacities in river deltas have experienced, and adapted to, relative SLR of several meters caused by land subsidence during the 20th century (Kaneko and Toyota, 2011; Esteban et al., 2019). »

There are two biases in these statements:

- the performance of a system of protection cannot be judged solely on the performance of the defenses against water ingress. The problem of protection against coastal flooding is more complex and should address the functioning of the system in a more global approach, including the defense against water inlets, but also the drainage of continental waters. The methodological guides cited are certainly very useful for the design and maintenance of defenses against marine flooding, but are not intended to address the system as a whole;
- conclusions on the successful adaptation of coastal megacities on deltas are based on a period of observation:
 - of insufficient duration: considering the situations created in the 20th century, it is impossible at the beginning of the 21st century, a few decades later, when cities have not suffered major meteo-oceanic events, to conclude that the risks are controlled;
 - without a significant increase in risk. Future situations of sites facing rising sea levels are not equivalent to situations of cities prone to subsidence, the extent of which may be limited to water extraction sectors, and therefore does not necessarily alter, nor in the same way, the conditions of wave propagation.

Underestimation of the cost of protection systems

The estimation of the cost of protection systems has already been addressed at the beginning of this chapter through the critical analysis of studies conducted at a global scale by Lincke and Hinkel (2018) and Tiggeloven et al. (2020). In particular, it appeared necessary in the estimates:

- to better take into account site-specific constraints (*i. e.*, the natural environment and built environment);
- to ensure that maintenance costs are not underestimated (requiring a minimum value of 2% of the investment cost) and that discount rates are not overestimated (a long-term rate of 1.5% is recommended by the institution France Stratégies). The global cost of a protection project is very sensitive to these two parameters. A sensitivity study must therefore be carried out to cover the range of uncertainty.

These two points are addressed here in more detail. The first involves spatial analyses, and the second involves mainly temporal analyses.

As for the technical aspects, it is important to avoid approaching coastal flood protection from an economic perspective with overly simplified approaches. As coastal flood protection systems consist of a set of structures such as levees (sometimes layered in several rows), breakwaters, seawalls, which are possibly supplemented by storm barriers and natural features, the economic assessment should be based on:

- the length (or better, the volume) of the structures and not the length of the coastline. Where possible, consideration should also be given to the height of the structures (as proposed by Lenk et al. (2017) for coastal levees). In general, a three-dimensional approach is necessary: for dune-beach systems for example, it is preferable to take into account the volume of sediment opposing resistance to hydraulic actions, rather than a dune length exceeding a certain height. Similarly, the biomass of mangroves and the shape of coral reefs should be considered;
- the search for protection structure combinations, with the aim of optimizing costs. In particular, coupling natural features with artificial structures, which in turn strengthen the natural features, is a good way to limit long-term spending. Ideally the economic study should cover an even wider spectrum, encompassing the natural environment, the protection system, and the built environment. This was proposed by Aerts (2018), who researched unit costs for six broad categories of flood adaptation measures: (1) the flood proofing of buildings, (2) flood protection, (3) beach and dune nourishment, (4) nature-based solutions for coastal ecosystems, (5) channel management and nature-based solutions for riverine systems, and (6) urban drainage.

The studies of Lenk et al. (2017) and Aerts (2018) provided interesting theoretical contributions to cost assessment. However, the results obtained remain fragmented, and the uncertainties on unit costs are far too high for a construction manager to utilize for cost estimates for a particular project (a rapid estimate on the basis of the unit costs appearing in current public work contracts would be more accurate). The main reason is that the initial data used for these studies comes from bibliographic reviews, with data of multiple international origins. In reality, estimates can only be made on the basis of costs observed currently in the given context (which therefore assumes the availability of recent national or regional studies), because the availability of resources and the general economic context are decisive.

The international state of the art in this area should therefore progress, not by seeking cost estimates, but by supplementing and refining the methodology for observing costs in a territory, as presented in chapter 5.

Nevertheless, the cost of management and maintenance operations for different types of structures, expressed as a function of the investment cost (as a percentage) deserves in-depth discussion. As indicated in the analysis of strategies at a global scale at the beginning of this chapter, the values adopted are generally not justified by the study of investment programs and of maintenance budgets that ensure effective protection. They are hypothetical values that are considered likely (as part of comprehensive studies incorporating multiple parameters) because they are adopted in areas other than flood protection. These very low values can only correspond to situations where the maintenance and management of the structures are not properly ensured. Before Xynthia hit the French Atlantic coast and a review of coastal flood protection systems was undertaken, management and maintenance costs could also have been roughly estimated at 1% of the cost of construction, the latter being itself very difficult to evaluate, since the structures were very old. But this was a situation where many of the structures were not maintained or even inventoried (Bersani et al., 2010).

Under conditions where the state of the structures is regularly checked and maintenance operations are carried out to ensure the desired performance is achieved, maintenance costs in the order of 2% are observed (Cerema, 2018a). This percentage may be used for structures operating under current conditions. But this does not properly estimate maintenance costs if the work is subjected to greater or more regular stressors, such as those derived from climate change. In this case, the global cost

necessarily increases, either by the increase in maintenance costs, or because a structure that is resized to take into account greater stressors will have been built. In the latter case, the higher investment cost will most likely be followed by less frequent but more costly maintenance operations.

With regard to maintenance costs, it should be noted that under the right conditions, and to a limited extent, ecosystem-based adaptation measures are free of maintenance costs because they respond and adapt to changes in their coastal environment. However, maintenance can become important in the aftermath of damage by storms or human action, for example, when wetlands and reefs are damaged by high winds, waves, and surges, or affected by dredging operations (Smith III et al., 2009; Puotinen et al., 2016).

3.5.2 Adaptation strategies with upper-level constraints

Defining strategies for the adaptation of protection systems without taking into account the orientations that should be taken at the level of the territory, the region, or the planet, can lead to globally counterproductive results (maladaptation). Protection actions by inappropriate engineering programs are mainly concerned.

The purpose of this section is to identify the main types of maladaptation and to propose alternative strategies to avoid them.

The undesirable consequences of maladaptation all include ecosystem degradation and increased risk. The modes of maladaptation will therefore be presented according to categories that are specific to the subject treated, seeking their connection to the different levels of the panarchy:

- at the level of the territory in which the protection system is set up, the development of dependence on technologies, including water retention and pumping technologies;
- at the territorial and regional level, the inappropriate management of resources results in conflicts of interest between flood protection and agricultural or industrial activities.

At the planet level, maladaptation risks arise from the previous two levels, increasing dependence on technologies and inadequate resource management, both contributing to increased greenhouse gas emissions, increased global warming, and the previously mentioned adverse effects (ecosystem degradation and increased risk). The risks of maladaptation at the planet level will therefore not be further discussed.

Avoiding increasing reliance on technology

The increased reliance on technology can result in the inappropriate use of the protection system components, such as:

- levees. If sea level rise does not stabilize beyond 2100, which is most likely based on current research (IPCC, 2019), raising the level of civil engineering structures will run the risk of being locked into an impasse in which development intensifies behind higher and higher defenses, with escalating severe consequences in the event of protection failure (Wong et al., 2014; Welch et al., 2017). This impasse results from protection promoting further economic development in the flood zone within defenses, which then leads to further defense raising with RSL rise, and an increasing value of exposed assets;
- surge barriers. To protect against floods (or for other purposes: agriculture, pasture, salt production, flood prevention, transportation, and access to uplands), structures were built to restrict tides. These structures interrupt mass flow processes (including water, nutrients, and sediments), and thus impact tidal ecosystems. The impact depends on the type of restriction, its severity, and the geomorphology of the system (Burdick and Roman, 2012). Restoration of tidal exchange is important to restore various ESs, such as essential fish habitats, and to

reestablish a self-maintaining system. Unfortunately, in the cases studied by Burdick and Roman (2012), tidal restrictions have enabled the construction of dwellings and infrastructure within areas that were once flooded by the highest tides. For this reason, restoration of such systems has been only marginally successful;

- pumping and drainage systems. Gradually rising water tables behind defenses is also an issue that can be managed by increasing pumping and drainage (Aerts, 2018). Maintaining effectiveness over time requires regular monitoring and maintenance, as well as accounting for changing conditions such as RSL rise and widespread erosional trends in front of the defenses. Examples include southeast Florida, which has protected areas that can be flooded by rising groundwater through underlying porous limestone (Bloetscher et al., 2011).

All these technical devices are likely to disturb the natural environment. When hard structures are built without consideration for the impacts on the buffering coastal ecosystems, they can actually reduce the adaptation potential of the coast. Coastal squeeze and the starvation of sediments from the construction of canals and levees are examples of this (Campbell et al., 2009).

Avoiding the inappropriate management of resources

Protection against coastal flooding should not eclipse other issues such as access to freshwater, sediments, and other materials (such as armourstone and wood) used in agriculture, building construction, and land use planning. Conflicts of interest exist, or are likely to emerge between agricultural and industrial actors and those involved in protecting against the risk of coastal flooding. This problem may depend on:

- the regional level (at the delta or watershed scale). In deltaic environments, Renaud et al. (2013) considered that a tipping point will be reached when specific ESs cannot be relied upon anymore, leading to shifts in the ecological state and/or human activities (such as changes in agroecosystems, changes in livelihoods, and migrations). A tipping point can also be reached when the current management approach simply cannot be maintained because of growing resource constraints. Some territories will only be able to maintain their habitability over the long term through recovery basin-scale management that allows more natural flows of water and sediments through the system. Strategies for long-term flood mitigation include improved river-floodplain connectivity, the controlled redirection of a river during times of elevated sediment loads, the removal of levees, and the redirection of future development to lands less prone to extreme flooding (Renaud et al., 2013; Day et al., 2016; Brakenridge et al., 2017);
- the territory benefiting from the protection system. Coastal adaptation governance can be complicated by existing conflicts over resources. For example, illegal coastal sand mining is currently a major driver of coastal erosion in many parts of the developing world (Peduzzi, 2014). A further emerging issue is sediment scarcity mainly driven by demand of sand and gravel for construction, but also for beach and shore nourishment (Peduzzi, 2014; Torres et al., 2017), which makes sourcing the increasing volumes required to sustain beaches in the face of RSL rise more expensive and challenging.

On this last point, it should also be pointed out that:

- seabed dredging of sand and gravel can have negative impacts on marine ecosystems such as seagrass meadows and corals (Erftemeijer and Lewis III, 2006; Erftemeijer et al., 2012) ;
- nourishment practices on sandy beaches have also been shown to have drawbacks for local ecosystems if habitat factors are not taken into consideration when planning and implementing these interventions (Speybroeck et al., 2006).

These operations, even if carried out with the aim of improving protection against coastal flooding, can prove counterproductive if they harm natural formations that provide protection.

3.5.3 Conclusion of the supplementary analysis

The final analysis was intended to provide additional insight on a few key points previously provided by:

- the comprehensive approaches that are fair, but imprecise with regard to protection systems; and
- the simplified approaches which, on the other hand, claim to be precise, but generally fail to do so because of a lack of accuracy.

This analysis was undertaken with reference to the conceptual framework presented in chapter 2, according to the levels of the SES panarchy, distinguishing between the level of the protection system and the higher levels of the territory, the region, and the planet.

At the level of the protection system, the conclusions of many authors converge on the protection that should be given, as a priority, to urban areas with the highest stakes. Furthermore, it appears that:

- in urban contexts, adaptation strategies will certainly have greater financial resources, but they will also be subject to greater constraints, the rigidity imposed by the urban fabric, and the conflicts of interest which can arise in response to a change in the levels of protection or the appropriation of the areas necessary for the adaptation of the system. Stable institutions with strong prerogatives will be necessary to carry out these projects with sufficient anticipation and involvement of the community according to the principles of adaptive co-management;
- relevant forms of adaptation can only be achieved through adequate knowledge of the system in place including all of its anthropogenic and natural components. The comparison of several options for adaptation at various time horizons can be carried out by economic evaluations. However, the cost of adapting and maintaining the structures can only be estimated in the regional economic context. Therefore, it is more important to look for methodological frameworks that can be applied in different contexts on the basis of local cost observation, than to seek unit costs at the international level, which cannot be applied universally.

At the higher levels (territory, region, and planet), the analysis shows the value of integrating the adaptation strategies of protection systems into more global strategies, with the aim of avoiding maladaptations which generate one or more adverse effects. It appears that, in general, the principles of traditional development using civil engineering for the construction of levees and drainage systems lead inevitably to a degradation of the ESs of protection, and therefore to an increase in risk following processes that correspond to:

- increased dependence on technologies (such as levees, pumping and drainage systems, and storm barriers in estuaries). In the future, it will be necessary to develop ecosystem-based solutions. However, under changing climatic conditions, there are limits to the effectiveness of ecosystem-based adaptation, and these limits are currently difficult to determine (IPCC, 2019);
- unsustainable resource management. Fresh water, sand, armourstone, and wood are multiple-use resources. Clarification is needed on the status of these resources and their optimal use. It would seem more relevant in the context of climate change and RSL rise to direct these resources preferentially towards the protection of threatened territories than towards the construction of new buildings on exposed sectors.

Ultimately, regardless of the SES considered, and beyond the reduction in greenhouse gas emissions that corresponds to a general climate change mitigation measure, long-term adaptation of coastal territories consists mainly of two actions:

- the preservation or restoration of ecosystems that play a protective role and their support in the face of the effects of climate change. However, in the long term, such adaptation does assume that the climate can be stabilized;
- reduction in exposure to hazards, in particular by developing retreat strategies or, at minimum, by revising planning schemes, redistributing urbanization to less vulnerable areas, or via neighborhood decongestion measures to facilitate evacuation in the event of a hazard. Risk management is thus integrated into land use planning and management (Cerema, 2019a).

Other accommodation measures exist, including protection structures. Nevertheless, these measures should be considered as temporary measures, given the increase in hazard: economic challenges to hard protection increase with higher sea levels and will make adaptation unaffordable before technical limits are reached. Therefore, investing in levee systems not knowing the extent to which such systems can protect against future events is only acceptable if it does not impede upon the implementation of other actions contributing to risk protection with more long-term assurance. In this sense, short-term benefits should be sought only if the cost of the transitional measures is low enough, so that it does not penalize investment in longer-term strategies.

Economic challenges are further accentuated by societal challenges, particularly those of governance and financing. Psychological aspects of adaptation will also contribute to reducing the implementation capabilities of these technical solutions: how can we continue to invest when the impression of insecurity behind the structures is increasingly strong? Beyond a certain level of risk, this type of consideration will certainly prevail over rational approaches based on economic calculation. After Hurricane Katrina devastated New Orleans, the city lost 30% of its population in the years following the event (CensusViewer, 2020). This reduction in the population also corresponds to a loss of resource availability for flood protection. A phenomenon of impoverishment can occur either at the level of the most threatened neighborhoods, or at the scale of the city, with the inhabitants remaining belonging to a low-income demographic who did not have the means to settle in safer places.

Lastly, a multi-risk analysis leads to the conclusion that some areas may become uninhabitable for other reasons, including salinization of land, and depletion of land and marine resources. In which case, it would not be appropriate to invest in strengthening the coastal flood protection system.

3.6 Synthesis and conclusion

Adaptation or transformation strategies can be considered using two joint approaches:

- considering territories and their coastal flood protection systems as CASs. With this perspective, principles and options for adaptation have been sought in relation to the observed and projected responses of the natural and built environment;
- considering the rise of RSL as a major parameter in the evolution of coastal hazards, including coastal flooding or salinization of inland waters and soils.

Ecosystem-based analysis should be conducted on SESs consistent with the multiple themes that an adaptation project must address:

- the watershed is a SES relevant for the consideration of global and local changes, especially when they affect the management of water, sediments, and other materials that may be utilized for protection against coastal flooding (for example, armourstone, and wood);
- the territory makes it possible to take into account the changes in the natural environment and the built environment and to plan for adaptations of the protection systems in a coordinated manner with these changes.

The main interest of the approach focused on RSL rise is to provide spatio-temporal benchmarks in the definition of protection strategies. This parameter is also used in global studies to identify, under several scenarios, the exposed territories, the associated demographics, and economic issues in order to determine the benefits that could be expected from effective protection. Nevertheless, the results of these studies appear to be fragile when it comes to assessing the real possibilities for adaptation of territories and their protection systems. This fragility naturally increases over longer-term projections.

In practice, these two approaches should be coordinated: CAS management principles (maintaining redundancy and diversity, managing connectivity, and managing slow variables and feedback) are a means of ensuring the relevance of results derived from simplifying assumptions. In all cases, assessing the real possibilities of adaptation at various times requires taking into account all the components of protection (the natural environment, the built environment, and the levee system), and seeking the optimization of performance coupled to the reduction of expenditures over the long term.

The definition of these strategies should be integrated into a territorial project in order to avoid forms of maladaptation which invariably result in environmental degradation and higher risks due to processes of increasing dependence on technologies and inappropriate resource management. Only long-term planning, consisting of a redevelopment of territories to preserve or restore the protection ESs, and limiting exposure to hazards will make it possible to gradually reduce dependence on containment technologies and to progress in implementing the principles of adaptive co-management. Whatever the SES considered, the existence of stable institutions capable of carrying out and financing projects over their entire duration is an essential condition for the effective implementation of the strategies.

4 RESEARCH QUESTIONS AND RELATED ISSUES

The bibliographic analysis shows that the coexistence of two conceptual approaches – social-ecological resilience and technical resilience – applied to two distinct systems (the territory and its protection system, respectively) over distant time horizons, generates a form of compartmentalization in risk analysis methods and in the definition of adaptation strategies used in both land use planning and coastal flood protection. This lack of integration leads to a definition of protection systems based on poorly justified simplifying assumptions, not adequately framed by comprehensive and systemic approaches at the territorial level or higher scales. As a result, these analyses may result in:

- an overestimation of the performance of the protection systems and an underestimation of their cost, two biases likely to strongly alter the prognosis on the maintenance or adaptation of the systems, and in some cases, on the habitability of the territories;
- various forms of maladaptation resulting in increased risk, increased dependence on technology, inappropriate resource management, and/or environmental degradation.

This leads to the first question: What can be done to improve the development of strategies for adapting the protection systems and territories concerned?

There are multiple ways to do so. However, when it comes to informing or supporting decision-making, methodological developments should be central to the system. To confirm this, we need only return to the initial objective of promoting the sustainable development of systems by strengthening their resilience, while keeping in mind the definition of social-ecological resilience: « Resilience is a positive attribute when it maintains capacity for adaptation, learning, and/or transformation (Walker et al., 2004) ». Methodological development is a way of capitalizing on knowledge. In particular, feedback enriches the methodological production and constitutes a form of learning that is oriented towards the adaptation and transformation of systems. Methodologies should therefore be considered as an essential component of resilience development.

Nevertheless, flood protection and resilience building are topics on which many methodological developments have already been established, as shown by the extensive bibliographic corpus. This leads to a second question: What are the reasons for considering new methodological developments?

In the field of coastal flooding and more generally, coastal hazards, many factors lead to an increase in risk or the emergence of new risks: climate change, demographic change, unplanned and rapid urbanization, poor land management, weak institutional arrangements, complex supply chains, limited availability of technology, unsustainable uses of natural resources, and declining ecosystems (UNISDR, 2015). It is certain that this situation requires redoubled efforts in the observation of territories, analysis of feedback experiences, and development of prediction and anticipation systems in order to adapt the decision support tools. The adaptation of territories and protection systems therefore requires the adaptation of methodologies. Indeed, methodological developments and practical actions carried out in the territories should be mutually enriching. Reflecting the continuous improvement sought in reality, the development of the methodological corpus should be part of a process of continuous improvement.

These reflections lead to a third question, at the core of the subject: In which ways should research continue in order to lead to methodological developments in the adaptation of protection systems?

This question reflects the problem of strengthening the resilience of protection systems through methodological developments. To address this problem in a more structured way, the implications of the concept of resilience on methodological developments must be sought to clearly identify the main lines of research. The topics explored in my research work over the period 2010-2018 will be placed within this defined context.

4.1 Implications of the concept of resilience on methodological developments

In order to realign the methodological development for flood protection with the objectives of strengthening the resilience of systems, it is necessary to have benchmarks in areas of knowledge that need to be further developed and on the conditions necessary for effective action. In order to obtain these benchmarks, the definition of the resilience of a system was used with the objective of deriving implications for decision support. This topic was discussed in detail in Igigabel et al. (2020), whose analyses showed that methodological developments meeting the requirements of the concept of resilience fall into two categories:

- « sectoral » methodological developments. The application of the concept of resilience requires improved knowledge in the following three areas:
 - the definition of the system to which the concept of resilience is applied;
 - the changes, disruptions, and hazards that the system faces; and
 - the modes of action for the preservation, adaptation, or transformation of the system;
- « integration and coordination » methodological developments. The efficiency and effectiveness of resilience-building actions depend on implementation conditions and governance patterns that go beyond the framework of protection system management. To enhance the adaptability of protection systems subject to these constraints, specific recommendations should be made to ensure:
 - better integration of strategies for adapting protection systems at larger spatial and longer temporal scales, whether in terms of land use planning or reducing greenhouse gas emissions;
 - better coordination of decision support tools. This should result in the coordinated management of methodological frameworks, information (including databases and mapping), and operational tools, in particular to improve their compatibility.

With reference to this formal framework, and considering the limitations of the state of the art identified in the previous chapters, the following guidelines can be defined:

- sectoral methodological developments should aim primarily at supporting decision-making in defining measures to adapt protection systems, while avoiding the pitfalls of overestimation of performance and underestimation of costs;
- « integration and coordination » methodological developments, by broadening the scope of the analysis, should reduce the risk of maladaptation.

In reference to the SES resilience management principles established by Biggs et al. (2012), these two types of methodological developments relate to the key generic SES properties and to key attributes of their governance systems, respectively.

4.2 The search for sectoral methodological developments

One of the key ideas developed in (Igigabel et al., 2020) is that one must focus on first identifying the protection system and gather knowledge of the hazard instead of initiating with modes of action. In the field of risk management, the willingness to act may in fact unconsciously limit the time devoted to acquiring knowledge. The main issues for sectoral methodological developments are presented below for the three sectors identified, namely: (i) the definition of the protection system; (ii) the knowledge of changes, disturbances, and hazards likely to affect it; and (iii) the definition of the modes of action for its preservation, adaptation, or transformation.

4.2.1 Definition of the system to which the concept of resilience is applied

The literature review confirms the need to better identify and characterize protection systems. This knowledge is crucial for understanding the system through its relations with the natural environment, the built environment, society and its institutions. In short, the methodologies should reconsider protection systems as SESs in their own right, and make recommendations that take into account the position of these systems in relation to higher-level systems (*i. e.*, the territory, region, and planet). Conversely, lower-level systems or subsystems (structures belonging to the protection system, components of these structures, etc.) are more naturally integrated into the analysis and decision-making regarding coastal flood protection systems. No specific problems were identified in this area.

Progress in the methods of identification and characterization of protection systems as SESs and CASs is therefore the major issue. Responding to this problem should make it possible to better understand the response of systems to all types of action, and to better define adaptation strategies. Formulating methodological recommendations in this respect requires revising the concept of the protection system to give it a broader basis than that obtained by considering only man-made structures according to an approach favoring the technical aspects. The concept developed should be sufficiently robust so that general recommendations (in particular on the diagnosis, management, or evolution of these systems) can find a relevant application regardless of the coastline concerned. As the geography of each site is unique, the constraints related to the natural environment (such as topography, water bodies, water courses, and various coastal features) and the built environment (including infrastructure, buildings, etc.) require a precise, multidisciplinary foundation of knowledge of the system of protection before any adaptation project or transformation can take place.

4.2.2 Changes, disruptions, and hazards facing the protection system

The state of the art reveals the multiplicity of developments that need to be taken into account to improve the understanding of risks. Therefore, the problem is that of taking into account, particularly at the stage of defining the protection system, all the developments, slow or rapid, localized or diffuse (in the case of pollution) that are likely to affect the system. It is therefore not only a question of defining a reference hazard – although it should be described precisely and take into account the projections for the RSL – but also of paying attention to physical changes (*e. g.*, sedimentary changes, changes in land use, etc.), as well as the biological aspects that can trigger sudden changes, particularly under pressure from urbanization and climate change.

4.2.3 Modes of action for the preservation, adaptation, or transformation of the system

Modes of action should be defined in accordance with the principles of resilience development. Several options can be considered for the function or structure of the system: its preservation, restoration, or adaptation. When the maintenance of the function or structure of the system is not possible, transformations should be followed.

The adoption of systemic approaches should avoid overly simplified approaches, such as those that arise from conventional RSL adaptation schemes, or cost estimates with reference to the coastline length.

4.3 The search for « integration and coordination » methodological developments

Strengthening the resilience of protection systems requires broadening the scope of the review to include modes of governance, methodological inputs, and operational tools. Two of the problems that arise are:

- the integration of adaptation strategies; and
- the coordination of decision support tools.

While a formal distinction can be made between these two issues, in practice, the coordination of decision support tools contributes to the integration of adaptation strategies.

4.3.1 Integration of adaptation strategies

As a result of the conceptual framework set out in chapter 2, strategies for adapting protection systems need to be integrated with higher-level strategies in the SES panarchy to which they belong. This implies that:

- at the territorial level, the integration of anthropogenic structures within a protection system encompasses:
 - natural features (such as coral reefs, mangroves, beaches and dunes, salt marshes, and other wetlands) that play a role in protection against coastal flooding; and
 - urban water management systems (*e. g.*, ditches, retention ponds, or infiltration ponds);
- at the regional level (at the scale of the catchment area or the hydrosedimentary cell), the integration of waterway and coastal management into action programs is necessary, particularly when it comes to controlling the risks of erosion and shoreline retreat;
- at the global level, the reduction of the carbon footprint of action programs should be considered by including objectives for forest conservation and/or the limitation of greenhouse gas-emitting activities (for example, the transport of materials).

At each level, and for both the natural environment and the built environment, strategies for adapting protection systems should:

- favor nature-based solutions to develop synergies with other public policies. Measures should be defined not only to improve protection against coastal flooding, but also to strengthen all regulating ESs, and also provisioning, and cultural ESs as defined by Millenn. Ecosyst. Assess. (2005); and
- be part of a more comprehensive approach combining risk analysis (especially flooding, subsidence, and land movement) and management of resources such as water, sediments, armourstone, and wood according to the principles of a circular economy.

Responding to this problem requires the development of participatory approaches, including learning and experimentation, following the concept of adaptive co-management.

4.3.2 The coordination of decision support tools

In regards to the adaptation of protection systems, decision-making is largely influenced, at least when the institutions are sufficiently well structured, by:

- directives, laws, regulations, and standards;
- methodologies and other documents which report knowledge and express recommendations (all of which form the « state of the art »);
- databases and operational tools (including land observation and resource management).

These three levels need to be coordinated in their evolution, so that each level best respects the formal framework of the other levels.

If only one field of action were involved, this requirement would be relatively easy to meet in a top-down approach. But this is never the case: the same information is used for several purposes in several areas and bottom-up approaches intersect top-down approaches. The development of decision support documents and tools should therefore be subject to arbitration and compromise at each level to maximize the efficiency and effectiveness of the whole. This effort is all the more necessary in the context of ecological and digital transitions carried out in parallel, and often in reaction to the multiple developments previously mentioned.

The creation of a methodological approach promoting the development of protection system resilience involves going beyond the framework of sectoral approaches to seek unity and consistency. Therefore, it is recommended to:

- adapt methodologies in the context of the ecological transition and digital revolution; and
- coordinate governance, expertise, and planning with the development of methodologies.

4.4 Synthesis and conclusion

The literature review has allowed making theoretical progress by reconsidering a coastal flood protection system as an SES, CAS not limited to man-made structures, but that integrates elements of the natural environment and the built environment, as well as the social and institutional environment. The management principles for strengthening its resilience were thus clarified. However, the state of the art is lacking when it comes to defining adaptation strategies in an operational manner while taking into account the specificity of the sites and their evolution. The evolving context of the 21st century is creating imperatives that will need to be met more and more regularly, including system performance assessments and the development and monitoring of system adaptation (or transformation) programs. These imperatives justify not only the revision of the concept of a protection system, but also the definition of precise and fairly rapid ways of identifying and characterizing these systems.

The identification and characterization of a coastal flood protection system on a broad conceptual basis is therefore a major issue. Addressing this issue opens up two avenues for concrete progress in the area of flood risk management:

- the establishment of methods, relevant to any given coastline, for:
 - identifying changes, disruptions, and hazards facing the system;
 - defining appropriate modes of action to ensure the preservation, adaptation, or transformation of the system;
- the integration of the protection system adaptation strategies into spatial planning, resource management, and environmental conservation policies.

Improving the overall efficiency and effectiveness of the system can also be sought through the coordinated development of information management systems, methodologies, and operational tools.

5 PRESENTATION OF MY RESEARCH

My research was initiated in the aftermath of storm Xynthia, which affected the French Atlantic coast in February 2010. Through an empirical approach, the primary objective was to strengthen the resilience of protection systems, contributing to the rapid recovery of their performance and their adaptation to current and projected changes. In particular, the aim was to define methodological frameworks dedicated to:

- the analysis of the response of coastal flood protection systems (a.k.a., system diagnosis), in particular after a meteo-oceanic event exceeding the nominal operating conditions;
- the long-term definition of adaptation strategies for these systems, integrating the costs, in terms of investment and maintenance, of the different modes of intervention for levees and other civil engineering structures (such as seawalls, groynes, breakwaters, etc.), as well as beaches and dunes;
- emergency preparedness for these systems, both in terms of overall organization (strategy, preparedness, training), and in terms of specific arrangements (equipment and materials, training and exercises, monitoring, and interventions on structures);
- the supply of materials whose characteristics guarantee the safety of the structures, but whose production conditions, transport, and processing also respect the principles of reasonable resource management and reduction of greenhouse gas emissions.

The realization of this work has incorporated multiple disciplines: both engineering sciences, such as hydraulics and geotechnical engineering to properly understand physical phenomena, but also geography and history to put in perspective, in space and time, the expected functions of the structures. Achieving the objectives therefore required exploring the modalities of cooperation between these disciplines and the production of specific recommendations on this subject. As the work progressed, it appeared necessary to deepen the concept of a protection system, with the consequent revision of the principles of action relating to each of the above mentioned points.

The dissemination of the results in the scientific community has been ensured by the production of papers and by participation in national and international conferences on these subjects. In addition, the methodologies were also disseminated through a series of books, especially for local and regional authorities wanting to progress in the understanding of coastal hazards and in the definition of global strategies. A complete list of references corresponding to this production is given in chapter 8. These references, specific to the work presented here, are categorized into two groups and are designated by separate citation types:

- published scientific papers are identified by numbers, for example [1];
- published works (mainly by Cerema) are designated by letters, for example [A];

The list of conference presentations follows the lists of scientific papers and books, but are not referenced in the text.

This chapter sets out the context of the work, the main results obtained, and finally the methods used to conduct the research.

A presentation of these elements in a more integrative form was the subject of the article [H] published in French by the Éditions Techniques de l'Ingénieur.

5.1 Context of my research

It is clear from the state of the art presented above that the methodologies depend closely, in their elaboration and implementation, on the institutional, historical, legislative, and regulatory context. An assessment of the influence of these conditions is therefore necessary. These preliminary analyses will help determine the limits of validity of the results and the possibilities of extrapolating them to other contexts by following the methods described in section 5.3.

5.1.1 The institutional context

My research work was carried out over the period of 2010-2018 at the Cerema, a French public agency whose mission is to develop and capitalize expertise. The Cerema is particularly involved in partnership research, through the creation of an interface between companies and local and regional authorities. This interface is used to co-develop and deploy innovative solutions to enable territories to succeed in the challenges of ecological and digital transitions in the fields of infrastructure, urban planning, mobility, and natural hazards.

One of the main missions of the Cerema is to develop, experiment, and support innovations for the benefit of the territories by relying on:

- multidisciplinary, which makes it possible to associate profiles with different perspectives and modes of thinking (e. g., researchers, engineers, planners, sociologists, geographers, etc.);
- partnership culture, through the utilization of several actors, including central governments, territorial institutions, research centers, and companies.

The activities of the Cerema fall within the scope of research, but also concern methodological, national, and international developments, with achievements such as the International Levee Handbook (CIRIA et al., 2013).

The stance and mission of Cerema therefore promote « learning and experimentation » within the framework of « systemic » and « participatory » approaches utilizing a plurality of actors and disciplines, according to the adaptive co-management principles identified by Biggs et al. (2012).

5.1.2 The historical, legislative, and regulatory context

Multiple inundations and marine submersions affected Europe and the United States between 2000 and 2010, which strongly encouraged the revision of national risk prevention strategies and the evolution of legislative and regulatory frameworks. In Europe and France, research in the field of flood protection has been influenced by:

- the European Directive 2007/60/EC, presented in more detail in section 1.3.2;
- Law No. 2014-58 of January 27, 2014, which gives the municipalities the means to address the joint problems of « water security » and « environmental protection ».

The common ambition of these texts is to achieve an integrated flood risk management policy in each territory, shared by all stakeholders. This historical, legislative, and regulatory context provides favorable conditions for the application of the « polycentricity » principle recommended by Biggs et al. (2012) in the management of SESs, since there is a coordinated risk prevention policy at multiple geographical scales (including Europe, countries, river basins, and territories).

The Cerema, which works both to define public policies with central governments and to implement them alongside local and regional authorities, has the potential to be involved at all decision-making levels: research and methodological development activities carried out at national or international level are accompanied by expertise activities, which are necessarily local. It should be noted that for the research presented here, the sites selected to conduct the case studies have benefited from the experience gained in producing expert opinions at other sites affected by the storm Xynthia and for which a review of the protection systems was envisaged. These sites are:

- in Charente-Maritime (France), in the municipalities of Yves, Châtelailon, Aix, and Fouras, as well as Saint Trojan-les-Bains (Île d'Oléron) and Loix (Île de Ré);
- in Vendée (France), in the municipality of Aiguillon-sur-Mer.

5.2 Protection system: the concept and principles of action

The renewal of approaches to the protection against coastal flooding, and more particularly, against marine flooding, first and foremost involved an extension of the concept of a protection system. These results were then used to define principles for action. While the focus of my research was on flood protection performance, each of the results obtained is a contribution to the integration of protection systems into land use planning at territorial or more global scales.

5.2.1 The concept of a marine flood protection system

Whether it is to understand the functions and malfunctions of protective devices, to improve their performance, or to manage them better in normal times or under heavy stress, my research first focused on the geographical boundaries within which the analyses should be carried out and on the components that constitute the protection systems against marine flooding.

Limiting the scope of the review to a single structure or to a limited group of structures leads to expose the protection system to a hydraulic bypassing. The idea that water should be prevented from progressing in the desired area to protect may nevertheless, too quickly, lead to limiting the representation of a protection system to a continuous line of structures forming a « bulwark » against a meteo-oceanic event. This linear approach can only represent a first step and should therefore be substantially enriched:

- by integrating the other elements structuring the territory into the analysis, such as:
 - the soil, which by its topography and permeability, remains the first element to be considered;
 - the embankment infrastructure (*e. g.*, roads and railways), which has not been assigned any role in relation to floods at the design stage, but which nevertheless and often negatively influences them, prompting the spread and accumulation of water at the level of the vulnerable areas;
 - buildings that can strongly influence the spread of water, especially when they are in an unbroken alignment;
- by considering the different types of reference events against which such a system must provide protection: the various sea states that may appear during the passage of a storm, and the multiple components of the sea level. This usually involves considering several scenarios. The analysis can be even more complex in the case of an estuary where hydraulic actions and morphological changes are also determined by a river;

- and above all by placing the stakes at the centre of the analysis and by not considering the entire territory behind the defense line as an area where the level of protection should be uniform.

Figure 89 illustrates this concept and responds to the need to identify a contour that delimits the system in relation to the external environment with which it interacts, in order to define a protection system. This contour must be continuous and closed. Generally, it will include:

- lines representing the limit of land areas that are not submerged under normal circumstances. These lines can be called « defense lines ». During a meteo-oceanic event, important exchanges of water can take place across these lines; and
- lines drawn through land areas that are not prone to flooding due to their elevation or to their distance from the source of the flood. These lines can be called « sheltered lines ». No noticeable exchanges take place across these lines during a submersion event.

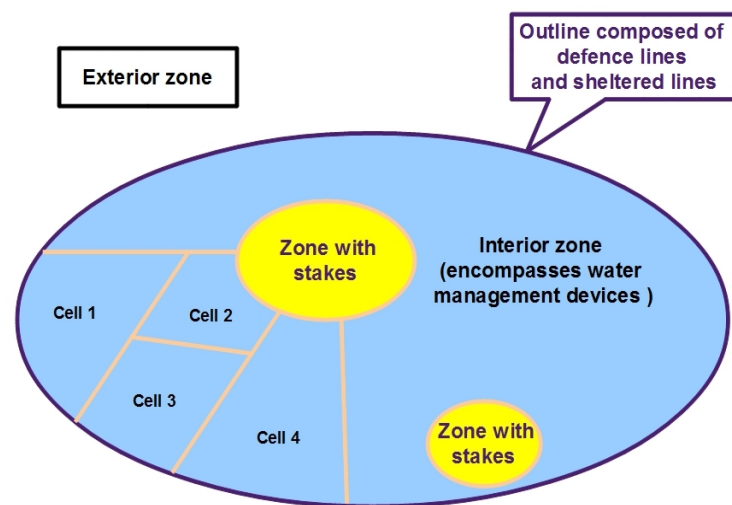


Figure 89: Conceptual diagram of a marine flood protection system [13].

Such as defined, this outline represents an object that is geographically closed but hydraulically open: controlled or uncontrolled water exchanges exist with the exterior environment (only across defense lines).

If we consider the interior of the contour (the interior zone), stakes vulnerable to flooding are not uniformly distributed in this zone: they are often concentrated within significantly smaller areas. In the interior zone, the characteristics of the hazard are also variable. Therefore, for a more precise analysis, restricted geographical areas must be delimited in the interior zone.

Additionally, in order to correctly analyze the hydraulic phenomena that can extend over several square kilometers in a territory, it is necessary to determine the scale that is most appropriate to study the main phenomena. For this purpose, a classic choice for hydraulic studies consists in defining « hydraulic cells »³², which visually can be likened to a container:

- whose edges fit relief elements such as: defense structures, internal levees, infrastructure, or the natural topography if it reaches a sufficient altitude. In the plan view, these edges form a continuous and closed line;
- whose bottom is formed by the surface of the ground included in the perimeter previously described.

³² The method for defining the system and its hydraulic cells is specified in [13].

It follows from the above definition that areas covered by hydraulic cells are leveed areas or areas whose topography forms a basin, while areas outside of the hydraulic cells are lands that are not within the area of influence of a retaining structure and are not in a basin. Land without hydraulic cells can therefore be plains across which water spreads freely, or slopes on which water rises following the movement of the tide (*i. e.*, the slow motion at the end of the ascending phase of the astronomical tide, possibly slightly accelerated in case of synchronization with the surge).

It is essential to decide whether a stake belongs to a hydraulic cell. If so, the stake may be subject to rapid flooding. Otherwise, the stake may be flooded, but the speed of water rise will be less than or equal to the rate of sea level rise.

Determining the external contour and structural elements of the protection system is a means of assessing the consistency of the study scope with respect to the risk of flooding, and ensuring a good understanding of the internal organization of the system. An example of schematization developed according to this concept is given for the Loix site on the island of Ré (France) in figure 90. In the production of such a scheme, great attention must be paid to the choice of topographical thresholds for the delimitation of system boundaries. These will generally be based on the maximum mean level observed at the site during a reference event, or on the level of the highest astronomical waters, with the crest of the structures being normally at a slightly higher altitude.

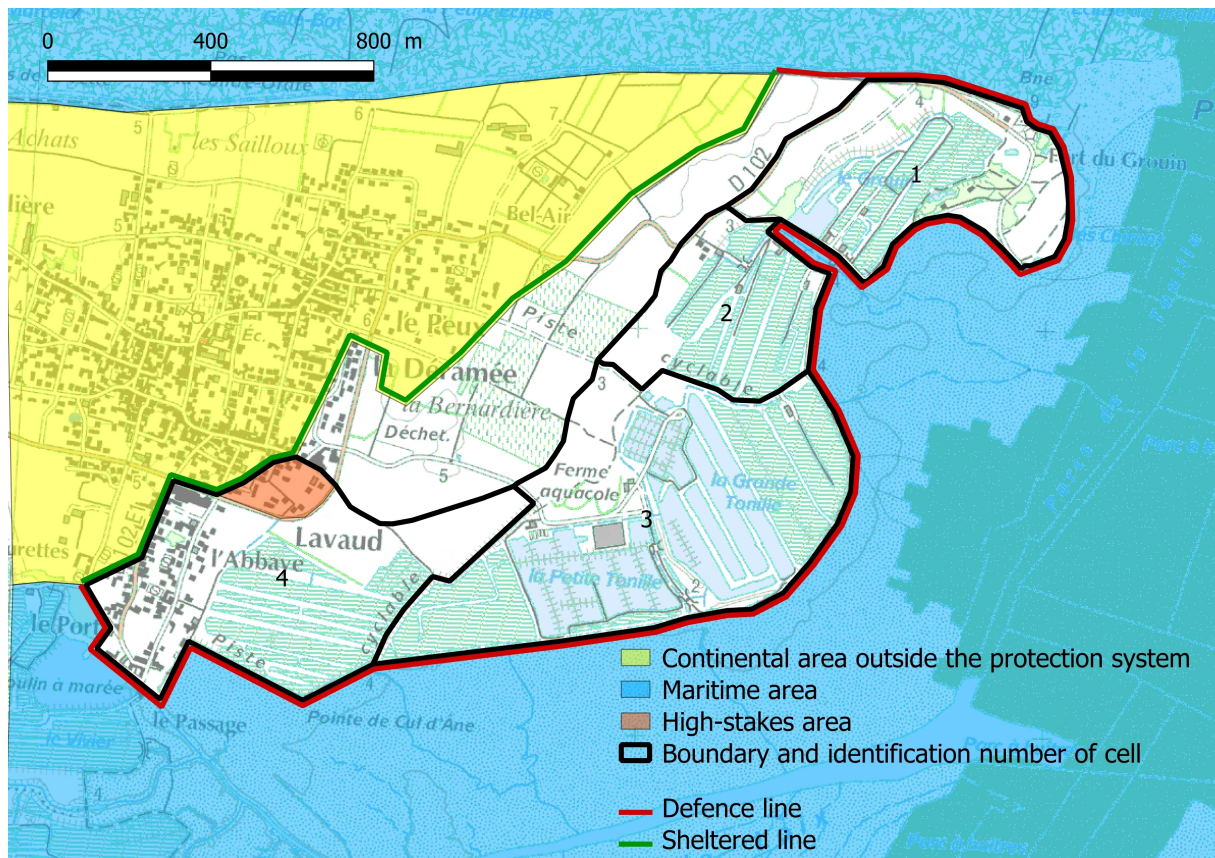


Figure 90: Schematic representation of the Loix protection system [13].

In conclusion, the renewal of the protection system concept and the spatial analysis carried out as part of the schematization contribute to the identification and repositioning of all the components of the system in their natural environment and their built environment, integrating all uses of the territory. This approach is crucial for revising the principles of diagnosis, adaptation, crisis management, and supply of materials for protection systems.

5.2.2 System diagnostic principles

In France, the diagnostic objectives are defined by Decree No. 2015-526 of 12 May 2015 on the conduct of hazard studies:

« The hazard study presents the protected area in an appropriate cartographic form. It defines river floods, marine floods and any other hazardous natural event that the system or arrangement provides protection against. For a levee system, it includes an in-depth diagnosis of the condition of the structures and takes into account the behavior of natural elements located between sections of levees or at the end of a levee or a structure composing the system. »

The concept of a protection system, as presented above, is used directly to define the « analysis framework » necessary for diagnosis. It is only on the basis of such a scheme that, for a group of identified issues, hydraulic phenomena can be studied systematically:

- by surveying the contour (shown in green and red in the example in figure 90), which delimits the system to assess any possible water inflows: discontinuities of the line of defense, hydraulic bypass of the existing structures, openings (e. g., stairs, slipways, sluices, and valves), and sections favoring wave overtopping;
- then by studying the dynamics of the flows within each of the cells and between the cells. The water entering the system must be manageable for the duration of the event (if applicable, this may cover several tidal cycles).

To better exploit this concept in the diagnostic phase, I initiated a study of the strategies and methods of analysis intended to identify the functioning and failures of the protection systems. One of the most significant results was the transposition of the so-called « bowtie » risk analysis method, which was originally applied to the loss of containment in industrial storage facilities. This method has been adapted to the phenomena of water intrusion into the protection systems.

As illustrated in figure 91, the bowtie method makes it possible to match, in the context of an event feedback, two corresponding analyses:

- a fault tree which establishes the chain of events leading to the stakes zone flooding (the central dreaded event);
- an event tree which, considering this flooding, determines all of the potential consequences.

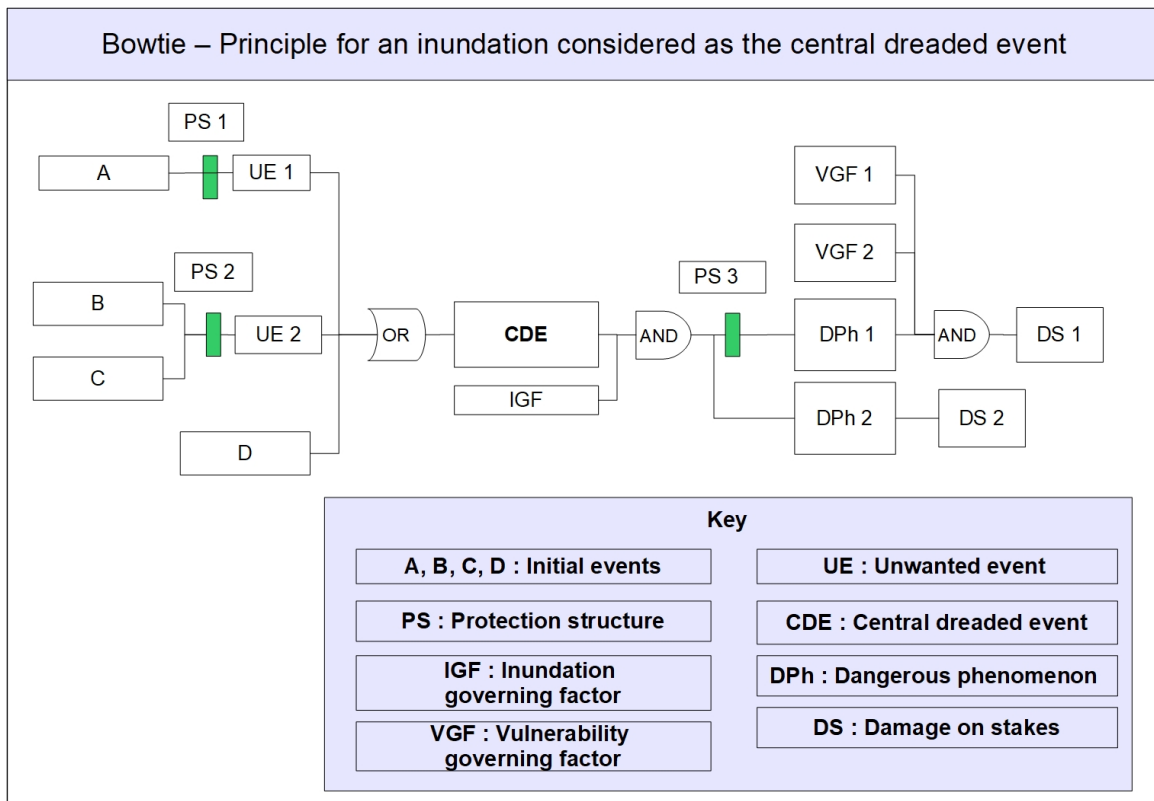


Figure 91: Generic representation of a bowtie approach [13].

These flowcharts provide a framework adapted to a systematic analysis based on:

- the schematization of protection systems, following the above principle; and
- hydraulic models that can be used to represent phenomena in a global and coherent way.

The development of a method based on the principle of placing the flooding of high-risk areas at the centre of the analysis is a valuable aid in conducting the studies.

The application of this method of analysis at the Loix site is represented by the flowchart in figure 92.

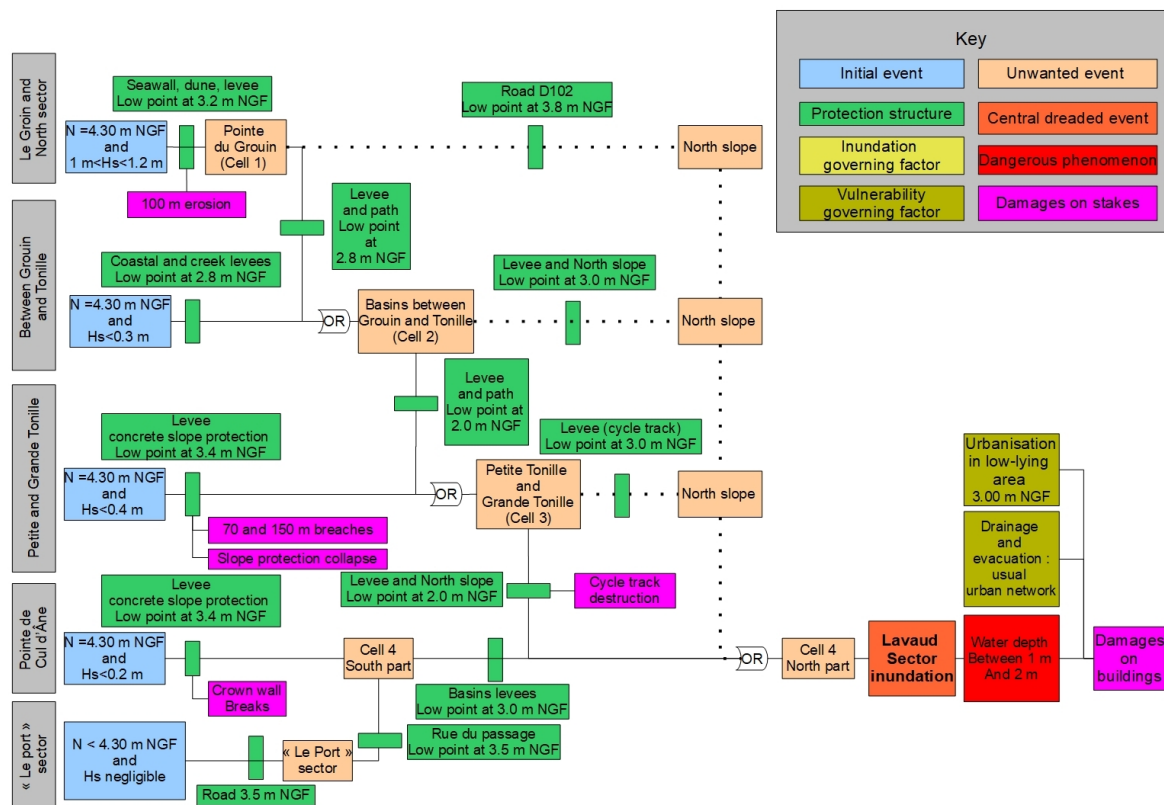


Figure 92: Bowtie tree of the Loix protection system based on the observations following the storm Xynthia [13].

In the example of Loix, in addition to the legend, it should be noted that the flowchart represents:

- the different sections of the waterfront (in grey, on the left) corresponding to the sections numbered from 1 (Le Groin and the North Sector) to 4 (Le port and Pointe de Cul d'Âne together in a single sector) in figure 90;
- the hydraulic actions (in blue) of these different sections of the waterfront.

In this flowchart, the hydraulic pathways appearing in the first phases of the event are represented by the black, unbroken lines. The hydraulic pathways appearing on the « north slope » after the filling of the cells are represented by dotted lines.

In conclusion, it appears that beyond the understanding of the reaction of hydraulic structures, the interactions with the natural environment (sea, soil, dune, etc.) and with the built environment (roads and urban networks, ponds used for fish farming, buildings, etc.) are well represented by the diagram of the protection system and by the flowchart of its functioning during a marine submersion event. Thus, the concept developed enables us to better study the protection system as a component of a territory and to adopt more integrated approaches.

The principles of system diagnosis and their implementation in four case studies were detailed in the methodological handbook [E] and in articles [1], [3], [5], [6] and [13]. A brochure for elected officials of local and regional authorities [I] was also written and distributed.

5.2.3 Principles of system adaptation

In order to develop adaptation recommendations for coastal areas, I used the concept of a marine flood protection system in conjunction with two other concepts:

- the « global cost of a project », including investment, management, and maintenance costs;
- the « environmental integration » of the activities carried out on the life cycle of the protection structures.

The principles of system adaptation were detailed in a methodological handbook [K]³³ and in articles [8] and [10]. A brochure for elected officials of local and regional authorities [L] was also written and distributed. In addition, a guide specific to river systems was produced [D], as well as an article [2].

Principles for assessing the global cost of a project

In France, the law on multiannual planning of public finances was introduced on December 31st, 2012, and it detailed the requirement for prior socio-economic evaluation of all public investment projects. By quantifying the costs and benefits that public investment can bring, socioeconomic evaluation provides essential insight for decision-making.

With regards to protection systems, the main problem of adaptation strategies concerns the evaluation of expenditures on these systems. Although the economic evaluation of benefits has not been directly addressed, it is nevertheless clear that the system diagnostic recommendations referred to above constitute the basis for the evaluation of benefits, in that they provide a means of assessing the level of protection of the stakes.

Considering that there are some similarities between building management and levee management, including the use of the concept of a « life cycle », my research has established principles for calculating the global cost of protection systems by transposing some of the precepts set out in the ISO 15686-5:2017 « Buildings and constructed assets » to the case of protection systems. The overall cost approach is ultimately intended to provide the contracting authority or the manager with an adaptive arbitration method that allows the impact of deferred costs to be better taken into account in the investment choice. More specifically, it is a question of explaining the consequences of investment decisions over a well-defined time horizon.

To carry out this calculation for protection structures, the outline of the project must also be well defined by integrating the intellectual services, possible land acquisitions, and especially, associated elements corresponding to a function other than the protection against littoral hazards (such as public road networks, access to the foreshore, and buildings) that are created or impacted by the work. Costs of interventions on these associated elements can be equivalent or even higher than those of the hydraulic works. In particular, these associated elements can have a significant impact on long-term costs.

Estimates must take into account the timeline that is specific to each project, but must be explicitly defined:

- if – for the purpose of enhancing the technical resilience of the system – the project aims only to maintain a level of protection, the estimations can, for example, be established over a 30-year horizon;
- if – from a broader perspective of strengthening the social-ecological resilience of the system – an issue is raised in regard to the protection objectives and a comparison with the value of the stakes must be established, it can then be preferable to consider a duration of 50 or 100 years or more, while taking into account climate change effects and other changes.

³³ Previously, in 2002, I conducted a first study [A] focused on the construction costs of sea defenses.

The calculation must be done using a reference date which, in general, is the project completion date. It should be kept in mind here that discounting is the mathematical operation that reduces deferred costs to their reference date equivalent.

The present global cost of a structure is defined as the sum of the initial investment cost and the management and maintenance costs during the life of the project. Within the framework of cost-benefit analyses, its calculation is based on costs without the value-added tax (taxes are considered transfers, and not net losses or gains).

Consequently, the present global cost of a project is equal to the difference between:

- the global cost of the reference scenario excluding the implementation of the project. The initial cost of investment is then zero and the management and maintenance expenditures follow their « natural trend »;
- the global cost resulting from the project, namely the sum of the initial investment cost and the management and maintenance costs.

For each term of this difference, according to ISO 15686-5:2017, the global cost for an n-year time horizon is:

$$C_{\text{Global}} = C_0 + \sum_{i=0}^n \frac{C_i}{(1+r_i)^i}$$

with :

C_0 the initial investment cost without value-added tax

C_i the cost of the management and maintenance expenditures occurring in year i

r_i the discount rate in the year i . France Stratégie (2013) recommends a 2.5% discount rate until 2070 and then a 1.5% discount rate within the framework of risk management investments.

The calculation of the present global cost must be accompanied by sensitivity analyses, in particular of the following parameters:

- the discount rate;
- the period of analysis; and
- uncertainties about lifespan and costs.

Thanks to this method, the use of available financial resources can be optimized.

The application of this method makes it possible to translate the concept of the life cycle of a structure into quantitative approaches. Based on the conceptual framework described in chapter 2, it can be added that by considering a protection system as an SES, this method makes it possible to better understand its evolution.

Principles of environmental integration

The objective of limiting the impacts of the activities carried out on the life cycle of the structures was pursued according to the principle of « avoid, reduce, compensate³⁴ », which led to the formulation, as part of the study of the cost of protection against coastal hazards [K], of adaptation recommendations, preferably oriented:

- towards ecosystem-based solutions: for example, restoring shorelines to restore normal functioning of beaches and dunes;
- towards better management of flows within levee systems, for example, by using ditches and levees covered with vegetation, if necessary in several rows, rather than raising levees on the sea front and covering them with riprap.

Nevertheless, in areas with high stakes in low-lying areas, the use of civil engineering structures may be necessary in the short and medium term. In this case, the recommendations are intended to:

- reduce the overall impact by preferentially using materials with a lower carbon footprint (e. g., soil, sand, armourstone, and wood over metal and concrete) and promoting local supplies;
- reduce local impact by selecting resources to limit waste and by building reversible structures.

My research in this area has mainly consisted of:

- facilitating access to the data required for conducting qualitative and quantitative studies. Thus, the study of the cost of protection against coastal hazards [K] exposes the unit costs and allows for the comparison of the overall cost associated with the use of different techniques;
- implementing tools to support sound resource management: an Armourstone Quarry Atlas [F; G] and a French edition of a notice for the selection of alternative hardwood timbers for marine and freshwater construction [B] were produced.

In conclusion, considering a protection system as an SES positioned within a panarchy, environmental integration can be considered at three higher levels:

- the territory, with the aim of limiting environmental impacts at each stage of the life cycle of the structures;
- the region, with the objective of optimizing the management of resources;
- the planet, with the overall objective of reducing greenhouse gas emissions.

5.2.4 Principles of Emergency Response

Among the different natural phenomena that cause floods, coastal storms generate a particular type of hazard: a sudden rise of water to unusual levels (over a period of about an hour). This occurs with large volumes that cover large areas of land and energetic sea states accentuating coastal damage by the effect of waves.

Recommendations on emergency preparedness and crisis management should be based on the principles that drive continuous improvement processes, namely the regular evaluation and

34 Introduced in French law by the 1976 Nature Protection Act, the guide « Avoid, Reduce, Compensate » has a solid legislative base at both French and European levels (MEEM, 2017).

improvement of the system. These principles require the production and regular updating of a plan. My research in this area has led to the production of a methodological framework for the development and updating of this type of plan.

The updating of a plan may result from conducting studies, completing exercises, or gathering feedback after a storm. Changes in the plan may be global (for example, as a result of risk analysis or feedback), or conversely, small improvements made at regular intervals (more likely as a result of exercises).

To establish recommendations that can be operationally translated into the response plans, two spatial scales have been distinguished: that of the protection system and that of the structures. In each case, interactions with the other components of the territory were sought.

Principles at the level of the protection system

An emergency response to a coastal protection structure is decided based on the risk to vulnerable populations and stakes. If interventions on protection structures are generally determined by precise and complete studies, interventions in emergency situations are subject to time constraints that require the rapid identification of the most relevant technical solutions and their implementation also within a limited time. The management of time constraints related to the emergency can therefore only be resolved by:

- an adapted organization;
- operational preparation prior to interventions; and
- mastery of technical knowledge.

At the level of the protection system, the proposed methodological developments focus on the first point: the general organization of the emergency management plan.

An emergency management plan should prepare for interventions by differentiating between sectors according to their role, fragility, or importance with regard to the protection of populations, which implies a risk analysis. To carry out such an analysis, a precise and organized knowledge of the system is necessary in order to anticipate its behavior in crisis situations by forecasting flows and accumulation zones. Based on knowledge of the organization of the system, it is also possible to:

- identify strategic points that must be protected. For example, the data collected after the storm Xynthia revealed that hydraulic structures positioned on the waterfront (often referred to as the « sea gates ») are highly vulnerable. Unlike a section of levee, the rapid repair of this type of structure is impossible. However, because of their drainage function, these structures are essential to restoring a normal situation. They should therefore be protected against any phenomenon that could lead to their deterioration or ruin. In particular, overtopping and overflowing, which are likely to cause scour at the ends of the structure, must be avoided;
- define appropriate management rules (by operating hydraulic structures and directing flows towards predefined zones);
- carry out emergency operations on the structures under optimum conditions. This implies that the equipment and materials must be positioned in locations that will remain accessible in the event of flooding and that will allow rapid intervention on the structures.

Principles at the level of the structures

In order to best prepare for emergency responses, it is necessary to assess the risks of failure specific to each of the structures. It is not only a question of assessing this risk in terms of probability, but also of assessing the physical mechanisms at work during the failure events. The proposed methodological developments have clarified the links between the visible signs and the actions to be undertaken in the case of marine submersion phenomena. The recommendations established based on the literature review and feedback from Storm Xynthia, facilitate the decision-making on the modes of action intended to hinder the course of deterioration mechanisms and to restore the structures to a condition in which they can perform their function of protection.

In addition, the proposed methodological framework establishes a management plan that meets the following objectives:

- ensure the availability of equipment and materials, in particular by adapting these resources to the types of interventions considered in response to failure modes;
- monitor structures in crisis situations, including looking for characteristic signs of failure modes;
- intervene on structures, including defining appropriate intervention protocols.

The emergency management plan should provide for the education and training of the protection structure management personnel in the recognition of failure modes and the definition of intervention modes in response to these situations.

In conclusion, in the representation of a protection system as an SES, the social component stands out strongly in the area of emergency response: when a protection system is subjected to actions exceeding its nominal operating conditions, only human intervention can keep the situation under control and limit the consequences of the event. The methodological recommendations aim to improve the functioning of protection systems by proposing adjustments, mainly in their social organization. Moreover, the dependence on resources, in particular the armourstone used to consolidate structures exposed on the seafront, is such that crisis management plans would benefit from provisions to assess the state of stocks.

The principles of system adaptation were detailed in the methodological handbook [J] and in article [9].

5.2.5 Principles of Material Supply

With regard to the objectives of reducing the risk of flooding and environmental integration, two natural resources that are widely used for protection against marine flooding deserve special attention: armourstone and wood. These materials tend to be imported over long distances, sometimes even from very distant origins, such as Norway for armourstone or Africa, Asia, South America, and Indonesia for wood. Although the technical characteristics of these materials are fairly well controlled by the application of a normative framework, their production and transport conditions are not always controlled.

On this subject, the objective is therefore twofold:

- to promote sustainable or reasoned management of resources (wood, a renewable resource, is possible to maintain sustainably, while mineral resources, whose renewal takes place on geological timescales, the only possibility is a reasoned management);
- to promote the use of materials that are available locally or that have an acceptable carbon footprint.

In order to achieve these two objectives while fulfilling the requirements related to the technical characteristics of the materials, an improvement in the knowledge of the production sites and the characteristics of the products is essential, as well as making this information available to users.

Selection of armourstone

Armourstone is a material that is regularly used in harbor structures and flood protection structures (see figure 93). Its use is typically aimed at preventing erosion and scour. Consequently, in maritime, riverine, and torrential fields, armourstone is a strategic resource for the safety of populations and many activities.



Figure 93: The loading of a piece of armourstone in the port of Marseille. Credit: Grand Port Maritime de Marseille.

However, the properties of this material vary greatly depending on the geology of the sites they were derived from. To monitor their suitability for the intended use, legislation and regulatory provisions have therefore been adopted in recent years:

- the standards, which express the required level of performance, allow the choice of materials by specifications on geometric, physical, chemical, and durability characteristics. These standards define the categories (and threshold values) of the products and the corresponding tests;
- the European Construction Products Regulation (CPR) provides the Assessment and Verification of Constancy of Performance (AVCP) for armourstone used in hydraulic structures, ensuring initial knowledge of the deposit and control of production.

These actions aim to make better use of resources and contribute to the construction of sustainable structures at the best cost to society. At the operational level, they share a common objective: to anticipate demand by providing better visibility on the characteristics of the available resource. This anticipation is fundamental to the smooth running of operations in the context of often complex global projects, or in tense crisis management contexts.

For this reason, I organized a series of round table discussions covering all the regions of the French metropolitan territory and involving all the actors in the armourstone industry. This was a means of making collective progress in the appropriation of these tools. The proceedings of the National Conference on armourstone [F] reflects the state of thinking that has benefited from the diversity of situations, with each region presenting different resources and uses. I also led the production of the Armourstone Quarry Atlas [G] that is an operational tool that respects the formal framework of standards and regulations, and is shared by all stakeholders.

Selection of hardwood timbers

In Europe, most major construction industries have historically promoted a narrow range of hardwood timbers for seawater and freshwater applications. This was the case for example, for the rehabilitation of the west pier of the Port of Calais (see figure 94) whose deck was made of ekki (*Lophira alata*), which is part of a structure rarely sprayed by waves. This is mainly due to the fact that in a construction project using wood, the cost of the material represents only a small part of the total cost of the project. However, this large dependence on a few species of timber is not compatible with sustainable forest management. Overexploitation of some species is likely to harm both biodiversity and the security of supply.



Figure 94: Use of ekki on the deck of Calais West pier. Credit: Marc Igigabel, Cerema.

From a technical point of view, it appears that there is a tendency to exaggerate the technical requirements for a given use, particularly if mechanical strength is critical (Williams et al., 2010). This means that woods such as greenheart and ekki are often selected by default, rather than based on technical analyses. This impasse can only be avoided if reliable data on the performance of underemployed wood species are obtained. This objective was achieved through the production of the technical note (Environment Agency, 2010). My contribution was to lead the adaptation of this note to the French context [B].

In conclusion, the supply of strategic materials such as armourstone or wood is an area whose management goes far beyond the level of the protection system, both in the modes of production and transport and in the multiple uses of these materials. The high dependence of protection systems on these materials implies that specific analyses should be carried out at an appropriate scale (at least local or regional, and if necessary, national or international). To support these analyses, methodological recommendations and operational tools resulting from a shared consideration with all the actors in the sector (in the case of armourstone) or from laboratory tests (in the case of hardwood timbers) were produced.

5.2.6 Conclusions on conceptual inputs and principles of action

The concept of a protection system has been revised to reposition the vulnerable stakes at the centre of the reflection, and to integrate all the elements of the territory likely to exert an influence on water flow. Rules have been established to identify the boundaries of a protection system and to specify its structure.

On these new conceptual bases, and considering the objectives of strengthening the technical and social-ecological resilience of a system, « principles of action » have been established for:

- the diagnosis of protection systems. Applying the concept for identifying the structure of systems has paved the way for the transposition of risk analysis methods originally developed in industry. These methods are particularly suitable for conducting feedback analysis on the behavior of a system that has been subjected to a meteo-oceanic event;
- the management and adaptation of protection systems. The methods of economic analysis, especially those developed in the building sector, have been adapted for protection structures to calculate the present global cost of projects over the life cycle of the structures. In rapidly changing environments, such as coastlines, the development of such a calculation method allows for the comparative study of alternative solutions on a more objective basis through quantitative approaches;
- emergency management. The ways in which emergency management plans are produced and updated were compared with the principles that govern continuous improvement processes in order to clarify their overall organization at the system level. In addition, the relationships between field observations and actions to be undertaken have been clarified in order to achieve better responsiveness in interventions on structures.

In addition, for two strategic material resources (wood and armourstone), actions to identify and display technical characteristics were undertaken, promoting better management of the resources and closer links between actors in the sectors, thus guaranteeing better responsiveness.

Regular use of these tools in normal times is an essential condition for them to also be operational in emergency situations. This approach is all the more justified because it must never be disregarded for the permanent changes in levee systems under the effect of multiple natural and anthropogenic actions: management strategies in normal times (resistance to slow disruptions) should accompany crisis management strategies (resistance to shocks). The capitalization of knowledge and methodological development should therefore be designed to serve in all circumstances, within the framework of a comprehensive and integrated approach.

In light of the literature review, these conceptual inputs and methodological developments (dealing with technical, ecological, and socioeconomic aspects) are compatible with the broader conceptual framework presented in chapter 2, of SESs organized in a panarchy and managed as CASs. This compatibility opens the way for new developments:

- by using the recommendations for the management of CASs synthesized by Biggs et al. (2012) to develop their resilience by:
 - acting on parameters of diversity and redundancy (such as natural formations that complement the protection of structures), and connectivity (with aquatic and urban environments); and
 - ensuring the proper management of slow variables and feedback (with particular attention to the effects of climate change and land artificialization on the components of the protection system);
- in considering higher-level SESs (the territory, the region, and the planet) to incorporate additional recommendations, in terms of resource management and the reduction of greenhouse gas emissions.

5.3 Research methods

Coastal flood protection strategies can benefit from recommendations and methodological support only under two conditions: if they are adapted to the institutional context (*i. e.*, actors are in the capacity to take advantage of these tools owing to a structured organization and the skills available), and if they are also adapted to the biophysical and socioeconomic context. For these reasons, the methodological corpus developed in France cannot be considered *a priori* as being adaptable to another country. The international guides, because of the diversity of situations envisaged, are theoretically more suitable for more varied contexts. However, in practice, the application of the methodological recommendations requires the availability of corresponding local data (such as resource census, estimates of unit costs, etc.) in an adapted format. The presentation of research methods is therefore fundamental in order to identify the field of validity of methodological developments and to allow, where appropriate, their transposition to another context.

This section undertakes this presentation by maintaining the same structuring axes as before, namely by focusing on the essential actions marking the life cycle of protection systems (diagnosis, adaptation, and emergency interventions). In addition, methods used for the research on transversal actions relative to the selection of natural resources (such as armourstone or wood) will also be discussed.

These actions employ multiple disciplines, most of which have evolved over the past decades, benefiting from technological advances. These include hydraulics and geotechnical engineering, economics, as well as investigation and modeling techniques. The renewal of methodological frameworks has led to the search for ways of integrating the progress made in different disciplines into global and interdisciplinary approaches. On each of the structuring axes, the presentation of the development and composition of the methodological frameworks will therefore be accompanied by details on the modalities of interdisciplinary cooperation.

5.3.1 Diagnosis of protection systems

The diagnosis of protection systems should be preceded by regular field inspections. However, the length of structures to be monitored can be very significant (usually several kilometers, or even tens of kilometers), and the variations in the composition of structures and natural features generates many uncertainties in their performance. In the maritime domain, the difficulty in predicting their behavior is further increased by the effects of waves and objects they may transport. As a result, feedback from recent meteo-oceanic events is very valuable in assessing the actual behavior of systems. In the event of flooding, the study of the propagation of water in the system, particularly in kinetic terms, also offers the means to better define the crisis management system. These studies may also conclude that the protection system needs to be revised.

On February 28, 2010, Storm Xynthia severely affected the central third of the French Atlantic coastline, which corresponds to a considerable land area. As should always be the rule in such circumstances, feedback actions have been integrated into the different axes of the prevention policy: forecasting and warning, town planning, crisis management, etc. Research on protection systems has therefore become part of a larger work to which they have contributed, but from which they have also occasionally benefited, for example, from the gathering of information by the actors involved in crisis management, or from the modeling of meteo-oceanic phenomena.

Context of the study

The study of the behavior of the systems was initiated by considering four sites representative of the diversity of the territories affected by the storm Xynthia (see figure 95): Loix (on the island of Ré), Boyardville (on the island of Oléron), les Boucholeurs (on the coast of Charente-Maritime), and Batz-sur-Mer (on the Loire-Atlantique coast).

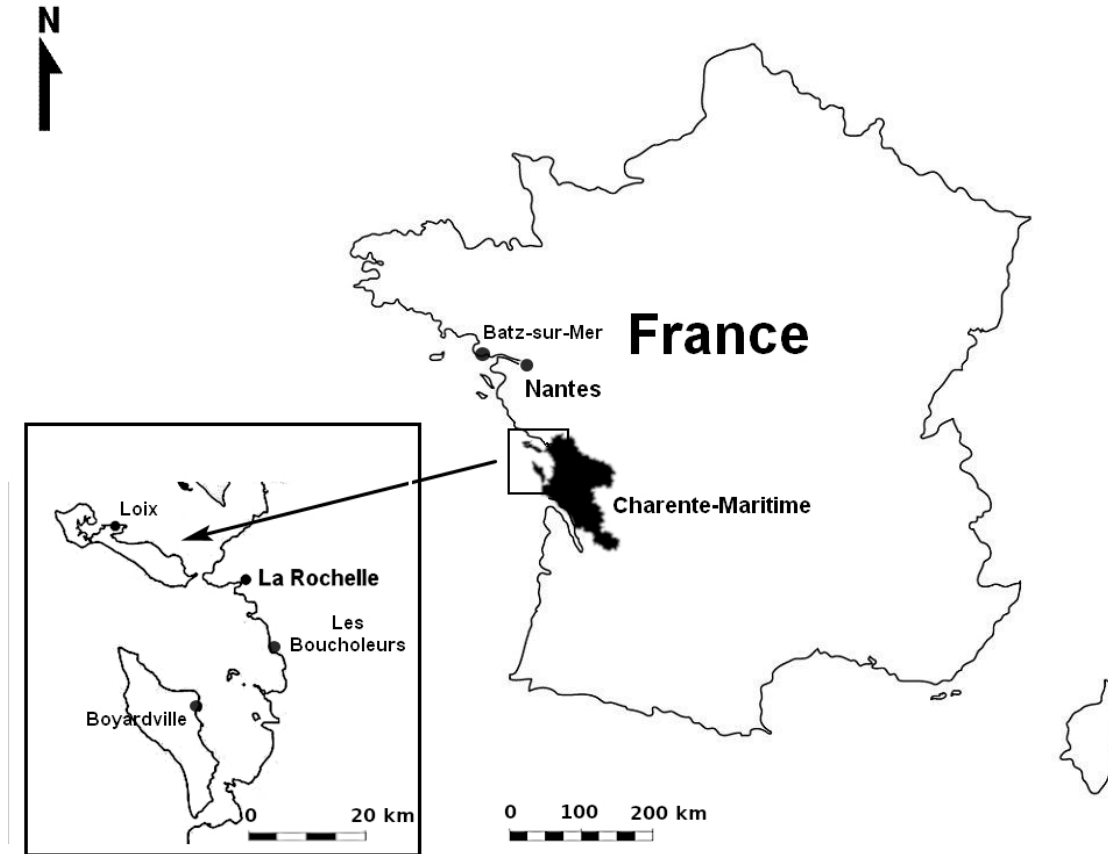


Figure 95: Locations of the four sites studied [E]. Credit: Yves Nédélec, Cerema.

The initial objective was to analyze the functions and malfunctions of the protection system at these sites. In each case, the aim was to ensure consistency between all available data in order to describe the sequence of events. These data can be very diverse: cartographic and topographic data, satellite images, aerial or ground photographs, meteorological data, tide gauge data, sea state data, descriptions of man-made structures and natural features, surveys of strandlines, sediment deposits, erosion traces, etc. The following illustrations for the Loix site show some « raw data » (ground and aerial photos in figure 96), and some « integrative data » (figures 97 and 98, showing respectively an integrative topographic map, and the analysis of aerial orthophotography showing degradation of structures and flow patterns on the ground).



Figure 96: Left: Ground view of the basins and the village of Loix taken from the coastal levee. Credit: Marc Igigabel. Right: Aerial view showing the flooding of the Petite Tonille and Grande Tonille basins, south east of Loix, taken February 28, 2010. Credit: Bruno Landreau, Cerema.

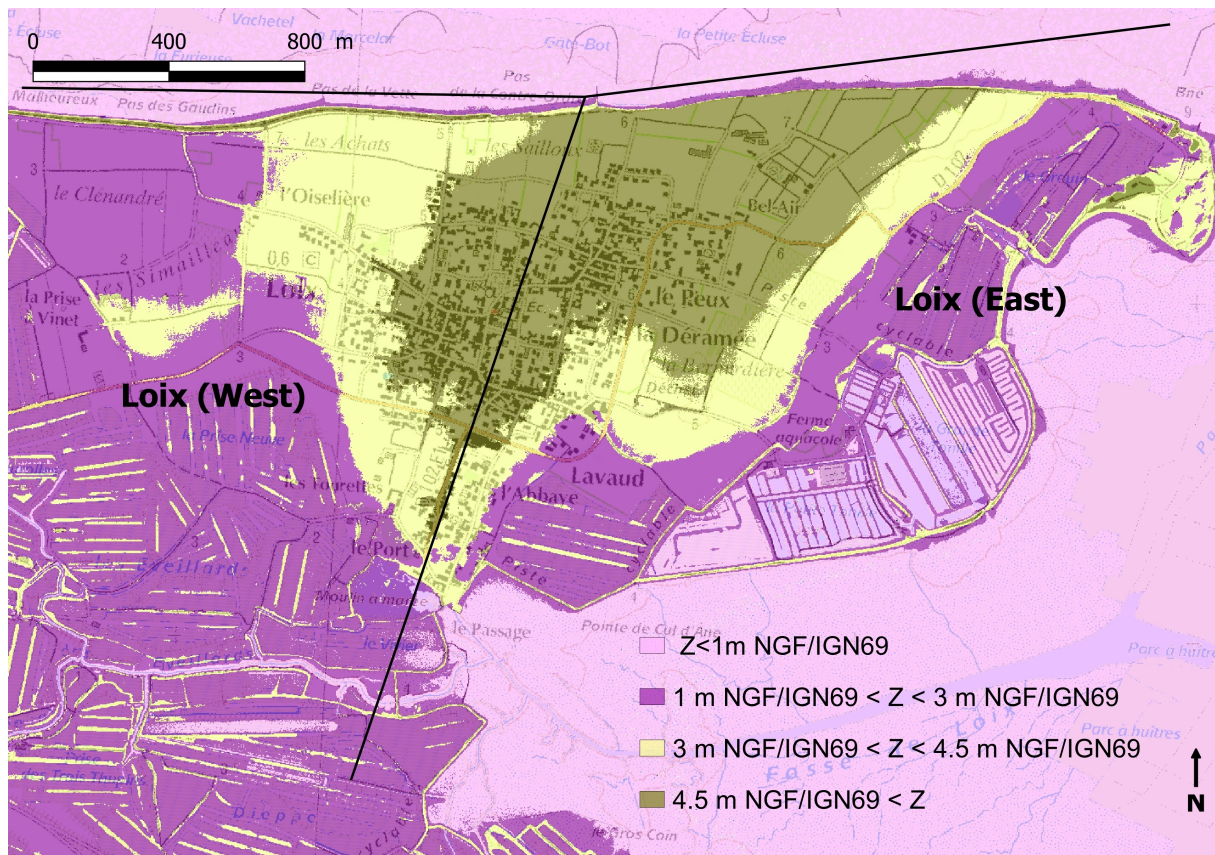


Figure 97: Topographic synthesis map. Credit: Yves Nédélec, Cerema.

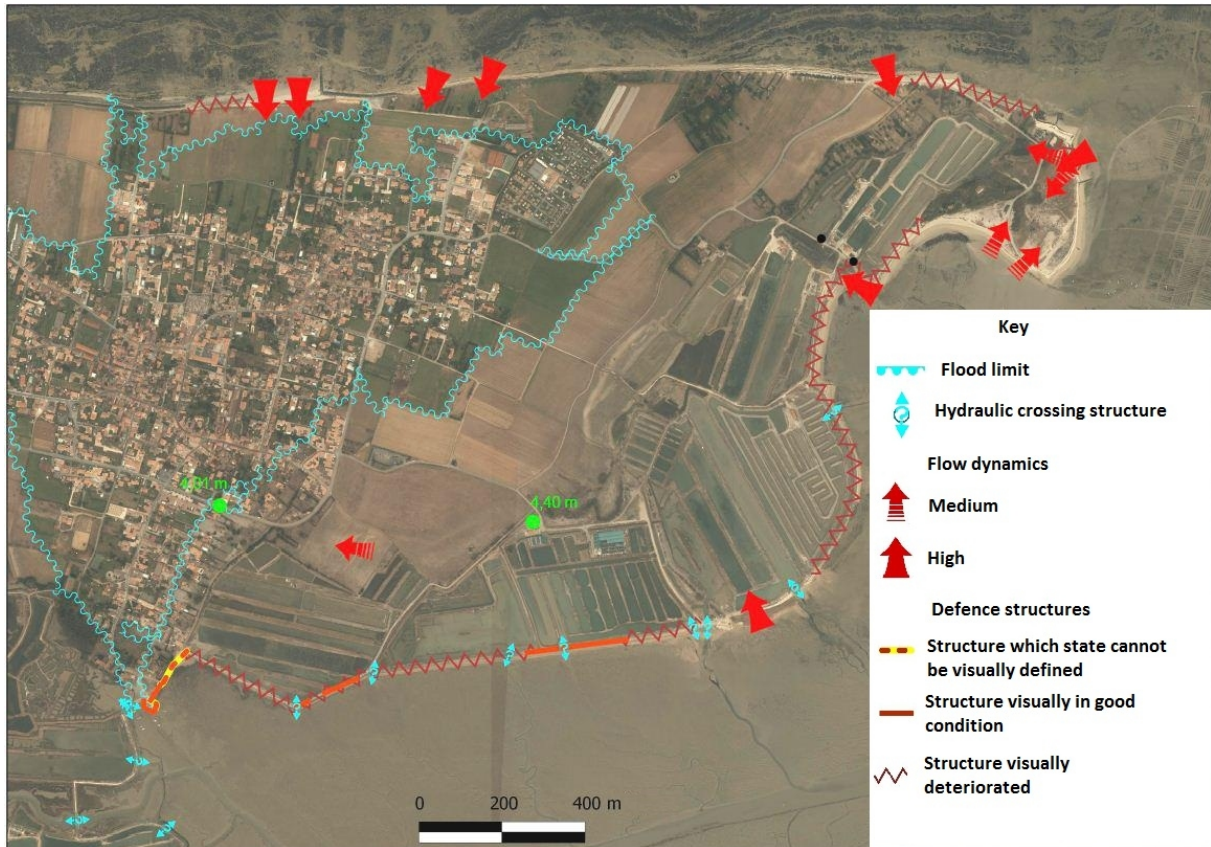


Figure 98: Photo-interpretation of the Xynthia event. Credit: Nicolas Flouest, Cerema.

First, the sharing of knowledge and analyses from the different specialties involved enabled the development of initial hypotheses about the pathways of water propagation, particularly considering the links between flows and changes in the state of the structures. However, some stumbling blocks hampered the progress of the study:

- the consistency between the elements observed in the field and the hydraulic model;
- the dissemination of analyses in the form of reports. The organization of the reports required a very rigorous framework, in connection with the organization of the territory studied.

The main challenge was to manage changes in scale, with some analyses at the system level, and others on hydraulic cells or structures. The aim was therefore to utilize multiple disciplines in a coordinated way so that the analyses followed a logical progression according to the protocol explicitly described (and which was, nevertheless, likely to vary as investigations and analyses progressed). The preparation of study reports also had to follow certain rules, in particular to effectively integrate products derived from hydraulic models, graphs, cartographic representations, images, and texts.

There was also a regular need to explain physical phenomena common to the different sites.

To address these challenges, a document to assist in the production of case studies was developed. The content of this document has been gradually expanded by:

- recording common technical elements. This was an opportunity to give precise descriptions of the observed physical phenomena, as well as the modes of operation and failure of the protection systems and their structures: levees, beaches, dunes, and structures used in the

management of the coastline (breakwaters, seawalls, groynes, retaining walls, etc.), as well as water management structures (valves, channels, storage areas, pumping stations, etc.);

- exploring and supplementing the state-of-the-art as much as possible with study strategies and methods of analysis and investigation. This research was carried out by considering that the conduct of analysis in a complex environment implies well-informed and clearly explained choices, but also that the field of validity should be defined before any method is used.

The development of this aid for the management of case studies ultimately resulted in the production of a methodology for studying the behavior of systems subject to a meteo-oceanic event. The development of the methodology and the preparation of case studies has progressed through iteration to ensure the relevance and applicability of the concepts, strategies, and analysis methods. Time and resource optimization was a constant concern in the establishment of recommendations.

Composition of the methodological framework

Figure 99 presents the composition of the methodological framework developed for the analysis of the behavior of protection systems subject to a meteo-oceanic event.

Part 1 introduces the concepts which serve as the basis for the study of protection systems (parts 2 and 3) and then the techniques of analysis, investigation and representation (parts 4 and 5).

Parts 2 and 3 describe the composition of the systems and their behavior during submersion. It seemed necessary to distinguish the level of the system (part 2) and the level of the structures (part 3).

Parts 4 and 5 present the strategies, the methods, and the investigation and modeling techniques to study the behavior of protection systems during submersions.

In addition, a framework for formalizing case studies is presented to provide assistance in the production of site analysis reports.

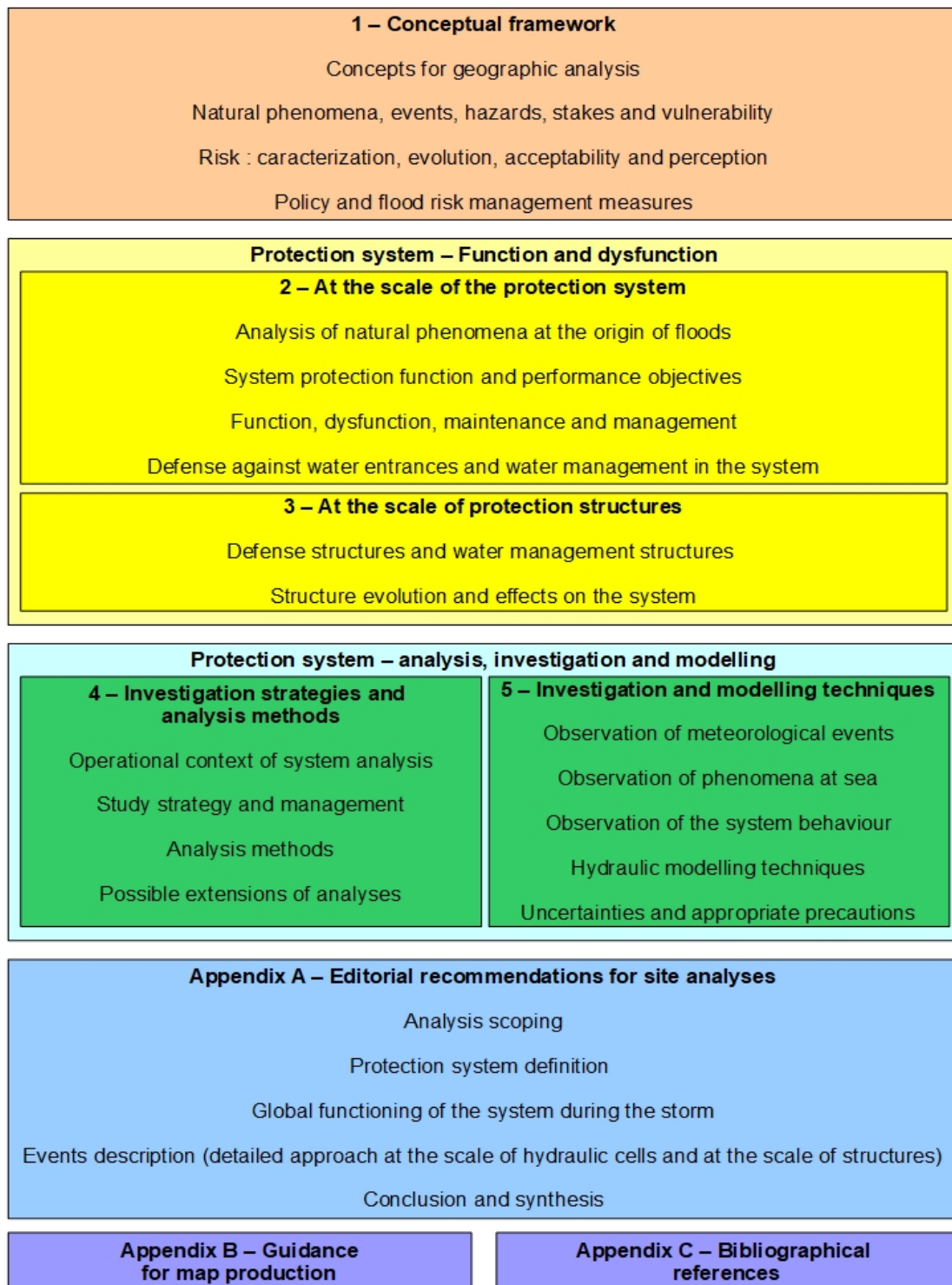


Figure 99: The methodological framework for the analysis of the behavior of protection systems [E].

Methods of interdisciplinary cooperation

The Cerema's organization of the first Xynthia feedback seminar on June 11, 2010, focused on three themes: « Information Gathering », « Feedback from the Hydraulic Analysis » and « Feedback from the Structure Analysis ». These initial exchanges were certainly necessary, if only to draw up an inventory of the available data and employable skills, but they mainly led to the conclusion that geotechnicians or hydraulicians alone were not able to progress separately to give complete feedback. Alone, they could give discipline-specific feedback, but very quickly had to call upon other specialized skills such as: analysis of cartographic and topographical data, collection and analysis of historical information (written and oral), geomorphology, geology and sedimentology, civil engineering, ecological engineering, risk analysis, and economics. Very early on, the question arose asking which competences should be utilized, and which interdisciplinary collaborations should be forged.

Partners outside of the Cerema were also sought to obtain data. Thus, the University of La Rochelle, local and regional authorities, and the decentralized services of the State have also contributed to the work by transmitting information relating to meteorological and marine conditions and to changes in natural features and anthropogenic structures during the storm Xynthia.

In order to regulate interdisciplinary cooperation, the methodological framework integrates a study protocol that indicates which specialties are appropriate for each stage of the work. The aim of this protocol is to produce a study report with a standardized structure. It is based on the principle that, as the expression of hazard varies spatially and temporally during the event, the study must first identify the areas where it is important to know the characteristics of the hazards – the areas with vulnerable stakes – and second, determine the factors influencing the expression of hazards. In order to achieve these two objectives, specific recommendations are given for choosing the spatial scales to be used for the analyses: overall system scale, hydraulic cell scale, or structure scale. Understanding the mechanisms of water propagation at each of these scales implies an organized collaboration between geotechnicians, hydraulicians, and all of the specialists involved in data collection.

5.3.2 Adaptation of protection systems

This work was part of a global review on socioeconomic analyses supporting decision-making on protection system projects, which was initiated alongside the French General Commission for Sustainable Development (in French, *Commissariat Général au Développement Durable* (CGDD)), in collaboration with the Directorate General for Risk Prevention (in French, *Direction générale de la prévention des risques* (DGPR)). This led to the production of two studies: one concerning the cost assessment of river flood protection projects ([D] ; [2]), and the other concerning the cost assessment of coastal hazard protection projects ([K] ; [8] ; [10]). The following will focus on the latter. It should be noted, however, that both studies may be useful when considering the case of estuaries.

Context of the study

Assessing the socioeconomic relevance of a program of protection measures requires analysis methods and quantitative data in order to estimate the cost of the measures and assess the expected benefits. At a time when the protection systems at sites affected by Xynthia were being reviewed, the provision of information synthesis to frame and feed the analyses was highly anticipated by the State, the local, and regional authorities. To this end:

- possible protection strategies have been explored;
- the methodology for calculating the present global cost of the measures has been specified;
- unit cost estimates have been developed to assess investment, maintenance, and management expenditures over time, providing the means for each type of development to estimate its global cost.

This work is based on the analysis of data collected from a large number of local authorities, the decentralized services of the State, and private consultancies. These data have been extracted:

- from investment, operation, and maintenance budgets for the work stocks (for the estimation of average linear investment costs on large-scale operations, as well as annual linear operation and maintenance costs);
- from work contracts. The analysis of a large number of past operations has revealed the structure-specific unit costs of construction, reconstruction, repair, reinforcement, or maintenance. Linear cost estimates were thus produced by considering the structure as a whole. In the same manner, estimates of surface, volume, or mass costs have been established by considering the implementation of specific techniques on one or more of the structural components.

In regard to this second point, the unit costs for interventions are therefore obtained on the basis of the elaboration of a typology combining the type of structure (such as beaches, dunes, levees, civil engineering works of various types, etc.) and the nature of the operation (construction, reconstruction, rehabilitation, reinforcement, repair, etc.). The main physical parameters influencing costs (the height of the structure and techniques or materials used) were identified, and additional analyses were carried out by exploiting these parameters, with the aim of allowing the user of the study to refine their estimates.

Figure 100 shows the locations where information on work contracts has been collected.

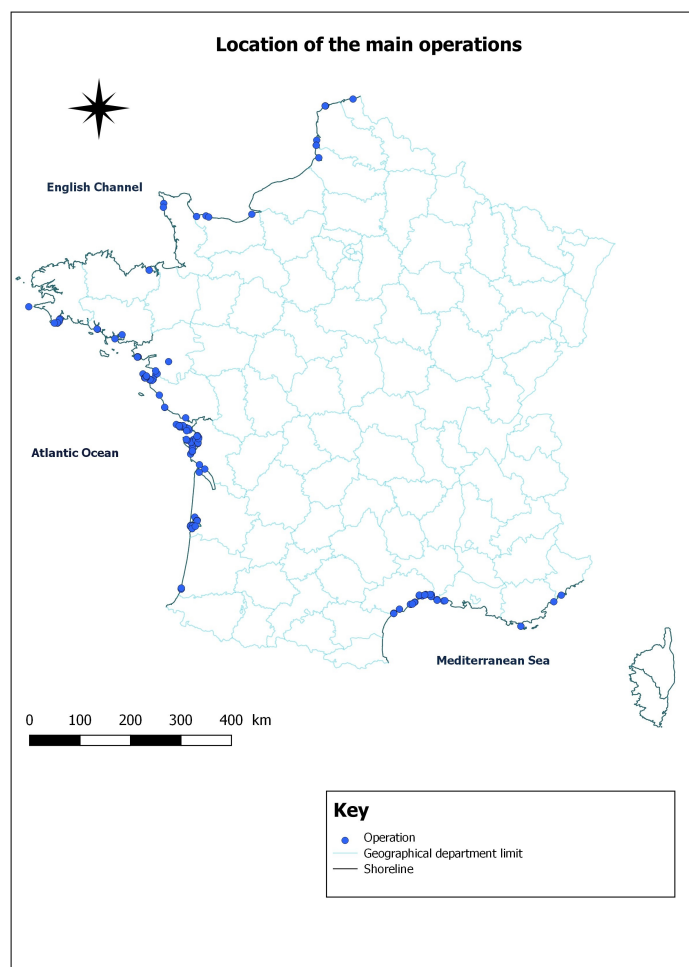


Figure 100: Locations where data from work contracts was collected. Credit: Mohamed El Fadili, Cerema.

Composition of the methodological framework

Figure 101 provides more detail on the composition of the methodological framework. In particular, three levels of analysis are distinguished:

- protection systems and more generally, comprehensive development programs (the study also looks at coastline management strategies, which are defined primarily in response to erosion phenomena, but which also contribute to protection against marine flooding);
- the structures composing the protection systems;
- the structural components on which the intervention techniques are applied.

The amount of information collected for the different types of structures offers the opportunity to carry out a transversal analysis of intervention techniques. For example, armourstone may be applied to levees, but also to seawalls, groynes, and breakwaters. The study of unit costs as a function of the type of work and its environment increases the sample size, which is a good way to refine estimates.

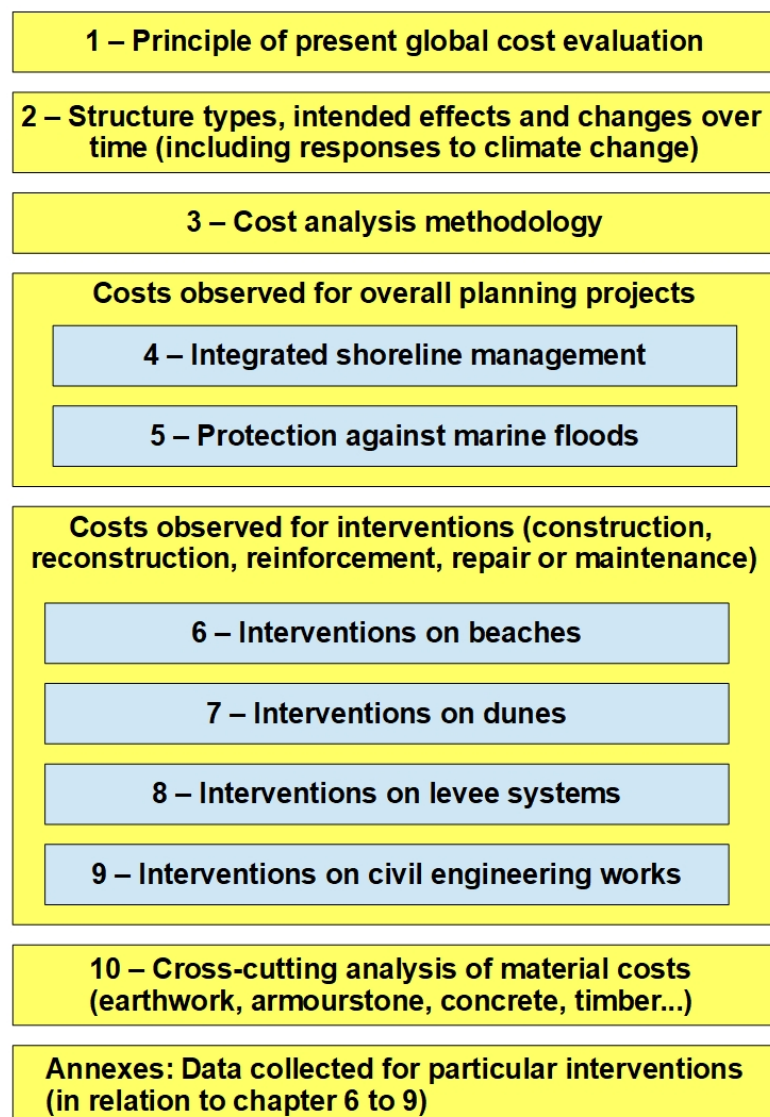


Figure 101: Methodological framework for the management and adaptation of protection systems [K].

Methods of interdisciplinary cooperation

Each unit cost estimate is of interest only if it relates to a well-defined « object » that can be located within an analysis framework whose lines have been well drawn, considering the rules for calculating the overall cost and the whole landscape of interventions on protection systems. Specifically, each object is located at the intersection of:

- a line specific to (i) intervention programs (affecting several structures), (ii) interventions on specific structures, or (iii) techniques specific to the components of the structure;
- a line indicating the nature of the operations: (i) maintenance, (ii) repair, or (iii) operations that are more adaptive (reinforcement, rehabilitation, or even construction or reconstruction).

Producing unit cost estimates to assist in the assessment of global costs therefore requires sufficiently accurate knowledge of:

- geomorphology, geotechnical engineering, hydraulics, civil engineering, and ecological engineering;
- economic approaches that should be adopted to seek expenditure optimization over the life cycle of the structure, and more generally, for the management and adaptation of protection systems.

To produce these analyses, engineering and economics skills are always required. Despite their multidisciplinary nature, it is preferable to entrust these analyses mainly to one person. This person may, nevertheless, in the scoping phase of the study, or in the case that specific questions arise during the study, call upon specialists from the relevant fields.

5.3.3 Emergency response for protection systems

Emergency response research has aimed to provide managers of coastal protection systems with a methodological framework and technical knowledge to improve crisis management.

Context of the study

This topic was explored using the feedback of Storm Xynthia, the review of regulatory references, and a literature review. The International Levee Handbook [C], especially chapter 6, « Emergency interventions », is the main bibliographic reference.

Composition of the methodological framework

The recommendations in [J] are intended to accompany the development of an emergency response plan for a protection system, with a clear distinction between:

- the development of the strategy, which is part of the « long-term » approach. Although certain common rules may be established for organization and practice, the development and updating of an intervention plan entails specific studies, which may extend over several months, and often over several years. This is performed at the system and component levels to meet specific conditions (including the stakes to be protected, hydraulic conditions, and the type and condition of structures);
- the « operational » actions required to prepare for and manage a crisis. These actions are carried out over a « short time » : the reservation of equipment and building up stocks of materials, training and exercises, monitoring actions, the interventions on levees, hydraulic structures, and networks, and the adaptation of actions to changing circumstances.

Figure 102 presents the composition of the proposed methodological framework.

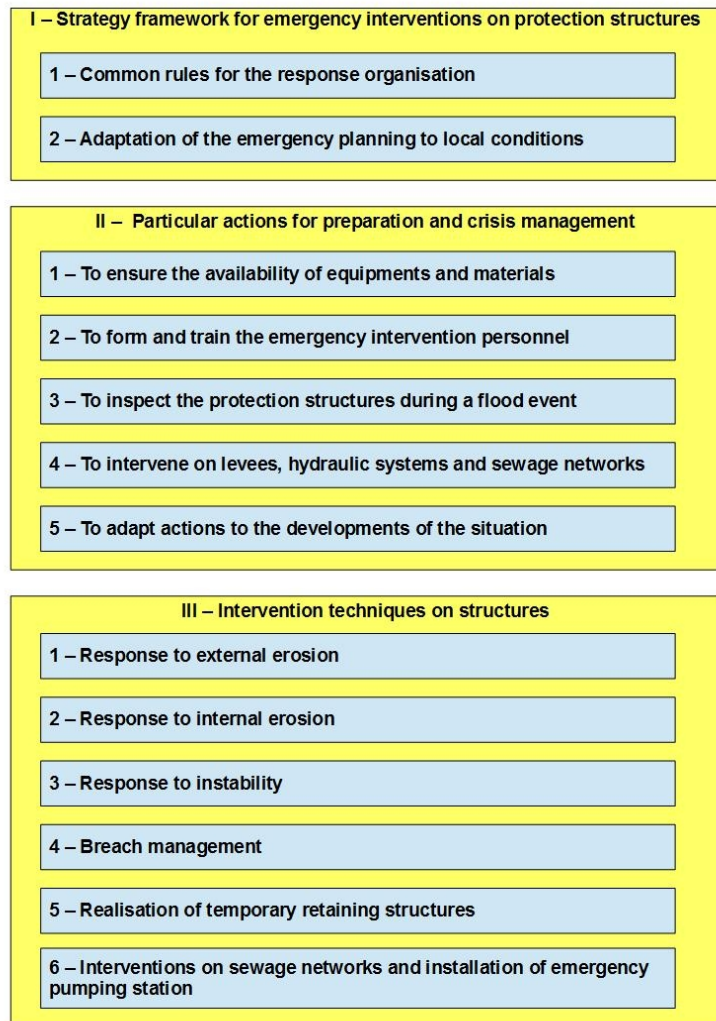


Figure 102: The methodological framework for emergency response [J].

Methods of interdisciplinary cooperation

The results of my research contribute to:

- a better coordination with the general crisis management system, through recommendations for rigorous data management and appropriate representation and communication methods;
- the utilization and coordination of specific skills to take into account the meteorological and hydraulic conditions of the site and to identify the risks of failure. Expertise in law is also required since the body of legislation and regulations in the area of risk prevention is extensive.

This interdisciplinary cooperation, which evolves via continuous improvement, is an essential component of the development of the resilience of protection systems.

Ultimately, the production of methodological recommendations for the establishment of emergency response plans for protection systems requires general knowledge (on the continuous improvement of systems, geomorphology, hydraulics, and geotechnics), as well as knowledge more specific to the territory concerned (knowledge of legislation, regulations, and special technical knowledge if the structures and the territory have certain specificities).

5.3.4 The selection of natural resources

The selection and utilization of resources such as armourstone and wood are governed by standards and regulations. My research in this field aimed to facilitate the proper application of these rules by developing innovative schemes. During these projects, focus was put on creating a dialogue between the armourstone and wood sectors (from the production to the implementation of these materials in the structures), rather than on the cooperation between the disciplines. No specific section will therefore be devoted to the latter.

Armourstone selection

The heterogeneity of deposits and the diversity of the structures often generate difficulties in identifying the quarries able to supply the required materials, while ensuring quality control.

To address this problem, the support of three major players in the armourstone industry was sought:

- the Union Nationale des Producteurs de Granulats (UNPG);
- the Carrières Indépendantes du Grand Ouest (CIGO);
- the Compagnie Nationale du Rhône (CNR). This company, a Rhône concession holder for hydroelectricity production, river transport, and agriculture, uses 60,000 tonnes of armourstone annually.

Within the framework of this partnership, three actions have been carried out to facilitate the selection and control of armourstone:

- popularize regulatory and normative tools related to the armourstone;
- provide information on the location of quarries and the characteristics and availability of materials through the production of an atlas of quarries;
- propose innovative methods and tools to facilitate the required standard testing.

The approach was led by a series of seven « round table » discussions bringing together all stakeholders in the sector (including project owners, project managers, laboratories, carriers), with the dual objectives of covering the metropolitan territory and addressing the widest possible variety of concrete situations. Along with the round tables, visits to emblematic sites in maritime (the ports of La Rochelle, Dunkirk, and Marseille), river (levees on the Loire), and torrential (reinforcement of the banks in the Pyrenees) domains have enriched the field experience. In addition, two days in Bron and Nancy, respectively, were devoted to sharing standards and laboratory expertise.

This « Tour de France » was also an opportunity to undertake a survey of armourstone resources among the quarries in each of the regions visited. Information was collected on existing stocks, production capacities, and material characteristics. The support of the trade unions representing career professionals was paramount in obtaining the support of the carriers in this approach.

All the data collected were recorded in an atlas [G], in pdf format, which has navigation functions³⁵.

Through meetings and consultations, exchanges with participants have made it possible to progress in the methods of making available regulations and standards, and developing a shared expertise on career trials and the diagnosis of structures already built. These meetings were also an opportunity to promote the innovative methods developed by the Cerema laboratory (located in Angers) for faster, safer, and less expensive tests: the automatic measurement of the speed of sound (to evaluate the continuity index of armourstone), 3D scanning (to assess the volume of armourstone), etc.

35 The report is available at: <https://doc.cerema.fr/Default/doc/SYRACUSE/15787>

In response to the round table discussions, a national restitution conference was organized in Paris on October 27, 2015 under the auspices of the Ministry for the Environment. Its proceedings [F] offer a consolidated view of the state of knowledge about these subjects.

This conference also served as a launch event for the first edition of the Atlas of Armourstone Quarries [G], which was carried out by the Angers laboratory. This atlas, which describes more than 120 sites, is now, owing to the partnership with the quarries and trade unions that represent them, a lasting reference on armourstone. The atlas offers career managers the possibility to regularly update information on stocks and cut rock faces. Access to data is available to a wide audience including managers and workers at marine and river ports, levees, and coastlines.

Hardwood timber selection

Initially, a research project was conducted by HR Wallingford, the Environment Agency and the Cerema, resulting in the publication of a notice entitled « Alternative Hardwood Timbers for Use in Marine and Fresh Water Construction (Environment Agency, 2011) ».

The production of the French edition of this leaflet was undertaken with the support of the Cerema laboratory in Nancy. During this work, an adaptation was carried out by including, in the form of inserts, regulations and standards specific to French territories.

5.3.5 Conclusions on the methods used for my research

The principles of action, defined using the concept of coastal flood protection systems, were used to establish methodological frameworks for the diagnosis, adaptation, and management of protection systems, in normal times and in crisis, including the strategic issue of material supplies.

The construction of these methodological frameworks has been ensured by involving multiple partners (central government, local and regional authorities, managers of levee systems, port managers, project managers, quarry operators, laboratories, universities, etc.). The research methods adopted combine « learning and experimentation » and « participatory approaches », and thus follow the guiding principles of « adaptive co-management » identified in the literature review. In addition to the results obtained in terms of methodological development, the collective learning of the actors involved in these projects should be recognized as an important added value. The management of these projects has thus contributed, especially in French territories, to a rise in collective competence on each of the key stages of the life cycle of protection systems.

The transposition of the methodology of these projects to other contexts is possible by applying the methods explicitly described in this section, provided that:

- the operational methodologies (and tools associated) are consistent with the legislative, regulatory, and normative framework, with available resources and with the economic and social context;
- synergies are favored between risk prevention policies and other public policies, in particular those of the ecological and solidarity transition (to avoid risks of maladaptation);
- the skills available in the given context meet the skills required to apply the methodologies.

5.4 Synthesis and conclusion

The institutional, historical, legislative, and regulatory context of the time period 2010-2018 in France was conducive to the formation of research programs to support the adaptation of coastal flood protection systems through adaptive co-management approaches utilizing a plurality of actors and disciplines. My research led to:

- the proposal of new conceptual contributions on the definition of coastal flood protection systems, specifying the links between protection structures and other structural elements of the territory, including both the stakes to be protected, as well as the infrastructure, and natural features;
- the development of new methods and operational tools that can be used in coastal flood protection strategies, particularly in the areas of:
 - diagnosis, through the development of a methodology to assess the system's response to flood dynamics;
 - strategies for adapting protection systems, through the development of a methodology for calculating the present global cost of a project, a methodology supported by the precise analysis of expenditures observed in the territory of metropolitan France since 2010 (after storm Xynthia);
 - crisis management, through the production of a methodology for developing emergency response plans for coastal flood protection systems and their structures;
 - development of supply chains for strategic material resources necessary for the proper maintenance of protection systems (especially armourstone and hardwood timbers). In particular, an atlas of armourstone quarries in metropolitan France was created by involving all of the actors in the sector.

In these methodological approaches, a protection system is no longer considered only as a set of civil engineering structures, but as a component of the territory subject to multiple constraints related to the natural and built environment, and within the social and institutional contexts. The results achieved thus contribute to integrating risk management into other public policies, including land use planning and ecological and solidarity-based transitions. Indeed, the methodological frameworks leads, by construction or by its content, to modes of action in accordance with other public policies, including the preservation of aquatic ecosystems, the reduction of environmental impacts, and the reasoned management of resources.

The methodological frameworks developed can, in some cases, not be applicable directly to territories other than France. However, the research methods adopted may be applied, where appropriate with certain adaptations, leading to the development of similar frameworks and operational tools in line with the biophysical and socioeconomic contexts.

6 CONCLUSION

Over the past 50 years, the state-of-the-art in the field of coastal flood prevention has grown considerably: integrated flood risk management has enabled progress to be made in various aspects of the SPRC conceptual framework; multiple explorations of the concept of resilience have made it possible to identify new paths that better respond to the specificity of each territory; and systemic approaches have been developed to complement analytical approaches in response to the occurrence of other natural or anthropogenic hazards arising in combination or as a result of flood risk..

During the same period, population growth along the coast appeared to be much higher, both globally and in France, than the average increase in population; increasing urbanization has invariably led to the degradation of shores that have lost their role as a buffer between land and sea; in some places, extraction of water or hydrocarbons from the ground has resulted in subsidence, and the disruption of sediment fluxes has further increased exposure to hazards or weakened natural features normally providing effective forms of protection; on a global scale, climate change has multiple effects, varying from site to site, but very often detrimental, such as increasing sea levels, rising temperatures that reinforce cyclones, ocean acidification that degrades coral reefs, etc. The magnitude of these effects will increase, on average, until at least the end of the 21st century according to all predictions, by the mere inertia of the process engaged.

The findings are therefore twofold: first, science has progressed rapidly on the prevention of risks, and second there is an accelerated deterioration of the situation along the majority of coastlines. This gap between scientific progress and the development of the situation in the territories can be explained in two ways:

- as long as the communities do not perceive the danger in their territory, lessons learned from research in understanding risks and building resilience have a small impact in most societies, especially when their mode of governance is weak;
- urbanization in areas subject to natural hazards creates conditions for the emergence of multiple risks that require new and increasingly advanced methods of analysis, as well as the development of new protection strategies involving sophisticated devices (early warning systems, identification of strategic resources, and management of corresponding supply chains, etc.).

This second process risks further increasing the distance between research contributions that could become inapplicable because they are too complex, and the needs of populations living in increasingly evolving circumstances, which inevitably makes them less receptive to messages about long-term scenarios. To limit this risk, learning and experimentation in the field are essential, as well as wider awareness and participation of the population in the definition and implementation of strategies, which includes adapting governance methods. In this sense, there is a need for public and private sectors, civil society organizations, and academic, scientific, and research institutions to work more closely together and to create opportunities for collaboration.

My research addresses this general problem on a particular point: how can the necessary evolution of protection systems against coastal flooding and the development of territories coexist?

To address this problem, the protection systems and the territories have been described as two distinct SESs in terms of their objectives, their composition, and the actors that drive them. The relationship between these two SESs has also been studied: the habitability of many territories depends directly on the coordination between the reduction of the hazard operated by the protection system and the other risk reduction measures operated by the territory.

However, the conceptual approaches adopted for these two SESs tend to diverge, which can hinder the common and coordinated definition of adaptation strategies:

- specialists in levee systems, who are busy with the day-to-day management requirements of the structures, develop a technical approach to resilience in the short and medium term, with the social and ecological aspects left relatively neglected;
- conversely, actors in the territories find it difficult to perceive the technical constraints of maintaining the performance of protection systems, but can take a long-term view of the social and ecological aspects.

To reconcile these two approaches, methods for understanding risk and defining adaptation strategies were reviewed. Points of connection were sought between the methods of the protection system managers and the methods of those responsible for land use planning, particularly of urban environments, which benefit from the protection systems. Additionally, adaptation strategies were studied. General proposals to promote the link between protection systems and the territories concerned have been formulated, and consist, in general, of promoting the integration of protection systems into spatial planning processes through, in the words of Walker et al. (2004), « resilience analysis, adaptive resource management, and adaptive governance. » My research conducted between 2010 and 2018 following Storm Xynthia, was presented in relation to these general objectives:

- the resilience analysis is supported by new conceptual inputs on the definition of coastal flood protection systems, specifying the links between protection structures and other structural elements of the territory, including both the stakes to be protected, as well as the infrastructure and natural features;
- adaptive resource management and adaptive governance have been equipped with new methodological frameworks for diagnosis, strategies for the management and adaptation of protection systems, crisis management preparedness, and development of supply chains on strategic resources.

This work has provided information, for example, on the resources available and on the unit costs for the various types of interventions on protection structures. The use of this data in engineering activities must be informed by the principles of adaptation set out in this thesis. Failure to do so could result in inappropriate adaptations (maladaptation).

Ultimately, the primary objective should be to preserve ecosystems in their regulating functions (*e. g.*, flood and climate regulation) instead of immoderately seeking the development of provisioning functions (*e. g.*, crops, and meat production). Achieving this goal requires a general awakening of consciences and a modification of our lifestyles that are too focused on consumption, to the detriment of natural resources. Otherwise, adaptation strategies can only be used as remedial measures, but will not be able to curb the increases in risk.

In research on coastal flood protection systems, this objective implies favoring systemic approaches, to deal with complex systems faced with multiple hazards. More specifically, priority should be given to:

- ecosystem approaches to reduce risks over the long term, without prejudice to other territories (maladaptation risk reduction that includes climate change mitigation);
- socio-economic approaches, because, for the adaptation of protection systems, economic and social barriers arise well before technical limits.

Recommendations related to the development of CAS resilience can help to identify opportunities for adapting protection systems and territories:

- enhance diversity and redundancy in protection systems (natural formations that complement the protection of structures), and connectivity (with aquatic and urban environments);
- ensure the proper management of slow variables and feedback (with particular attention to the effects of climate change and land artificialization on the components of the protection system);
- consider higher-level SESs (the territory, the region, and the planet) to incorporate additional recommendations, in terms of resource management and reduction of greenhouse gas emissions.

Lastly, in terms of governance and management, improving overall efficiency and effectiveness can also be sought through the coordinated development of methodologies, information management systems and other operational tools.

7 RESEARCH PERSPECTIVES³⁶

The research perspectives can be defined, after a reminder of the foreseeable context of the coming decades, according to four axes established in reference to the conceptual framework proposed in this thesis, namely:

- its use for the development of observatories in support of risk management and land use strategies;
- how it will be adopted by stakeholders;
- its potential influence on risk perception and acceptable risk;
- its use in areas other than coastal flood risk.

7.1 Context for future research

By all estimates, in the 21st century, protection spending will remain at a very high level, although it cannot be assumed that such spending will be sufficient to avoid disasters. Examples include:

- in the Netherlands, until 2050, investments under the Delta Flood Risk Protection Plan should be between EUR 1.2 billion and EUR 1.5 billion per year, or 1% of GDP;
- in the United States, the economic challenges associated with natural disasters (notably in the States of Louisiana, Texas, Florida and New York) are colossal. Currently, USD 1 billion in protection of Manhattan should be considered a low investment compared to the cost of damage associated with a hurricane.

In some areas, the question is no longer one of adaptation, but of the permanent displacement of the population. Among the most threatened sites are:

- the small islands of the Pacific. COP 27 was an opportunity to discuss the solidarity mechanisms that need to be implemented, particularly at the international level with regard to small island states;
- cities located in low-lying coastal areas: the displacement of Jakarta undoubtedly paves the way for other movements of the same type for populations affected by the effects of climate change, as well as by the artificialization of lands and development decisions at the local level.

Finally, the context is marked by strong uncertainties, including:

- sea level rise, which leads to an exponential increase in the frequency of extreme events. If the ice caps of Antarctica and Greenland are unstable, the GMSL rise could reach 2 to 3 m by 2100;
- energy crises whose impact on flood protection strategies must also be appreciated. In particular, pumping and drainage systems consume a lot of energy. De Bruyn et al. (2022) show that in the Netherlands the option of protection of the coast by a continuous line would involve pumping means so important that this option is not technically and economically feasible. Other energy-efficient solutions must therefore be preferred.

7.2 Development of observatories in areas exposed to major risks

Since actions undertaken without an adequate level of information are generally inadequate, observation, analysis, and feedback should be research priorities. As can be seen from the description of the future context, particular attention must be paid to observing and forecasting the effects of climate change, the consequences of the increase in energy prices and the feedback from the operations of permanent displacement of populations. Using if possible the conceptual framework proposed in this thesis, the perspectives for action research are:

- clarification of the principles of observatory design;
- clarification of the practical details for setting up and using observatories.

³⁶ These perspectives have been defined within the framework of the thesis defense and are the product of fruitful exchanges with the members of the jury.

7.2.1 Identification of observatory design principles

This thesis was an opportunity to deepen the reflection on the concepts. From an action research perspective, it would be interesting to study how the conceptual framework could be used to set up observatories for the adaptation of territories in a context marked by multiple uncertainties. As a starting point for this reflection, it must be recognized that there are very diverse local conceptual bases and socio-cultural contexts. For example, in the United States, for resilience, reference is often made to the International Standard Organisation (ISO) definition in order to have a common definition. Applying this definition, two lines of action appear: system design and crisis management. By acting on the design of the system, a development orientation can consist in positioning populations in the least exposed areas and to value the urban spaces thus freed up in another way (parks, leisure areas, etc.). This option helps to limit the saturation of urban space and to diversify the uses of public space. However, in a State like Louisiana, there is a very strong attachment to roots, which can lead the population to favour a reverse orientation by adhering to the principle of restoring the initial state after a catastrophic event.

To achieve socio-cultural changes, education and public communication are essential actions. These actions must be carried out taking into account that, in the long term, the definition of coastal flood protection strategies involves not only the prevention of risks, but also the policy of water management in cities and more generally our way of life. Adherence to this type of orientation requires a close association of communities. For example, in Saint-Pierre and Miquelon (France), the population initially refused to leave a neighbourhood exposed to coastal hazards. However, when its inhabitants were invited to reflect on the design of a new district, then they were able to project themselves into a more desirable future on the new space identified to accommodate them.

In defining risk management strategies, the geographical scope definition, as well as a stakeholder analysis are essential. For example, in New York State, decision-making requires consultation between the mayor, the public advocate and consumers. Given the financial issues, beyond governance, this issue is also of interest to insurers. While the allocation of grants is generally limited, how can we convince the population to spend \$1 billion or more to protect Manhattan? To achieve this, the role of each actor must be well understood. In the current context, reflections on the geographical scope and on the relations between stakeholders can also lead to questions at the global level, such as the question of solidarity between States, discussed at the COP27.

In the United States, the Federal Emergency Management Agency (FEMA) plays an important role in developing territorial resilience³⁷. The Hazus³⁸ program allows assessing the risks in different sectors (transport, water, sanitation, etc.) on the basis of experience feedback, both in financial terms and in terms of restoring functionality. The development of this type of tool and more generally the establishment of observatories are extremely important measures. The modalities of cooperation between the United States and France, under the supervision of UNESCO, could be studied to meet this need. This would include studying how data can be collected and shared according to socio-cultural contexts.

37 The FEMA supports citizens and emergency personnel to build, sustain, and improve the nation's capability to prepare for, protect against, respond to, recover from, and mitigate all hazards.

38 FEMA's Hazus Program provides standardized tools and data for estimating risk from earthquakes, floods, tsunamis, and hurricanes. Hazus models combine expertise from many disciplines to create actionable risk information that increases community resilience. Hazus software is distributed as a GIS-based desktop application with a growing collection of simplified open-source tools. Products for flood, hurricane, earthquake and tsunami events across the country include: Historic and scenario-based modeling ; Economic losses ; Building damage and social impacts from historic events ; Planning scenarios.

7.2.2 Practical details for setting up and using observatories

In the field of methodological developments, it is essential to ensure the applicability of the principles and the realism of the identified strategies. The work presented in this thesis was mainly aimed at improving the understanding of the functioning and management of systems, and improving knowledge of the necessary and available resources. The applicability of the proposed methodologies has been demonstrated in the French context. Research could continue by testing these methodologies in other countries with contrasting geographical and socio-cultural characteristics.

In addition, other principles could be considered:

- the integration of data into a single information system ;
- the decartmentalization of disciplines and the search for historical data on hazards.

The following examples could inspire the implementation of these principles in future action research programmes.

Integration of data into a single information system

Managing complexity involves a large amount of data, with the need to connect and possibly merge information management systems. Current technologies make it possible to collect and process data on a very large scale. As the frequency of hazardous events increases, the use of data collection and analysis systems will make it possible to better understand and anticipate the response of different sites.

To use these technologies, a research perspective is to explore how the smart city concept (Shahrour and Xie, 2021) can contribute to building resilience. In this context, systemic approaches must be preferred, in particular to study interactions between the components. To this end, it is important to complement mitigation measures with adaptation measures to environmental changes. The first difficulty of adaptation is knowing which systems need to be adapted. Two projects that have contributed to progress in this area deserve to be cited as examples (among many others):

- the University of Lille is involved in a European project (POLDER2C³⁹) on protective works and is looking for ways to integrate all useful data into a knowledge system;
- The Grand Port Maritime of Bordeaux has initiated the creation of a digital twin⁴⁰, which will enable to simulate the effects of long-term climate change on the port's terminal facilities.

Setting up an observatory responds more generally to this problem and requires prior identification of objectives. In particular, an observatory can be used for short periods of time, particularly in crisis management and long periods, to support progressive or more radical adaptation. In the urban environment, the conceptual framework proposed in this thesis could serve as a reference to integrate information on several infrastructure systems managed separately, ensuring a dialogue with local policy makers. The observatory could be used to achieve objectives defined in terms of socio-ecological resilience, engineering resilience, ecological resilience or social resilience depending on the various issues identified.

Decartmentalization of disciplines and search for historical data on hazards

When setting up an observatory, the mobilization of several disciplines can be of paramount importance, especially when it comes to integrating historical data. The following two examples illustrate this point:

39 The common challenge is to pro-actively prepare all stakeholders to climate change challenges. They need to embed the potential impact of flooding in their plans, on a strategic, tactical and operational level. The biggest challenge is that stakeholders do not know exactly how strong the flood defences are and how well emergency response is organized in practice. Most scenarios and decision support systems are based on theoretical models. Another challenge is to raise awareness among the general public and stakeholders that no guarantee can be given for a full-proof flood defence.

40 ECCLIPSE project : European Territorial Cooperation Programme for South West Europe co-funded by the European Union.

- The study on archaeological settlements in the Fukushima region (Kikuchi and Nespoulous, 2015) revealed that these settlements are located outside the area affected by the 2011 tsunami. The projections used by the plant designers to determine the reference event were based on chronicles dating back to 1850. More relevant hypotheses could have been adopted by mobilizing archaeologists;
- the partitioning of disciplines was also penalizing on the estuary of the Gironde, since the work carried out on extreme levels from 1986 had not benefited from sufficient dissemination. Their inclusion could have prevented the Blayais nuclear power plant from being affected by the Martin storm (1999) that almost triggered a major nuclear accident.

Research programs should therefore ensure that multidisciplinary approaches are put in place and that historical data are integrated.

7.3 Adoption of the proposed conceptual framework by stakeholders

The adoption of the conceptual framework by stakeholders can be considered by answering two questions:

- How do individuals and institutions generally position themselves in relation to systemic and analytical approaches (broadening the question covered in this thesis by considering only levee managers and land use planners)?
- How can we foster the adoption of the recommended principles for understanding the response of territories to a flood event (particularly the “bow tie” conceptual framework)?

7.3.1 Positioning of individuals and institutions in relation to systemic and analytical approaches

An individual reacts to events by taking into account all the elements that he/she perceives in the local environment. For this reason, it can be considered that the individual scale mainly obeys systemic approaches. Conversely, since it is impossible to take into account the particularities of each site in defining laws and regulations, they tend to favour analytical approaches.

If inappropriate information is communicated to an individual (for example, by recommending protection against the wind when the flood hazard is more dangerous), the implemented protection may be inadequate. An effective prevention policy should therefore at the higher levels ensure compliance with rules applicable at all sites (in particular regulating construction in low areas) and provide quality information on the hazard (long-term prediction and short-term forecast as an event approaches). In addition, at the level of individuals and small communities, the culture of risk should be developed in order for these rules and the sharing of information to be applied and used properly, taking into account all other context elements more broadly. The challenge is to coordinate these two approaches, analytical and systemic, at the institutional and individual levels. This observation, made in a changing and uncertain context, led the French Directorate-General for Risk Prevention (DGPR) to consider that the State should no longer define measures for adaptation to climate change alone and that local and regional authorities will have to take an increasing role in decision-making in this area. Action research programs could be envisaged to study the modalities of implementation of this principle.

7.3.2 Applicability and adoption of the principles of bow-tie analysis by stakeholders

The “bow-tie” method (transposition of a method originally developed for industrial risk analysis) was implemented by a multidisciplinary team as part of Xynthia’s feedback. Following this work, it would be desirable to ensure that the territorial actors can appropriate this conceptual framework and thus reflect together and design a territorial resilience project.

The application of the bow-tie method should be promoted by theoretical training supplemented by training on techniques for collecting and analyzing data after an event. However, it would be necessary to explore how such training could be provided according to geographical and socio-cultural contexts.

The use of this conceptual framework, not as feedback, but as a means of assessing changes in risk, could also be considered. This includes research on the evolution of hazards in the context of climate change. A recent study on the evolution of coastal hazards along the façades of metropolitan France and the overseas territories was carried out in a collaboration between the Cerema, the SHOM and the European Commission's Joint Research Center⁴¹. This study aims to explain to the actors in the field the parameters determining the evolution of the hazard, without being limited to considering the single parameter of the sea level.

7.4 Potential influence of the proposed conceptual framework on risk perception and acceptable risk

We shall consider here that the question of acceptable risk raises the question of risk perception. Indeed, with a constant hazard, the more accurate the perception of risk is and the lower the level of risk, insofar as people will be less surprised by an event and better prepared to manage it.

With regard to the perception of risk, it must be stressed that it can change considerably over time, as has been shown with the floods of Elbe (Dresdner Wasserbauliche Mitteilungen, 2007) where two essential factors are noteworthy: the time between two events, and the existence of other historical events, such as wars. Specific actions should be taken to maintain and improve this risk culture. The proposed new conceptual framework, as well as the associated regulatory and methodological developments, are likely to change risk perception in time, and the social, technical and economic construction of the acceptable risk. Investigations could be carried out on multiple themes in this area. If we focus on protection systems and their structures, two particular issues arise:

- How can the systemic approach respond to the adverse effects of protection systems?
- How is the proposed conceptual framework likely to change the acceptability of protection structures?

7.4.1 Apprehension of adverse effects of protection systems by systemic approaches

Protection structures mask risk areas, create a false sense of security, and promote construction in these areas. The proposed conceptual framework invites us to consider protection systems as an integral part of the territories, not only as a set of structures that can hinder the progression of flows, but also as a set of spaces capable of receiving the volumes of water overflowing the lines of defense. These spaces should ideally have few vulnerable stakes and should be used to better protect areas with higher stakes. This integrated territorial view of protection systems should in general make it possible to better understand and respond to adverse effects than if the works are considered separately or in the form of a line of defence.

7.4.2 Potential impact of the proposed conceptual framework on the acceptability of protection structures

Liao (2012) recommends a drastic limitation of protective works, on the ground that the presence of these works constitutes a barrier to the adaptation of urban environments. The implementation of these recommendations implies that urban areas are regularly flooded by low water levels, which leads to a change in lifestyles. This posture can actually promote adaptation to hydraulic conditions corresponding to extreme events, either because people leave the site regularly flooded, or because they adapt by staying there. Liao's view shows that the issue of acceptable risk is inseparable from the

41 Igigabel M., Yates M., Vousdoukas, M. I., and Diab Y. (submitted in 2022). Assessing Changes in Coastal Hazards at Regional Level : Method and Case Studies

issue of adapting lifestyles in flood-prone areas. This involves training, education, and governance oriented towards risk management, resource preservation and more generally sustainable development. For training, education and governance, integrated management of these issues remains a challenge.

The conceptual framework proposed in this thesis, by advocating the application of the principles of adaptive co-management, can contribute to the population's increased appreciation of the limits of use of protective works. This should be reflected in particular in regulations that make those who benefit from the protection responsible, at least in part, for the cost of the protection. This measure has the advantage both of improving the perception of risk and of encouraging citizens to make coherent and responsible decisions. Research should continue to identify other measures with similar benefits.

7.5 Other applications of the proposed conceptual framework

This thesis led to the development of a conceptual framework adapted to coastal flood protection systems. It is interesting to investigate the possibilities of transposing the obtained results to other types of infrastructure systems. This reflection was conducted for a general case to define a conceptual framework common to several infrastructure managers that is intended to strengthen territorial resilience⁴².

The drafting of the report on the adaptation of port and river infrastructure management (IGEDD/IGAM, 2022) was an opportunity to consider the transposition of the conceptual framework to port and river systems. It became apparent that the pedagogical explanations had to focus on the nature of the hazard in order to bring the actors together to complete a joint analysis of the vulnerabilities of the corresponding systems. To this end, it is also necessary to provide infrastructure managers with precise data on the parameters determining the hazard at various points along the coastline.

The conceptual framework could also serve other areas such as maritime and coastal planning. In particular, the concept of a socio-ecological system could be used to analyse each use. For example, fishing activities could be studied using this concept by looking at aquatic organisms, fishermen and the entire chain from distribution and processing to the consumer. Interactions between marine and coastal uses could also be analysed using this concept and the associated models.

42 Igigabel M., Yates M., and Diab Y. (submitted in 2022). Development of a common conceptual framework for the adaptation of coastal flood protection systems.

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9 LIST OF MY PUBLICATIONS AND CONFERENCE PRESENTATIONS

9.1 List of my scientific articles

[1] Igigabel M. et al, 2013. Définition des systèmes de protection contre les submersions et analyse de leur fonctionnement – Méthodologie issue du retour d'expérience Xynthia. Actes du 2e colloque national Dignes maritimes et fluviales de protection contre les submersions – Dignes2013, 91-98.

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[13] Igigabel, M.; Nédélec, Y.; Bérenger, N.; Flouest, N.; Bernard, A.; Chassé, P.; Tiberi-Wadier, A.-L. Guidelines for Analysing Coastal Flood Protection Systems After a Submersion. *Water* 2022, 14, 15. <https://doi.org/10.3390/w14010015>

9.2 List of my published works

- [A] Cetmef, 2002. Évaluation du coût des ouvrages de défense contre la mer. 13 pages hors annexes.
- [B] Cetmef, 2012. Les essences de bois alternatives pour la construction maritime et fluviale. ISBN : 978-2-11-131067-4. 34 pages.
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- [J] Cerema, 2018. Interventions d'urgence sur les dispositifs de protection contre les submersions marines. Collection : Références. ISBN : 978-2-37180-226-1. 92 pages.
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- [M] CIRIA, Cerema. Guide International sur les Digués, « The International Levee Handbook, 2013 », version française, Cerema, Bron, à paraître en 2019

9.3 List of my conference presentations

Event Designation	Place and date	Title of the presentation
4th European Conference on Flood Risk Management (FloodRisk)	Virtual Conference, June 22-24 2021	Enhancing the resilience of levee systems with methodological developments
International Conference on Coastal Engineering (ICCE)	United States, Baltimore, July 30 to August 3, 2018	Cost study of coastal protection – methodological framework
Coastal and Maritime Mediterranean Conference (CM2)	Croatia, Split, November 29 to December 1, 2017	Presentation of two manuals : <ul style="list-style-type: none"> • Cost of coastal hazard protection • Emergency response on marine flood protection structures
3rd European Conference on Flood Risk Management (FloodRisk)	France, Lyon, October 17-21, 2016	Coastal flood protection systems – concepts and analysis
International Conference on Coastal Engineering (ICCE)	Turkey, Istanbul, July 18-22, 2016	Coastal flood protection systems – concepts and analysis (Presentation cancelled due to attempted coup in Turkey)
The Monitor Conference « Natural Risks in Construction »	France, Paris, April 4, 2016	Coastal developments and risks
National Armourstone Conference (Towards optimal use of armourstone)	France, Paris (La Défense), October 27, 2015	Presentation the conference introduction Presentation of two articles : <ul style="list-style-type: none"> • The general picture of the use of armourstone in France, • Investigations of armourstone in existing structures. Concluding remarks of the conference
Coastal and Maritime Mediterranean Conference (CM2)	Italy, Ferrare, November 25-27, 2015	Coastal flood protection systems – Xynthia feedback experience – case studies conclusion
55th Conference of Estuarine Coastal Sciences Association (ECSA)	United Kingdom, London, September 7-9, 2015	Coastal flood protection systems – Methodology Coastal flood protection systems – Case studies conclusion Toward an optimal use of armourstone
IUEM International Symposium , Coastal Risk Awareness and Understanding	France, Brest, from July 3-4, 2014	Presentation of the International Levee Handbook (ILH)
Seminar on the study of marine flood protection systems	France, Nantes, June 11, 2014	Presentation of the study of coastal flood protection systems
SHF Colloquium on Extreme Flooding Events	France, Lyon, November 13-14, 2013	Cost study of river flood protection techniques Study of protection systems against marine flooding
IRSTEA national symposium "Maritime and river dikes for protection against flooding".	France, Aix-en-Provence, June 14, 2013	Cost study of river flood protection structures Definition of flood protection systems and analysis of their functioning - Methodology resulting from the feedback of Storm Xynthia
Sixth International Conference on Scour and Erosion (ICSE)	France, Paris, August 27, 2012	Training on levees and flood risk management (ILH conceptual framework)

PART 2 – MY MAIN PUBLICATIONS

1 – Igigabel M, Diab Y and Yates M (2021) Exploring Methodological Approaches for Strengthening the Resilience of Coastal Flood Protection System. *Front. Earth Sci.* 9:756936. doi: 10.3389/feart.2021.756936

2 - Igigabel, M.; Nédélec, Y.; Bérenger, N.; Flouest, N.; Bernard, A.; Chassé, P.; Tiberi-Wadier, A.-L. **Guidelines for Analysing Coastal Flood Protection Systems After a Submersion.** *Water* 2022, 14, 15. <https://doi.org/10.3390/w14010015>

3 – Igigabel, M.; Nédélec, Y.; Bérenger, N.; Flouest, N.; Bernard, A.; Chassé, P.; Pitié, C. (2016). **Coastal Flood protection Systems. Xynthia Feedback Experience. Case Studies Conclusion.** *Revue Paralia* 9, 4. doi:10.5150/revueparalia.2016.s04

4 - Igigabel, M., and Yates, M. (2018). **Cost Study of Coastal protection.** *Int. Conf. Coastal. Eng.* 1 (36), 87. doi:10.9753/icce.v36.papers.87

5 - Le Turdu, V., Igigabel, M., Barlier, S., Masset, J.-P., Bodet, R., Dumas, M., et al. (2016). **Inventory of Armourstone.** *E3s Web Conf.* 7, 12006. doi:10.1051/e3sconf/20160712006



Exploring Methodological Approaches for Strengthening the Resilience of Coastal Flood Protection System

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Coastlines are subject to multiple developments related to land use planning and the effects of climate change. These developments generally lead to an increase in the risk of coastal flooding. This article focuses on systems to protect against this hazard, and presents a bibliographical analysis on methods and operational tools to strengthen their resilience. This analysis is carried out by considering that a system of protection is a component of the territory to which it provides protection and that it is therefore necessary to study in depth the relations between this system and the various components of the territory (the natural environment, the built environment and the social and institutional environment). Based on this hypothesis, the concepts of risk and resilience applied to floods are specified and the protection and adaptation strategies commonly used in recent decades are described. This retrospective on concepts and strategies leads us to structure the state-of-the-art analysis on methods and operational tools in relation to two issues: 1) understanding risks; 2) adapting and transforming protection systems. In each case, the use of the concept of resilience implies a clear distinction between systemic and analytical approaches. Finally, this bibliographical analysis reveals the need to revise the protection system concept in order to promote the integration of these systems in the territories. Accordingly, new methodological developments could be considered using ecosystem and socio-economic approaches.

Keywords: resilience, flood protection systems, climate change adaptation, methods, system analysis

1 INTRODUCTION

Coasts are subject to multiple changes: climate change, demographic growth, poor land management, the unsustainable use of natural resources, declining ecosystems (UNISDR, 2015), etc. These changes generate an increase in natural hazards, as well as the emergence of new risks, by combination or cascade effect (IPCC, 2019). The low elevation coastal zone (classified as having land less than 10 m above sea level), where people and infrastructure are most exposed to coastal hazards, is currently home to around 11% of the global population (around 680 million people). By the year 2050, the population in this zone is projected to grow to more than one billion under all socio-economic scenarios (Merkens et al., 2016). In the coming decades, the expected acceleration of sea level rise in response to continuing global warming will exacerbate the vulnerability of many low-lying, densely populated coastal regions of the world, and very likely will become a major threat in the near future for a significant fraction of humanity (Cazenave and Le Cozannet, 2013). Coastal flooding caused by marine flooding or insufficient drainage of continental waters to the sea is

generally the main hazard. The multiple changes and the increase of this hazard over a few decades raises the question of how to adapt the levee systems deployed over a millennium (Deboudt and Goeldner-Gianella, 2015; Guében-Venière, 2015; Welch et al., 2017), especially since the techniques used contribute greatly to the degradation of the protection provided by natural features (Syvitski and Saito, 2007; Syvitski, 2008; Syvitski et al., 2009). In order to reduce the risk of disaster, progressive or more radical changes will have to be considered, not in response to extreme events, but as part of a planned approach (Zevenbergen et al., 2008).

Flood protection may involve many components: event forecasting, protection structures, reduction of vulnerability with urban planning constraints, crisis management plans, etc. (FLOODsite, 2009a). Among all these measures, protection systems, including protection works and natural features, generally remain the first defense of a community. However, the proper functioning of the system requires continuous risk assessment and appropriate maintenance or adaptation strategies and actions (CIRIA MEDDE USACE, 2013). Thus, communities are confronted with two principal issues:

- Managing protection systems with limited material and human resources, to maintain performance;
- Adapting protection systems in response to changes in the environment, and if possible in anticipation of longer-term developments.

The fact that we inherit, generation after generation, the management of these systems, may lead to a preference for the first type of activity, which can result in conservative attitudes, resistance to change, and mainly technical approaches. In this case, methodological guides of structure management and adaptation, e.g., (CIRIA MEDDE USACE, 2013), are considered only as a form of support to continue to maintain the existing performance. Yet in the 21st century, with major disturbances in our environment, adaptation should prevail over resistance to change, to limit social and economic damage (Hallegatte et al., 2013; Klijn et al., 2015).

In this article, the aim is to review the methods and operational tools for managing and adapting flood protection systems, to identify any gaps in the state-of-the-art and to provide new insight for research on the theme of flood protection systems adaptation and transformation.

To achieve this objective, the concepts of risk and resilience applied to floods will be specified and the protection strategies commonly used in recent decades will be described. This retrospective on concepts and strategies will lead us to structure the state-of-the-art analysis on operational methods and tools in relation to two issues:

- Understanding risks;
- Adapting and transforming systems.

Finally, the discussion will focus on the shortcomings of the state-of-the-art and the corresponding avenues of research.

2 RETROSPECTIVE ON CONCEPTS AND STRATEGIES

In recent decades, flood protection strategies have been governed by two principles: risk management and resilience development (Disse et al., 2020). A retrospective of the evolution of strategies in relation to the concepts of risk and resilience is therefore essential to inform our thinking and to structure a critical analysis of the methods of understanding and reducing risks. This part will address successively:

- The definition of flood risk and flood risk management strategies;
- The concept of resilience and its definitions;
- The implications of the concept of resilience on methods to understand and reduce risk.

Considering these three points, a structure of the analysis of the state-of-the-art will be proposed.

2.1 Definition of Flood Risk and Flood Risk Management Strategies

Before the concept of resilience led to new approaches to risk prevention, many risk-based strategies were deployed. It is necessary to clarify this concept and to assess how it has been used.

2.1.1 Definition of Flood Risk

As a first approach, the risk of flooding can be understood through the “Source-Pathway-Receptor-Consequence (SPRC)” conceptual model (Gouldby and Samuels, 2005). This is a simple conceptual model for representing processes that lead to a particular consequence (FLOODsite, 2009a). For a risk to arise, there must be:

- A hazard that consists of a “source” or initiator event (e.g., in the marine domain, a cyclone or a tsunami, and in the land domain, coastal river flooding, runoff, rising water tables);
- A “receptor” (e.g., people or properties) that has the potential to be affected by the hazard; and
- A pathway between the source and the receptor (i.e., flood routes including through or over defences).

The SPRC model considers risk to be the result of the exposure of a vulnerable stake to a hazard. Therefore, flood risk can be defined in at least two alternative ways, the former being more suited to qualitative approaches and the latter to quantitative approaches (FLOODsite, 2009b).

The following formula reflects the first definition:

- 1) $\text{risk} = \text{hazard (flood)} * \text{exposure} * \text{vulnerability (of the society or the area)}$.

This first definition is often preferred by urban planners, who usually consider the hazard as a given and utilize spatial planning and crisis management as the means to adapt to that given. The

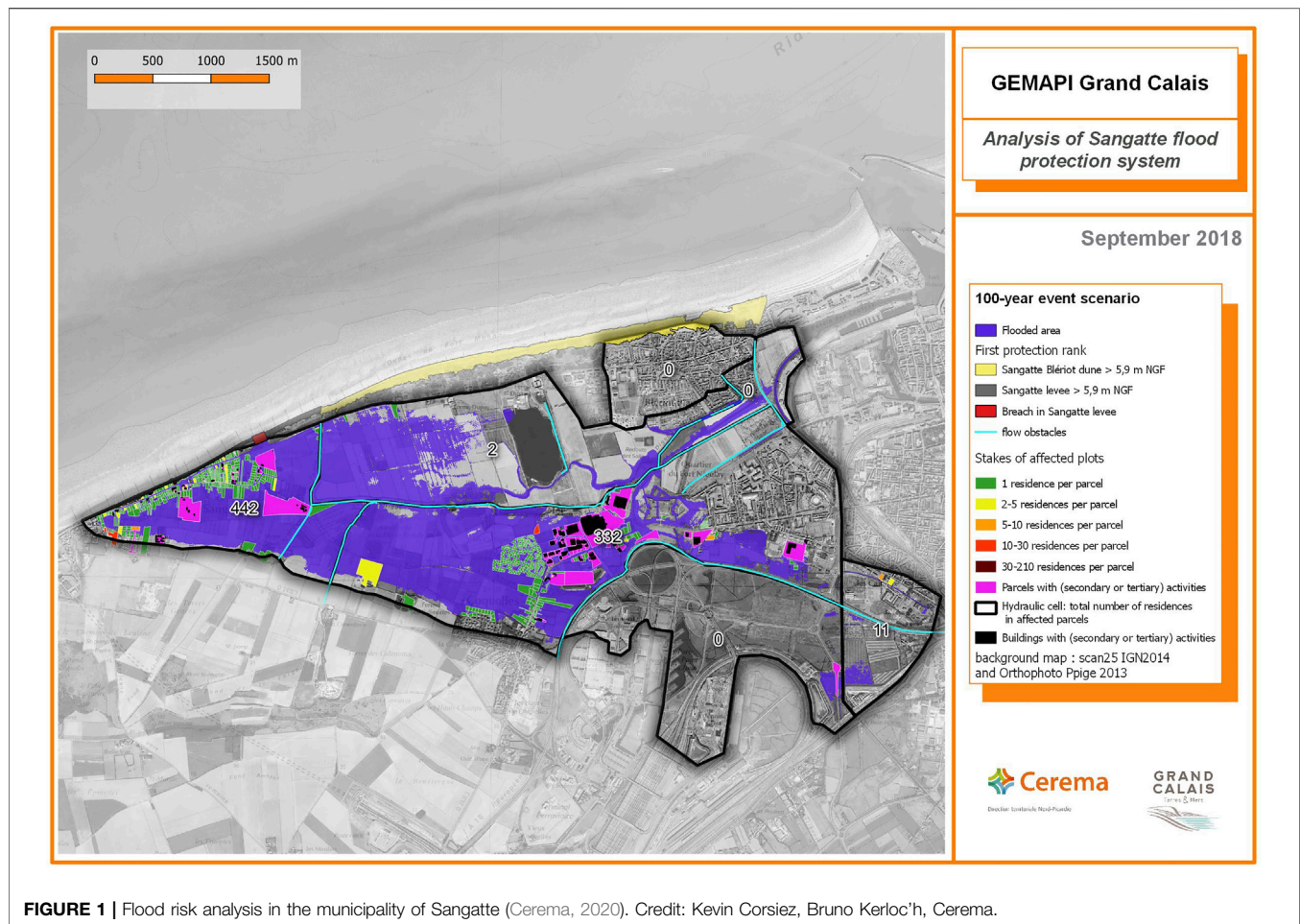


FIGURE 1 | Flood risk analysis in the municipality of Sangatte (Cerema, 2020). Credit: Kevin Corsiez, Bruno Kerloc'h, Cerema.

Figure 1 illustrates the application of this concept in the case of the impact assessment of coastal flooding on the Sangatte municipality (France). The cartographic representations of the hazard and the vulnerable exposed stakes give, by superposition, a representation of the risk.

However, in an attempt to quantify risk, and considering that the word « risk » suggests a probability of occurrence, a second definition may be sought. To do this:

- The two terms « exposure » and « vulnerability » are substituted by « consequences », with the consequences being generally more quantifiable (for example, in number of fatalities and economic damage) than the previous two terms;
- The hazard can be represented by its probability distribution.

This yields the second definition:

2) risk = probability (of the flood) * consequences.

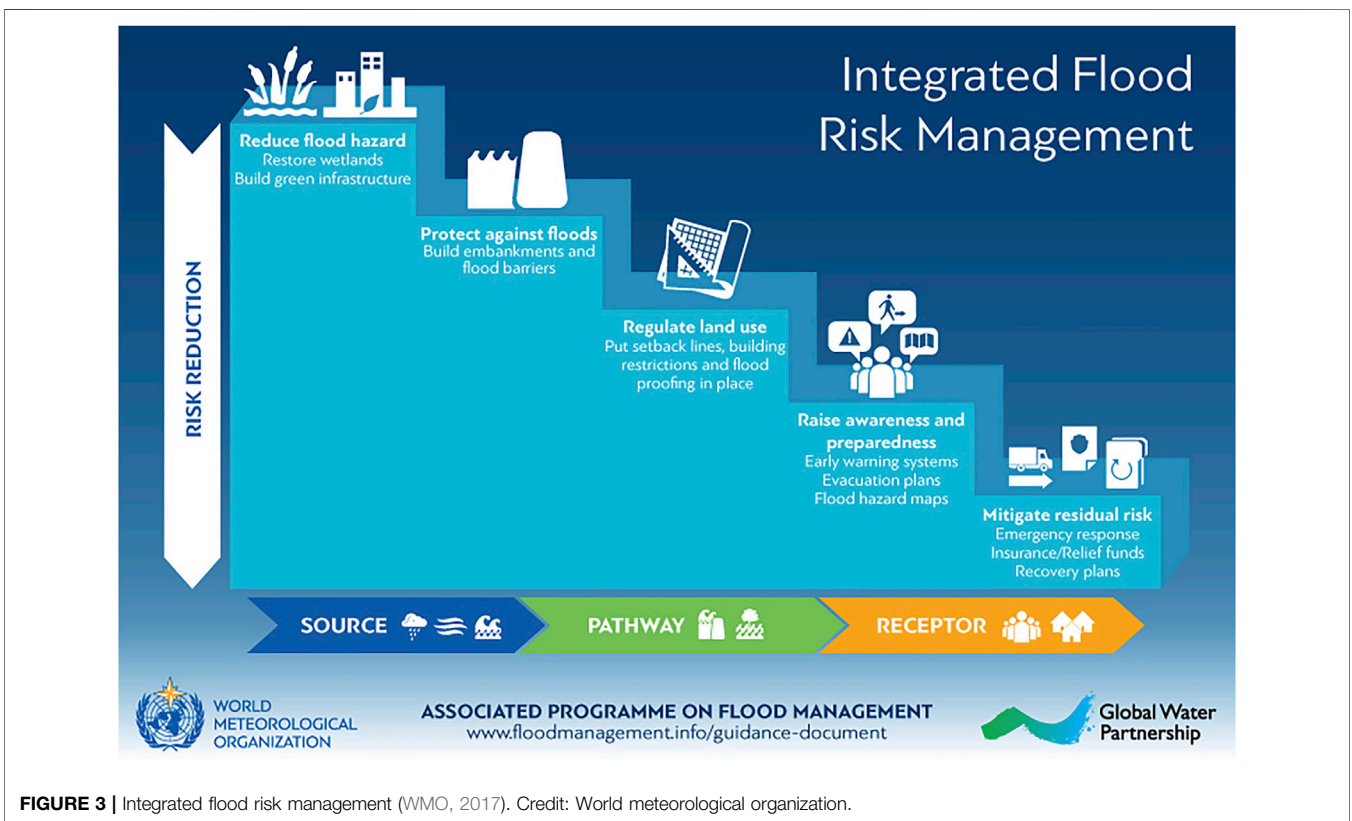
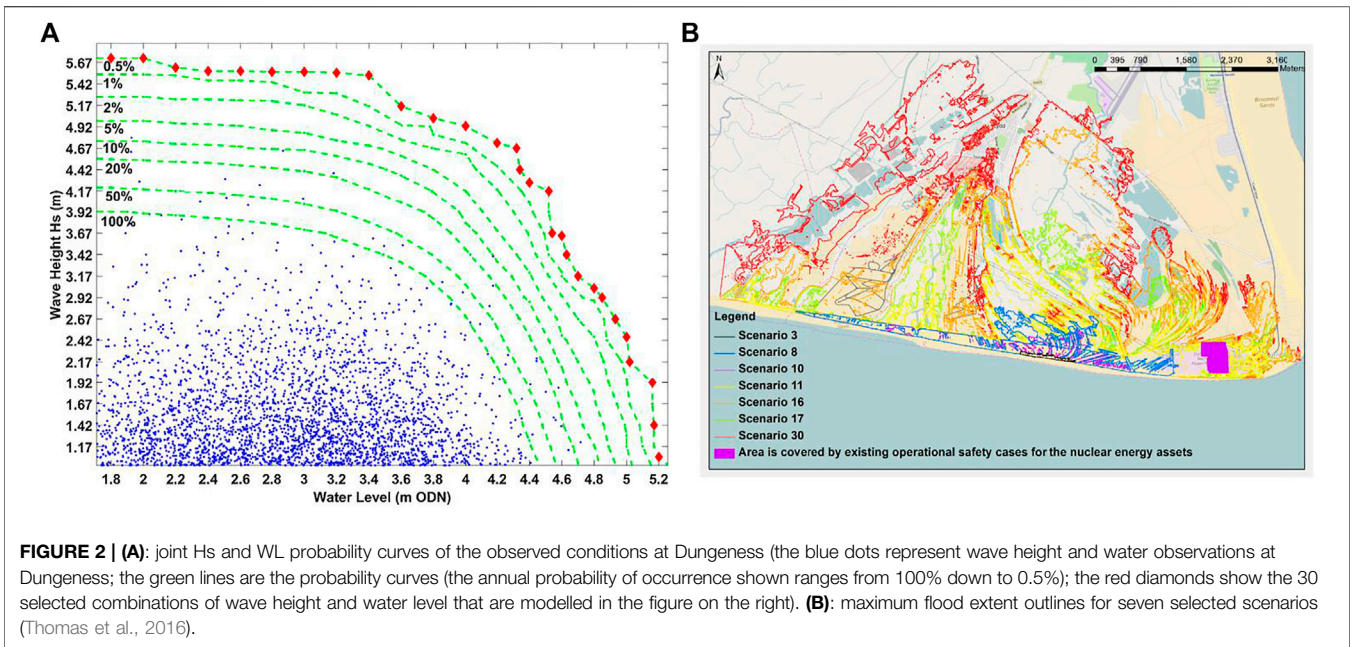
The second definition is preferred by engineers, who usually strive for a reduction of the probability of flooding with protection means, and hence need to be able to calculate risk. Thomas et al. (2016) illustrated this approach. These authors examined the Dungeness and Romney Marsh coastal zone

(United Kingdom), a region of high value in terms of habitat and energy assets. The objective was to redesign aging coastal defences in order to protect against a 0.5% annual probability event of flooding and to reduce consequences of storm surges to an acceptable level. Considering two parameters—the joint significant wave height (H_s) and water level (WL)—, Thomas et al. (2016) associated a storm impact model (simulating the overwashing discharge at the defence crest) with a flood inundation model (simulating the inundation extent and volume for the H_s and WL combination). Thus, they explored which combinations of wave and water levels generated the greatest threat, as shown by the **Figure 2**.

Klijn et al. (2015) showed that the two competing definitions can be reconciled and thus the dialogue between levee engineers and planners in charge of town planning can be facilitated.

2.1.2 Flood Risk Management

Flood risk management has changed significantly in recent decades: until the end of the 20th century, the main objective was with strong engineering means, to keep flood off the land. Focus has been on reducing the probability that communities would experience floods, generally through investing in such measures as flood embankments, channel enlargement, pumping schemes, and sea walls. From the 2000s, the main



objective became the reduction of risks for people and property. Therefore, measures to reduce the vulnerability of society were considered with the same attention as water management measures (FLOODsite, 2009a).

Figure 3 shows how, following the SPRC model, risk can be reduced by addressing one or more of the three risk factors: vulnerability, exposure, and/or hazard. The reduction of these three risk factors can be achieved through different policy and

action choices over time until limits to adaptation might be reached (IPCC, 2019). Diverse measures can be implemented (general land use planning, dedicated protection systems, application of urban planning rules, flood forecasting and warning systems), but a “residual risk” will always remain.

In support of these strategies, the use of numerical models is a well-established technique for the understanding and representation of weather-marine phenomena (Daniel et al., 2007; Tiberi-Wadier et al., 2021) and tsunamis (Sugawara, 2021), predicting their impacts on coastal zones and warn. In the fluvial field, studies using hydrodynamic models can also be utilised for flood management in general (Mehta et al., 2021), and in particular to make decision relating to the operation of dams, the relocation of people living in floodplain areas (Yadav and Mangukiya, 2021) and the developments of water courses and wetlands (Patel et al., 2018; Mehta and Yadav, 2020; Kumar and Mehta, 2021).

Flood risk management has proven successful at reducing the threat of some flooding hazards. It is a useful approach for assessing risks and guiding decisions on implementing protection measures (Disse et al., 2020). Nevertheless, in the changing context of the 21st century, marked by the increasing artificialization of soils and the multiplication of uses, the degradation of ecosystems and the services they provide (Millenn. Ecosyst. Assess., 2003; Millenn. Ecosyst. Assess., 2005; Campbell et al., 2009), flood risk management strategies based on the SPRC model or other simple models may be insufficient. To halt the ongoing processes in many territories, the scope of disaster risk reduction strategies needs to be broadened to address both natural and man-made hazards and all associated environmental, technological and biological risks (UNISDR, 2015).

To define these new strategies, the conceptual framework had to evolve. The concept of resilience corresponds to a new paradigm in the field of risk management and land use planning.

2.2 The Concept of Resilience and Its Definitions

Resilience enables people and ecosystems to cope with the shocks and stresses associated with changes, and to adapt and even transform themselves as needed. Indeed some changes are so substantial (and, often, abrupt) that they fundamentally alter the functioning of the system (Arctic Council, 2016). Therefore, the concept of resilience is essential to address the adaptation and transformation of the systems.

Resilience has a variety of definitions, although these all share a commonality in referring to the ability of a system to recover from disturbance. Definitions vary regarding what defines a « system » and as to what recovery means (Gersonius., 2016). In this section, we will therefore explore the various definitions that may have been given depending on the types of systems (Rodina, 2018): engineering systems, ecosystems, human societies, or systems encompassing all of these components (social-ecological systems).

According to Holling’s pioneering article (1973), it is possible to distinguish, without opposing them, two types of resilience, later renamed “technical resilience” and “ecological resilience” (Holling, 1996) which apply to engineering systems and ecosystems respectively:

- Engineering resilience is the ability of a system to return to an equilibrium state after a temporary disturbance. The more rapidly it returns, and with the least fluctuation, the more stable it is. The emphasis is on return time: for a « fail-safe » engineering design, efficiency, constancy, and predictability are all sought-after qualities.
- Ecological resilience determines the persistence of relationships within a system and is a measure of the ability of these systems to absorb changes of state variables, driving variables, and parameters, and still persist. Ecological resilience is not based on the equilibrium paradigm but considers multiple equilibria possible (Gunderson, 2000). Hence, resilience is not just about being persistent but also about developing new trajectories and evolving in a new system (Folke, 2006).

With these definitions in mind, a system can be very resilient and still fluctuate greatly, i.e., have low stability.

In addition, for systems such as human communities, social resilience is used to describe the ability of groups or communities to cope with external stresses and disturbances as a result of social, political, and environmental change (Adger, 2000).

Lastly, to address the issues arising in the context of global changes such as climate change and other major anthropogenic disturbances, the concept of resilience has been developed to cover social and ecological aspects more broadly. Socio-ecological resilience is defined as the capacity of interconnected social, economic, and ecological systems to cope with a hazardous event, trend, or disturbance, responding or reorganising in ways that maintain their essential function, identity, and structure. Resilience is a positive attribute when it maintains capacity for adaptation, learning, and/or transformation (Walker et al., 2004).

2.3 Implications of the Concept of Resilience on Methods to Understand and Reduce Risk

Risk management decision-making requires first a proper understanding of risks in order to be able to subsequently consider reducing them. In relation to these two objectives, the methods should therefore contribute to:

- Characterizing the resilience of systems. The objective is not only to assess their capabilities, but also to recognize the limitations of these capabilities and therefore to understand the risks, by identifying events, trends, and disruptions that systems would not be able to cope with.
- The adaptability of systems, that is, the ability of actors to influence resilience (Walker et al., 2004), knowing that their actions in relation to resilience development may be intentional or unintentional (Levin, 1998).

The concept of resilience has a major implication on the methods intended to understand and reduce risks: whatever the definition adopted, resilience refers to a system and consequently leads to a preference for systemic approaches,

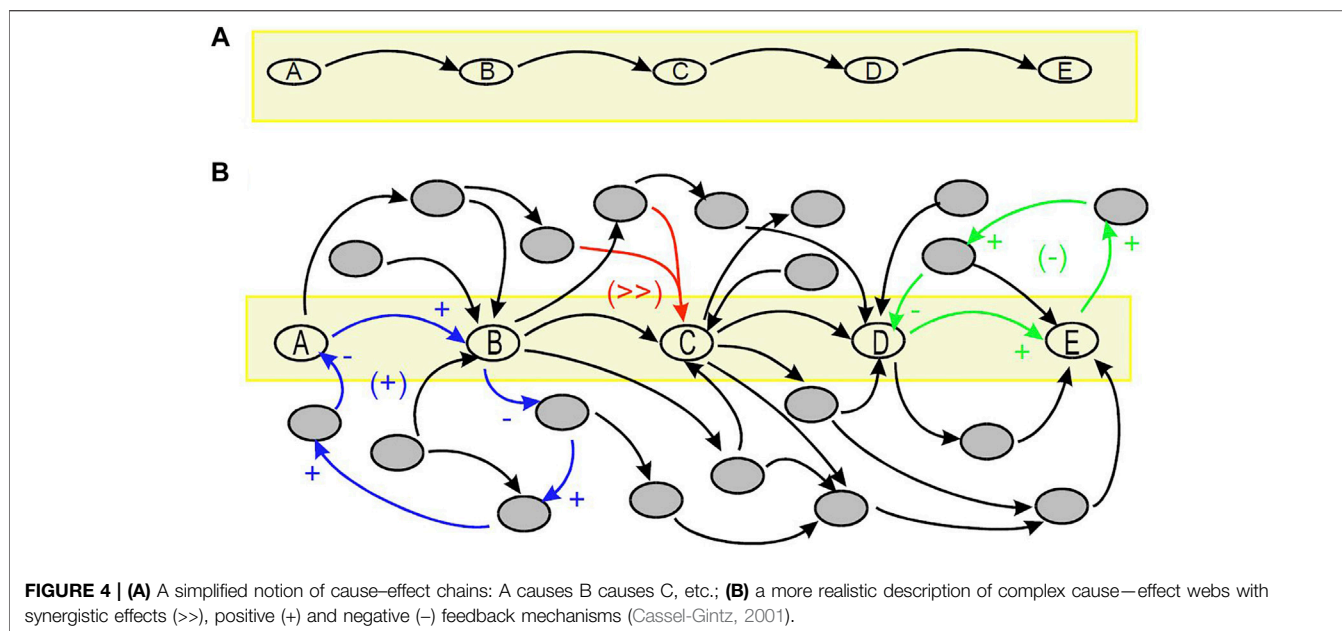


FIGURE 4 | (A) A simplified notion of cause–effect chains: A causes B causes C, etc.; **(B)** a more realistic description of complex cause–effect webs with synergistic effects (>>), positive (+) and negative (–) feedback mechanisms (Cassel-Gintz, 2001).

whereas methods based on simple models (such as the SPRC model) correspond mainly to analytical approaches. The fields of application and potential of these two approaches must be clearly identified in order to be able to use them in a relevant way.

Analytical approaches apply preferentially to stable systems, consisting of elements with so-called linear interactions, that is to say which can be described by fixed rules or by continuous mathematical laws. The guiding principle of these approaches is to proceed in the manner of Descartes (1637), whose principle was to “divide each of the difficulties examined into as many parcels as possible that would be required to best resolve them”. Analytical approaches were developed since the late 1930s and implemented in the industrial field, and then gradually extended to other sectors, including flood protection. Despite the undeniably positive results, the persistence of unanticipated disasters shows that this approach has limits. The emergence of non-detectable or uncontrollable risks through analytical approaches is due to the existence of complex systems, which include:

- The dynamics of interactions, especially the existence of feedback between the elements which makes it difficult to distinguish between causes and effects;
- The simultaneous presence of order and disorder that makes it difficult to predict changes;
- properties and « global » behaviour of the system that are not directly deduced from the properties and behaviour of each of its elements (IMdR, 2018).

In summary, Lissack (1999) defined emergence as an overall system behaviour that comes out of the interaction of many participants-behaviour that cannot be predicted or even envisioned from knowledge of what each component of a system does in isolation.

Contrary to what analytical approaches imply, in a process of aggregating a set of locally controlled situations, risks can emerge at a higher level. The examination of linear processes and cause-effect pairs is insufficient to understand the dynamic behaviour of the whole system (Figure 4). To understand the dynamics of these systems, it is necessary—but unfortunately not always sufficient—to represent the whole system as a « web » (Cassel and Hinsberger, 2017).

These two approaches are fundamentally different, to the point that they correspond to two distinct paradigms, of which Krob (2008), in his paper on complex industrial systems, made a comparison, which stated:

- A systemic approach aims for a comprehensive understanding, applies to heterogeneous systems, is based on views expressed in a collaborative framework, and produces relative conclusions (taking into account external constraints to the system) by utilising logic and systems representation;
- An analytical approach aims for a comprehensive understanding, applies to homogeneous systems, is based on detailed representation modes, utilises experts, and concludes with certainty, using scientific disciplines.

The territories and their protection systems correspond to environments where everything evolves and can be constantly questioned (over a period of a few hours, particularly during a meteo-oceanic event, or over a period of a few decades e.g., due to poorly controlled urbanisation). The dynamic nature and intrinsic complexity of these systems make their comprehension, design, and supervision extremely difficult and analytical approaches inoperative on a global scale. In this context, systemic analysis is intended to define « the architecture of a system », that is to say, its invariant part,

which can reasonably be considered as fixed over time (Krob, 2008).

Despite this formal opposition, systemic and analytical approaches are in fact complementary in practice: once the processes of risk emergence have been identified by systemic approaches, analytical approaches are needed to accurately describe the mechanisms at work and quantitatively characterise the hazard. Similarly, since protection principles have been established by a comprehensive systemic approach, the relay should be taken by the engineering analyst to ensure the proper sizing of the system. Therefore, it is the overall scheduling of investigations and analyses that deserves the most attention. Considering that it is preferable to have a global vision of a system before considering more targeted studies, a systemic analysis should generally be undertaken upstream, within the framework of an integrated approach (considering the multiple components of the territory) and should be inclusive (involving multiple stakeholders). This systemic analysis may then include recommendations in its conclusions as to any necessary analytical extensions.

Furthermore, if the complexity of a system depends on the intrinsic parameters, it also depends on extrinsic parameters (ImdR, 2018), including:

- The observer: complexity generally increases with its degree of expertise and requirement;
- The time horizon: complexity is greater on distant horizons with more uncertainty;
- The operating conditions and the available data: when the operating conditions are met and the available data are sufficient, a problem can be relatively simple, and when this is not the case, it can become complex (hence the importance of observation and monitoring).

Ultimately, the concept of resilience leads to the adoption of systemic approaches and in the implementation of these approaches, to being attentive to the nature of the system under consideration, to the context of the analysis, to the point of view adopted and to the time horizon to which it can be conducted. On this last point, it should be stressed that adaptation is an ongoing process of adjusting to changes, with no end point. This means that defining successful adaptation is more about the sustainability of processes and the principles of fairness and equity than it is about measuring outcomes at any given point in time (Stafford-Smith et al., 2011; Hurlimann et al., 2014; Barnett et al., 2015). Successful adaptation is therefore a matter of “socially and environmentally sustainable development pathways, including both social justice and environmental integrity” (Eriksen et al., 2011).

2.4 State-of-The-Art Analysis Principles

The objective of analysing operational methods and tools for strengthening the resilience of protection systems requires specifying the characteristics of the systems studied, the environment in which these systems operate, as well as the points of view according to which these systems should be examined.

2.4.1 System Characteristics

According to the International Levee Handbook (CIRIA MEDDE USACE, 2013), a levee system is defined as “a set of structures or protective elements, presenting an overall hydraulic coherence to ensure the effective protection of a previously identified group of stakes”.

However, this definition does not explicitly include natural formations, the essential role of which must be stressed in protecting against coastal flooding (IPCC, 2019). Moreover, the term “levee system” refers only to one of the two essential functions of protection systems; that of containing water by obstructing its passage. But a protection system must perform a second function; that of draining the water that accumulates inside the system by facilitating its flow outwards. Therefore, a broader and more explicit definition will be adopted for coastal flood protection systems, namely:

A set of anthropogenic structures and natural formations, presenting a global coherence from the hydraulic point of view to ensure the effective protection of a previously identified group of stakes against coastal flooding of marine, fluvial, pluvial, or phreatic origin.

Figure 5 shows schematically how these elements can be positioned in a coastal zone.

Anthropogenic or natural structures with a recognized protective role generally perform this function only in relation to other structures (e.g., salt marshes, mangroves and other wetlands). Mangroves, salt marshes, and coral reefs occur along about 40–50% of the world’s coastlines (Burke et al., 2011; Giri et al., 2011; McOwen et al., 2017; IPCC, 2019). These ecosystems provide important ecosystemic services including coastal protection by wave attenuation and shoreline stabilisation. A global meta-analysis of 69 studies demonstrated that, on average, these ecosystems together reduced wave heights between 35 and 71% at the delimited locations considered (Narayan et al., 2016), with coral reefs, salt marshes, mangroves, and seagrass/kelp beds reducing wave heights by 54–81%, 62–79%, 25–37% and 25–45% respectively. Moreover, sandy beaches and dunes occur at all latitudes covering approximately 34% of the world’s coastlines (Hardisty, 1994). The protection offered by these natural formations can be considered close to 100% for a robust dune belt in the absence of a major disturbance disrupting the hydrosedimentary cell functioning.

Protection systems are therefore an integrated set of technical and natural elements, which do not provide protection separately but in combination. Moreover, the regular action of managers of natural or anthropogenic structures (as well as other actors involved for example in regulation or financing) is a necessary condition for the proper functioning of these systems. Protection systems can therefore be considered as socio-ecological systems (SES). Such a system is defined by the IPCC (2019) as:

An integrated system that includes human societies and ecosystems, in which humans are part of nature. The functions of such a system arise from the interactions and interdependence of the social and ecological subsystems. The system’s structure is characterised by reciprocal feedbacks,

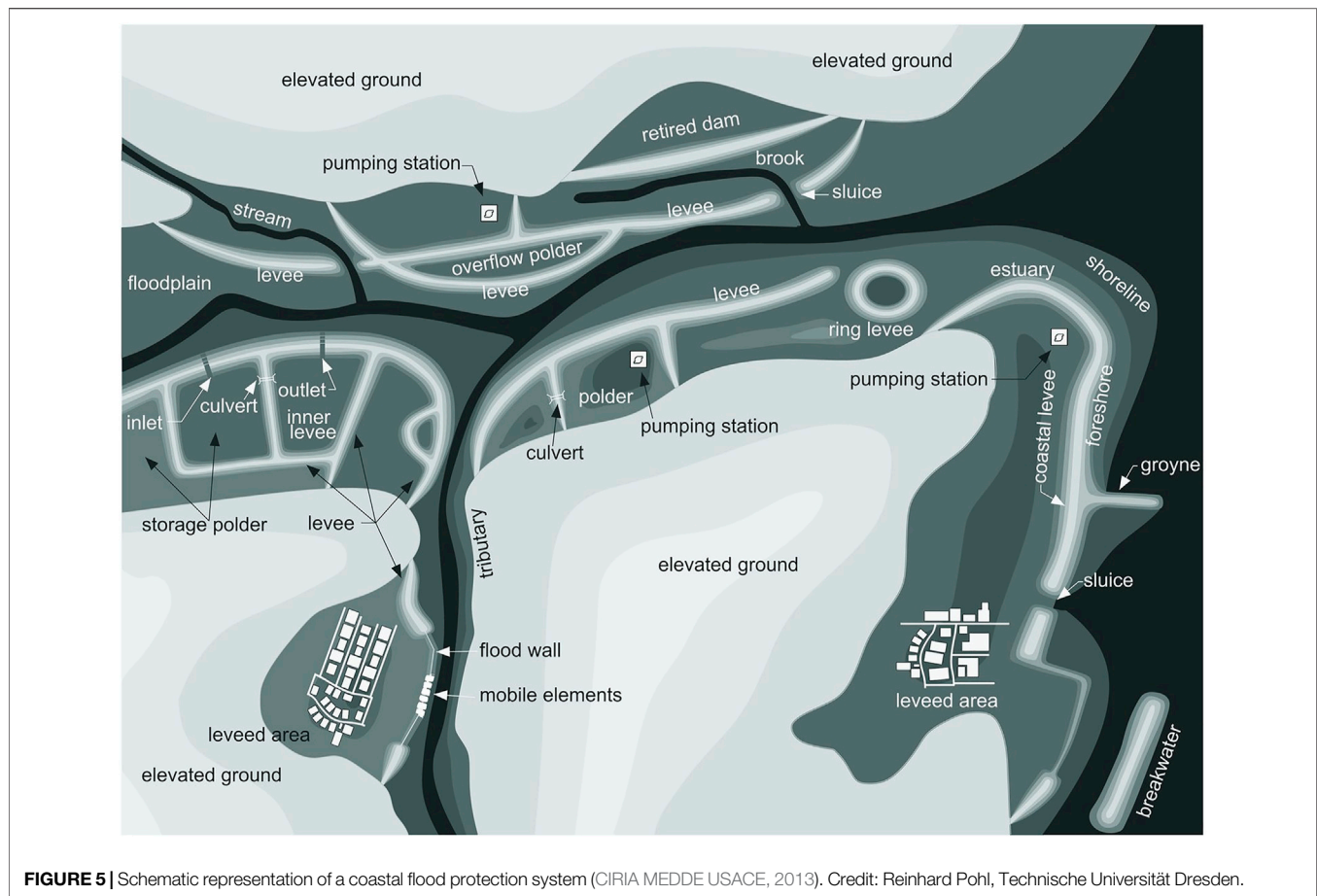


FIGURE 5 | Schematic representation of a coastal flood protection system (CIRIA MEDDE USACE, 2013). Credit: Reinhard Pohl, Technische Universität Dresden.

emphasising that humans must be seen as a part of, not apart from, nature (Berkes and Folke, 1998; Arctic Council, 2016).

According to (Millenn. Ecosyst. Assess., 2005), SESs produce a « bundle » of ecosystem services (ES), categorized as provisioning (e.g., freshwater, crops, and meat), regulating (e.g., flood and climate regulation), and cultural services (e.g., recreation and spiritual values).

SESs should be considered as Complex Adaptive Systems (CAS): a system of interconnected components characterised by emergent behavior, self-organisation, adaptation, and substantial uncertainties about system behavior (Biggs et al., 2012).

Building on this critical idea, Bigg et al. (2012) defines resilience as the capacity of an SES to sustain a desired set of ecosystem services in the face of disturbance and ongoing evolution and change.

2.4.2 System Environment

Studying coastal flood protection systems requires reframing them within the context of more comprehensive systems, considering not only the events against which they provide protection, but also changes and disturbances, slow or rapid, localized or diffuse, to which they are exposed, and more generally, all the constraints arising from the natural, the built and the social environment, at the level of the territory or at

higher levels (such as the region or the Earth). In summary, these elements can be described as follows.

In the current day and age, the coast is a space which is both particularly exposed to natural phenomena and yet remains attractive to people. It is also subject to the spread of urbanisation (Lichter et al., 2011; Jonkman et al., 2013; Güneralp et al., 2015; Neumann et al., 2015; Muis et al., 2016) in the context of increasing international trade and globalisation. These changes may lead to situations of local concern in terms of fitness for habitation and exposure to natural disasters (Hallegatte et al., 2013; Pycroft et al., 2016; Tiggeloven et al., 2020), in particular engendered by marine submersions.

Marine submersions are caused by storms or hurricanes (Harris, 1963; Graumann, 2006; Heurtefeux et al., 2007; Dietrich et al., 2010; Bertin et al., 2012; Mazas and Kergadallan, 2014; Emanuel, 2017; Emerton et al., 2020) or by earthquakes or other underwater terrain movements causing tsunamis (Margaritondo, 2005; Intergovernmental Oceanographic Commission, 2012; Archana and Twinkle, 2021; Schreurs, 2021). These events have been documented in the history of humanity as the origin of many major disasters, with arguably the deadliest events having been caused by phenomena of geophysical origin (Flather, 2001).

The phenomena at the origin of marine submersions are complex in both their mode of generation (weather-marine

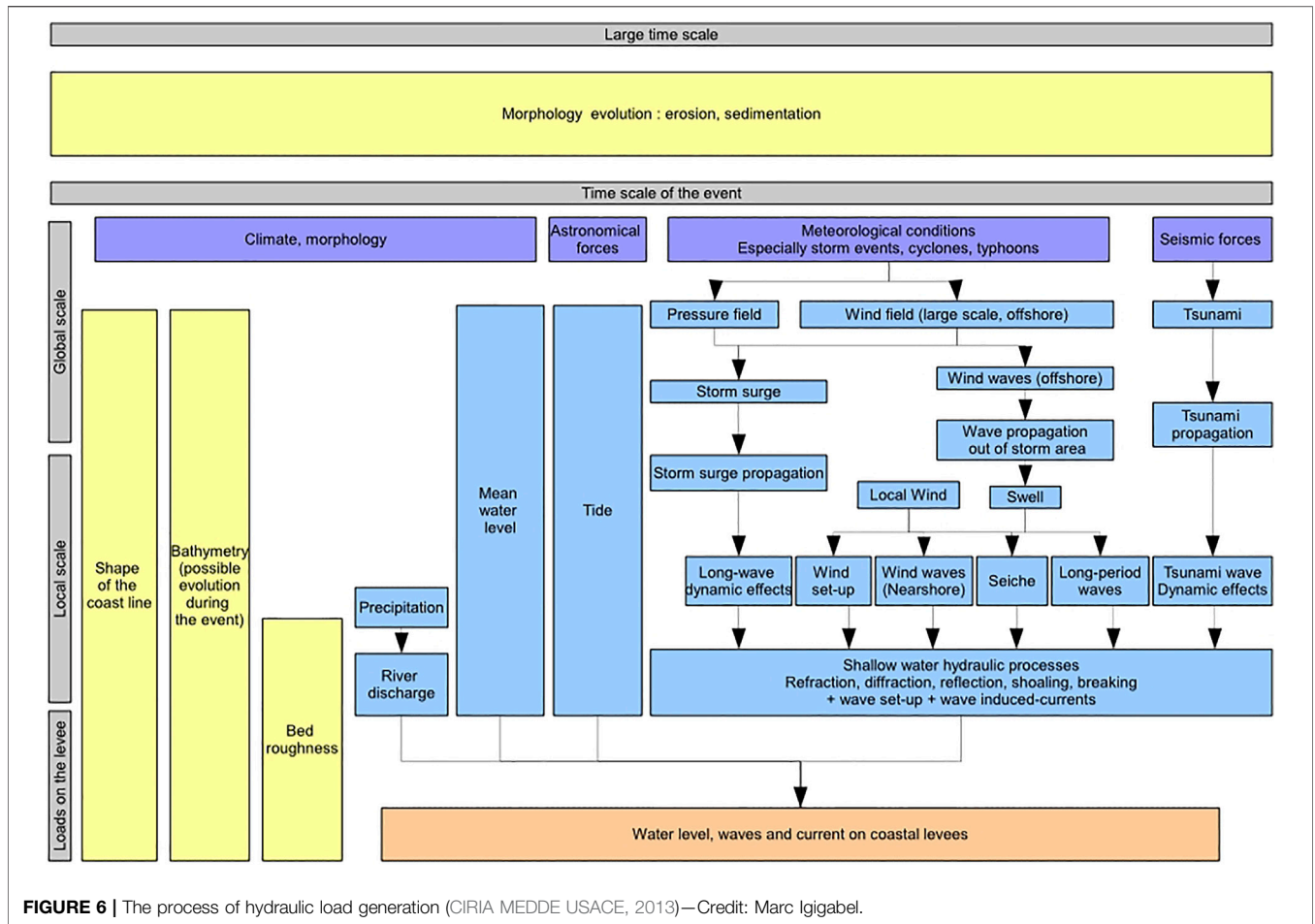


FIGURE 6 | The process of hydraulic load generation (CIRIA MEDDE USACE, 2013)—Credit: Marc Igigabel.

phenomena or tsunamis) and in their propagation to the coast, including their last phase of interaction with the coasts. The Figure 6 summarises the hydraulic processes in relation to the morphological evolutions that take place on the time scale of an event or on longer time scales.

The risk of coastal flooding is also generated by other phenomena that occur separately or jointly, such as the overflow of rivers, the accumulation of rainwater, and a rising water table. This situation requires special arrangements to be made in the design of protection systems: drainage of water in vulnerable areas must complement the defences against sea and river waters.

Risks on most coastlines will be greatly aggravated by sea level variations. In particular, rising sea levels, by increasing water depths, promote the propagation of waves to the coast and contribute greatly to the increase in the frequency of extreme events as well as to the weakening of coastlines, especially by erosion. Sea level variations occur for the following reasons, summarized by the IPCC (2019):

- Changes in ocean volume as a result of a change in the mass of water in the ocean (e.g., due to melting of glaciers and ice sheets);

- Changes in ocean volume as a result of changes in ocean water density (e.g., water volume expansion under warmer conditions);
- Changes in the shape of the ocean basins and changes in the Earth’s gravitational and rotational fields; and
- Local subsidence or uplift of the land.

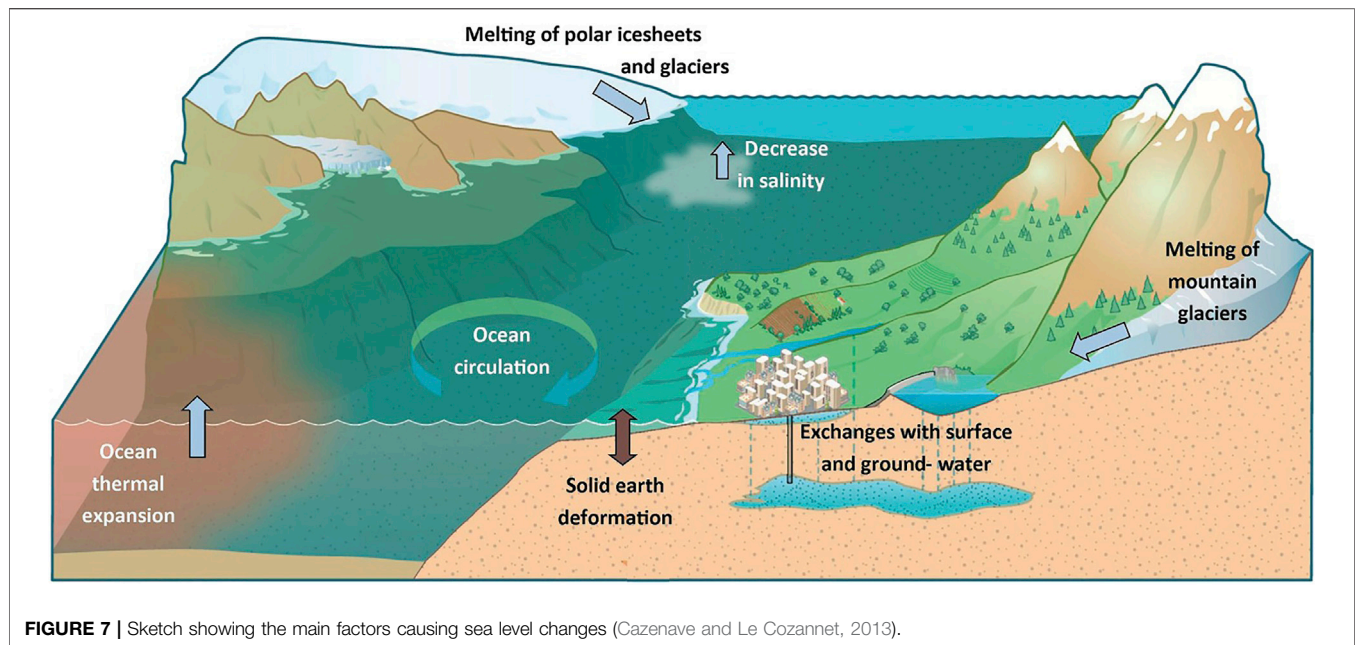
These processes are represented schematically in the Figure 7. Among the causes of sea level change identified by the IPCC (2019), it is possible to distinguish between changes in the masses or volume of the oceans, and changes of the land with respect to the sea surface. In the first case, a sea level change is defined as « eustatic »; otherwise, it is defined as « relative » (Rovere et al., 2016).

This leads to two essential definitions (IPCC, 2019):

- The Global Mean Sea Level (GMSL) can be defined as an average of the eustatic sea level at a global scale. The following definition can therefore be adopted:

Mean distance between the sea surface and the center of the Earth.

- The Relative Sea Level (RSL) can be defined as the following:



Sea level measured by a tide gauge with respect to the land upon which it is situated.

Climate change effects (described in the IPCC 2007; IPCC, 2012; IPCC, 2014; IPCC, 2019; IPCC, 2021), and in particular the RSL rise, is on most coastlines causing a worsening of coastal risks (not only does this include the risk of coastal flooding, but also the risks of erosion, shoreline retreat, and dune migration). However, at present, attributing impacts to sea level rise remains difficult in most regions (IPCC, 2019), since impacts were exacerbated by human-induced non-climatic drivers, such as land use change, land subsidence caused by groundwater and/or hydrocarbon extraction (Dixon et al., 2006; Nicholls et al., 2008; Erkens et al., 2015; Sarah and Soebowo, 2018; Tessler et al., 2018), disturbance of sedimentary movement in rivers and along coasts (Syvitski and Saito, 2007; Syvitski, 2008; Vinh et al., 2014; Tessler et al., 2015; Welch et al., 2017; Dunn et al., 2018; Ouillon, 2018; Tessler et al., 2018; Thi Ha et al., 2018), coastal erosion (Doody 2013; Pontee, 2013; Luijendijk et al., 2018; Ndour et al., 2018) and coastal habitat degradation (Dahl and Stedman, 2013; Mediterranean Wetlands Observatory, 2014; Murray et al., 2014; Gardner et al., 2015; Kummur et al., 2016; Ramsar, 2016; Li et al., 2018; Sippo et al., 2018).

In the coming decades, the frequency of extreme sea levels will vary significantly across coastlines (Buchanan et al., 2016). In particular, many coastal areas in the lower latitudes may expect amplification factors of 100 or larger by mid-century, regardless of the scenario. By the end of the century and in particular under RCP8.5, such amplification factors are widespread along the global coastlines (Vousdoukas et al., 2018).

Depending on the coastline, the risk of coastal flooding can vary. On a global scale, there are three cases of particular concern (IPCC, 2019):

- Deltas: the long-term sustainability of populated deltas is often more affected by large-scale engineering projects than

by sea-level rise. For deltas, accelerated soil compaction associated with petroleum and groundwater mining can exceed natural subsidence rates by an order of magnitude. Consequences include shoreline erosion, threatened mangrove swamps and wetlands, increased salinisation of cultivated land, and hundreds of millions of humans that are put at risk;

- Low-lying islands can be extremely exposed when they experience low variability in their water level (for statistical reasons, they then experience the effects of RSL rise more frequently) and this situation is compounded when the coral reefs or mangroves that protect the coasts suffer from the effects of climate change and local anthropogenic actions;
- Arctic regions whose coastlines are eroding as a result of thawing permafrost and reduced frozen sea surfaces, which promotes the formation and propagation of higher waves to land. These phenomena also naturally lead to an increase in the risk of marine flooding.

2.4.3 Analysis Points of View

In order to favour systemic approaches, it is important to consider that a protection system belongs to a larger system. For this reason, the system of protection will be considered as a component of the territory to which it provides protection, making it possible to pay particular attention to the methods dealing with the relations between this system and other elements of the territory. The bibliographical analysis will therefore cross-examine the points of view of specialists in protection structures and specialists in land use planning.

With regard to land planning, account will be taken of the fact that urban systems contain assets of high value and complex and interdependent infrastructure networks (e.g., power supplies, communications, water, transport, etc.). The infrastructure

networks are critical for the continuity of economic activities as well as for the population's basic living needs. The availability of these resources is also required for fast and effective recovery after flood disasters. Damage to critical infrastructure assets during flooding can result in significant secondary consequences which may be more serious than the direct damage caused by the flood. For example, the destructive power and widespread disruption to infrastructure caused by Sandy in 2012 to the east coast of North America and the Caribbean has led this hurricane to be ranked as one of the costliest storm events for insurers (FloodProBE, 2013).

3 RESULTS

Risk management decision-making requires methods to:

- Understand the risks through a global approach;
- Adapt the governance of protection systems;
- Define strategies for adapting protection systems.

The methods relating to these three objectives will be explored successively in this section, based on the conceptual framework and the principles established above. The emphasis will be more on systemic approaches, with the related analytical approaches being more relevant to the quantification of risk and the implementation of the technical and economic sizing of protection systems. Thus, for adaptation strategies, simplified approaches based mainly on the rise of RSL will be distinguished from global approaches.

To take better account of protection systems in their environment, the bibliographic analysis will focus on the following SESs:

- The territory which is an eminently complex system in terms of the number and diversity of the elements which constitute it (physical, biological, and anthropogenic constituents), and by the interconnection of these elements and their relations with the external environment;
- The coastal flood protection system, which may be regarded as a subsystem of the territory in which it is situated, which certainly has fewer and less diverse elements. However, a high degree of complexity is maintained when ecological and social dimensions are taken into account.

The latter will be considered as a subsystem of the former.

3.1 Methods of Risk Understanding

The study of the state-of-the-art will progress initially by following three axes that can be considered essential in the preparation of a systemic analysis:

- Multiple risk assessment on a coastal territory;
- Defining spatial-temporal analysis frameworks;
- Observing complex systems.

On this basis, investigations will then be carried out using the methods applicable at the territorial level, and then at the level of

the protection system. Considering the nature of SESs, guidelines will be sought not only in the physical and technical fields, but also in the social, economic and ecological fields.

3.1.1 Multiple Risk Assessment

At the shoreline, marine floodings are generated by tsunamis (the effects of the earthquake may also be felt at the submersion site) or occurs during the passage of atmospheric depressions, which are often associated with high winds and waves breaking inland of the intertidal zone. If interest is first on the coastal hydraulic phenomena, the hazard may also occur, not only by overflowing and overtopping from the sea, but also through coastal river flooding, runoff, rising water tables . . . However, the flooding can generate other phenomena: humid ground or powerful currents that may cause mudslides, tree falls, cliff failures, cavity collapses, or erosion impacting building foundations or local infrastructure . . . The adoption of a systemic approach to risk in the context of observed and projected global changes is required to comprehend, as openly as possible, the conditions for the emergence of risk. In this type of approach, the hazard should no longer be considered in a restricted manner resulting only from hydro-meteorological phenomena, but rather as emerging from a combination of phenomena, potentially of various natures which develop across a range of timescales. The definition of « hazard » in the Hyōgo Framework for Action 2005–2015 (UNISDR, 2015) is therefore more appropriate:

« A potentially damaging physical event, phenomenon or human activity that may cause the loss of life or injury, property damage, social and economic disruption, or environmental degradation. Hazards can include latent conditions that may represent future threats and can have different origins: natural (geological, hydrometeorological and biological) or induced by human processes (environmental degradation and technological hazards) ».

To study the hazard implies first analyzing the different physical components, their possible combinations and the chain of events. In a global approach, Gill and Malamud (2014) present a broad overview of the interaction relationships between 21 natural hazards. The **Figure 8** represents a selection of 16 of them, drawn from six hazard groups: geophysical, hydrological, shallow Earth, atmospheric, biophysical, and space hazards. As a necessary complement, Liu et al. (2016) provide a systematic hazard interaction classification based on the geophysical environment that allows for the consideration of all possible interactions (independent, mutual exclusion, parallel and series) between different hazards, and for the calculation of the probability and magnitude of multiple interacting natural hazards occurring together.

Increasingly, multi-hazard risk assessments are undertaken at the coast (IPCC, 2019). For example, Kunte et al. (2014) characterised the vulnerability of coastal lands in India to erosion, submersion, and inundation, and demonstrated that the inclusion of socio-economic parameters should be considered in the overall assessment of vulnerability. Van Hattum et al. (2020) also stressed the importance of socio-economic parameters and noted that poverty in particular

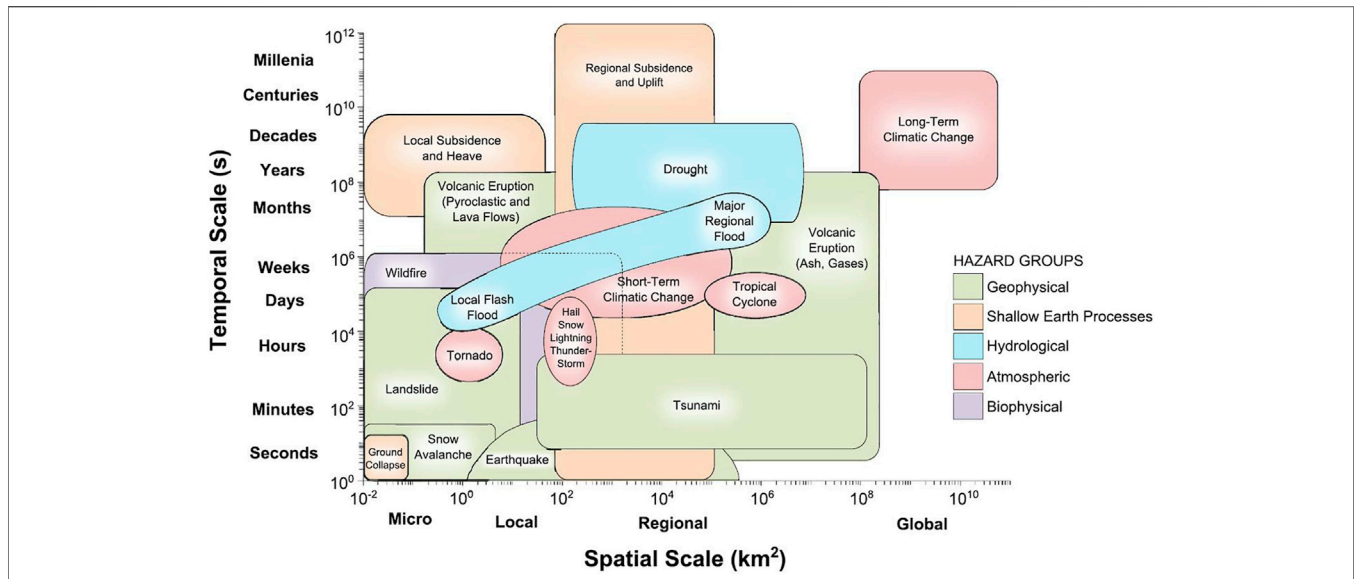


FIGURE 8 | Spatial and temporal scales of 16 selected natural hazards. Shown on logarithmic axes are the spatial and temporal scales over which the 16 natural hazards act (Gill and Malamud, 2014).

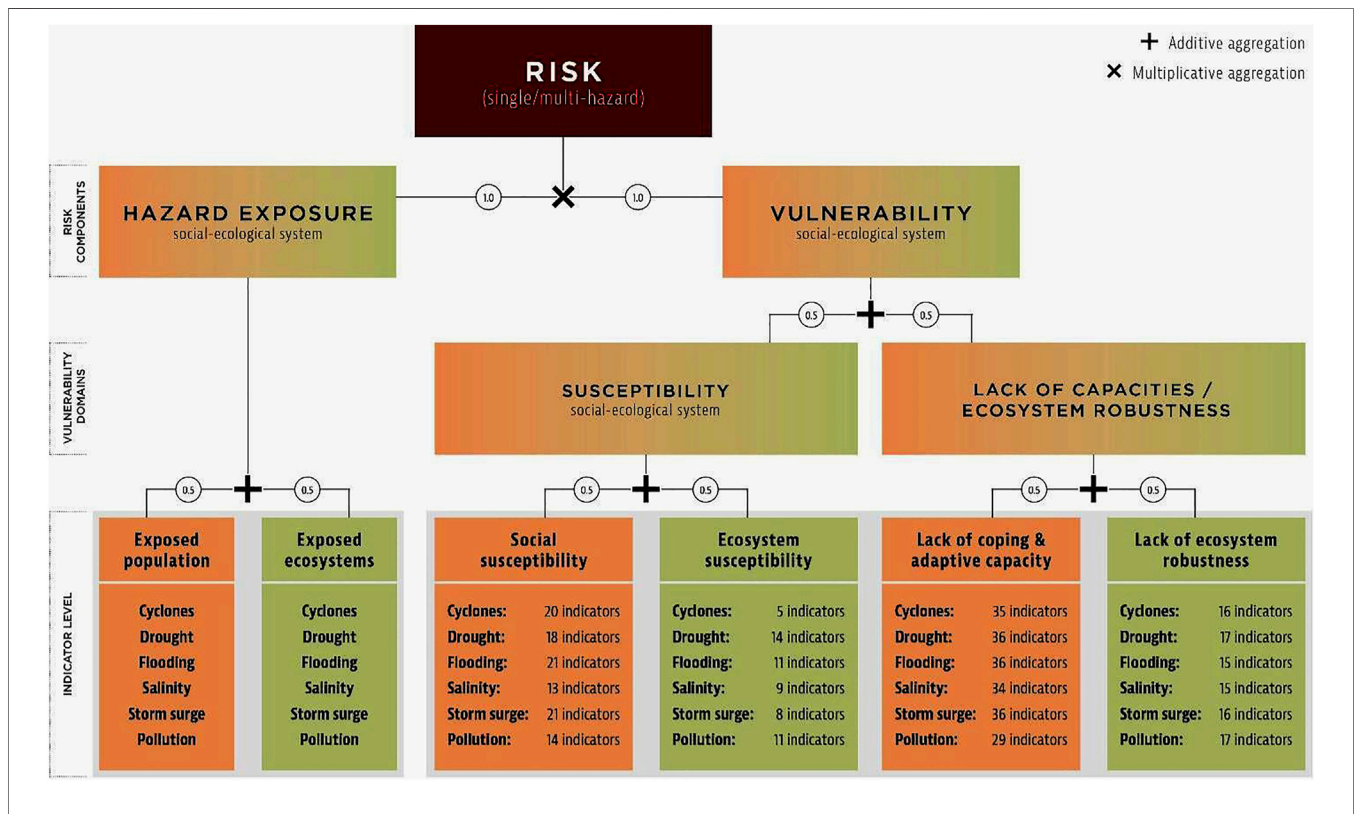


FIGURE 9 | The Global Risk Index: concept and structure. Credit: Hagenlocher et al. (2018).

magnifies the impact of floods as poor people are often highly exposed to floods, and are also more vulnerable and less resilient.

To comprehensively understand risk, Hagenlocher et al. (2018) have come to the conclusion that the definition of

adaptation strategies and measures (including ecosystem-based options) requires spatially explicit information on the exposure, vulnerabilities, and risks associated with different combinations of hazards in an integrative manner, not only focusing on societal

aspects or ecosystems alone, but also taking into account interactions with other systems, such as neighbouring territories. In particular, ecological dimension should be considered more systematically in risk assessments. Addressing this gap, the authors presented an innovative assessment concept and indicator-based methodology that is sensitive to the specific (multi-)hazard setting in a given territory (**Figure 9**). These modular sets of vulnerability indicators adapt flexibly to the hazard situation.

It should be noted, however, that this methodology is based on quantitative indicators and cannot report cascading effects and feedbacks. In addition, it ignores the hazards of biological origin, for example, the likelihood that floods degrade health conditions, in particular, by the deterioration of drinking water and sanitation systems. Analyses which widen the spectrum of investigations to include the emergence of risks should therefore be considered, but these analyses are conditional on their application in a smaller geographical area, allowing better consideration of local specificities. Thus, Cerema (2019) established, for the city of Semarang (Indonesia), a more open model of systemic functioning, with emphasis on the importance of domino effects and feedbacks.

Finally, it should be stressed that the multi-risk approach should not only apply at the level of the territories, but should also apply directly to protective structures since they are sensitive to a wide range of factors: meteorological, hydraulic, and morphological actions, as well as biological and anthropogenic actions. For example, the effects of prolonged periods of drought should be carefully considered, particularly in the context of climate change: levees are vulnerable to drought if the structure or its subsoil contains peat or highly organic clay in a zone/level below which the groundwater table may fall during drought. Dehydration of peat in levees causes shrinkage and a further loss of weight causes reduced stability. This may ultimately result in breaching due to horizontal sliding (CIRIA MEDDE USACE, 2013). An example of failure due to sliding occurred in Wilnis (**Supplementary Figure S1**), the Netherlands, in 2003. Bottema et al. (2020) described in detail the drought effects and drought management practices for Dutch and English levees.

3.1.2 Definition of Spatial-Temporal Analysis Frameworks

Whether one considers several phenomena in a risk analysis, or after preliminary investigations, one chooses to focus on one of them, it is always necessary:

- Spatially, to limit the territory in which the study is being carried out and within that territory, if necessary, carry out new spatial subdivisions (in particular if analytical approaches are to be considered);
- Temporally, to assess the risks in relation to changes in the situation at various times.

This framing can progress only by iteration with investigations about the context and the phenomena likely to contribute to the manifestation of risk.

Regarding the risk of urban flooding, considering that this hazard cannot be managed in isolation at the city scale, and responses to potential flood impacts are complicated by interlinked political, socio-economic, and environmental changes, Zevenbergen et al. (2008) suggested to develop a framework in which spatio-temporal relations are further defined and investigated, in order to « provide clarity regarding both the feedback loops that cause vulnerability, as well as those that build resilience, and how they interact across differing spatial scales ».

To achieve this objective, cities can be considered as an intermediate-level SES between a higher-level SES (in this example, the watershed) and lower-level SESs, (buildings, infrastructure, and networks). The **Figure 10** is a schematic depiction of the propagation of a flood wave through a territory in the case of a failure or overtopping of the protection system. In addition to its particular role in flood risk management, a coastal flood protection system could be considered in this scheme in the same category as buildings and other networks. A protection structure or a natural formation could therefore appear on the figure in place of a building.

For a « system of protection » SES, additional guidance is provided by research on:

- The assessment of levee performance and the development of geographic information systems for their maintenance (Serre et al., 2009; Michel, 2018);
- The development of a methodology for the analysis of the response of a protection system subject to a marine submersion event (Iggigabel, 2016; Iggigabel et al., 2022).

3.1.3 Complex Systems Observation

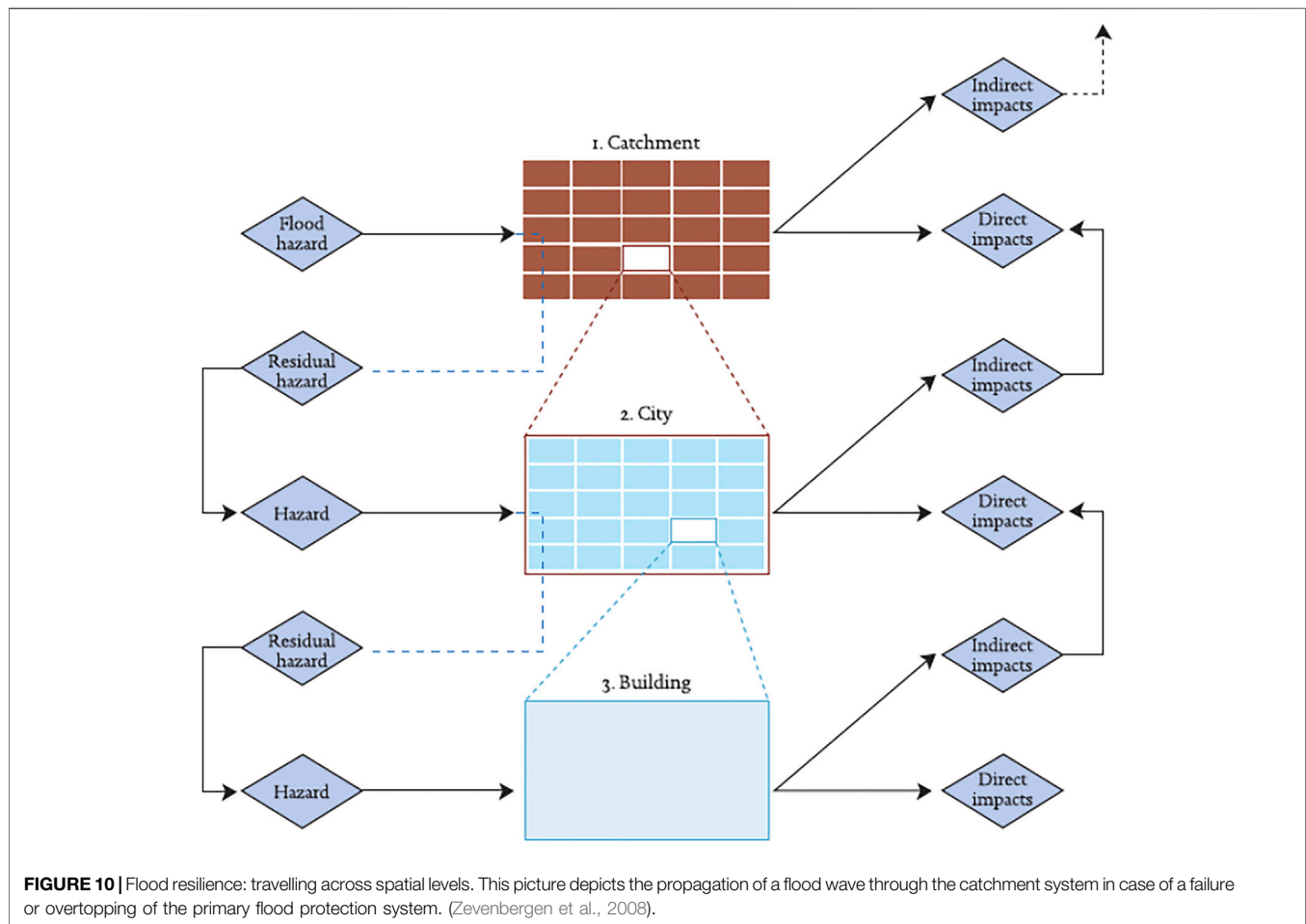
Understanding how phenomena interact with one another, and their significance for people and ecosystems, requires a holistic approach that looks at human and natural dynamics together. The concepts of resilience and SES contribute to provide this holistic view (Arctic Council, 2016).

The key starting point of this process is the integration of different kinds of knowledge and a variety of experiences in which scientists, the public, and decision-makers in policy and practice collaborate to generate not only scientifically reliable, but also context-appropriate, socially robust and actionable knowledge (Weichselgartner and Kaspersen, 2010), while always keeping in mind that knowledge integration is necessary but not sufficient: cooperation between actors must continue with resilience-building programmes (Weichselgartner and Kelman, 2014).

Increased interest in resilience management has driven the development of standardized tools for:

- Assessments that focus on deepening understanding of system dynamics; and
- Quantitative measures that aim to capture and quantify resilience in a rigorous and repeatable way. Resilience, however, as a property of CASs, is not easily measured.

Measuring and monitoring a narrow set of indicators or reducing resilience to a single unit of measurement may block



the deeper understanding of system dynamics needed to apply resilience thinking and inform management actions (Quinlan et al., 2016). This observation only reflects the aforementioned problem: analytical approaches may prove inappropriate to apprehend complex dynamic systems. Observation of these systems should necessarily involve systemic approaches. To manage the systemic approach of a theme (« risks to a coastal area » is a possible theme, for example) or a territory, an observatory may be a pertinent tool for providing information, but also for disseminating this information. An observatory can be defined as an observation system set up by one or more organisations to monitor the evolution of a phenomenon, an area or a portion of a territory in time and space; most observatories take the form of computer applications in which data are aggregated and presented in the form of tables, maps, or statistical indicators. The objectives, the users, and the temporalities considered by the observatory should be precisely defined (Bourlier et al., 2020).

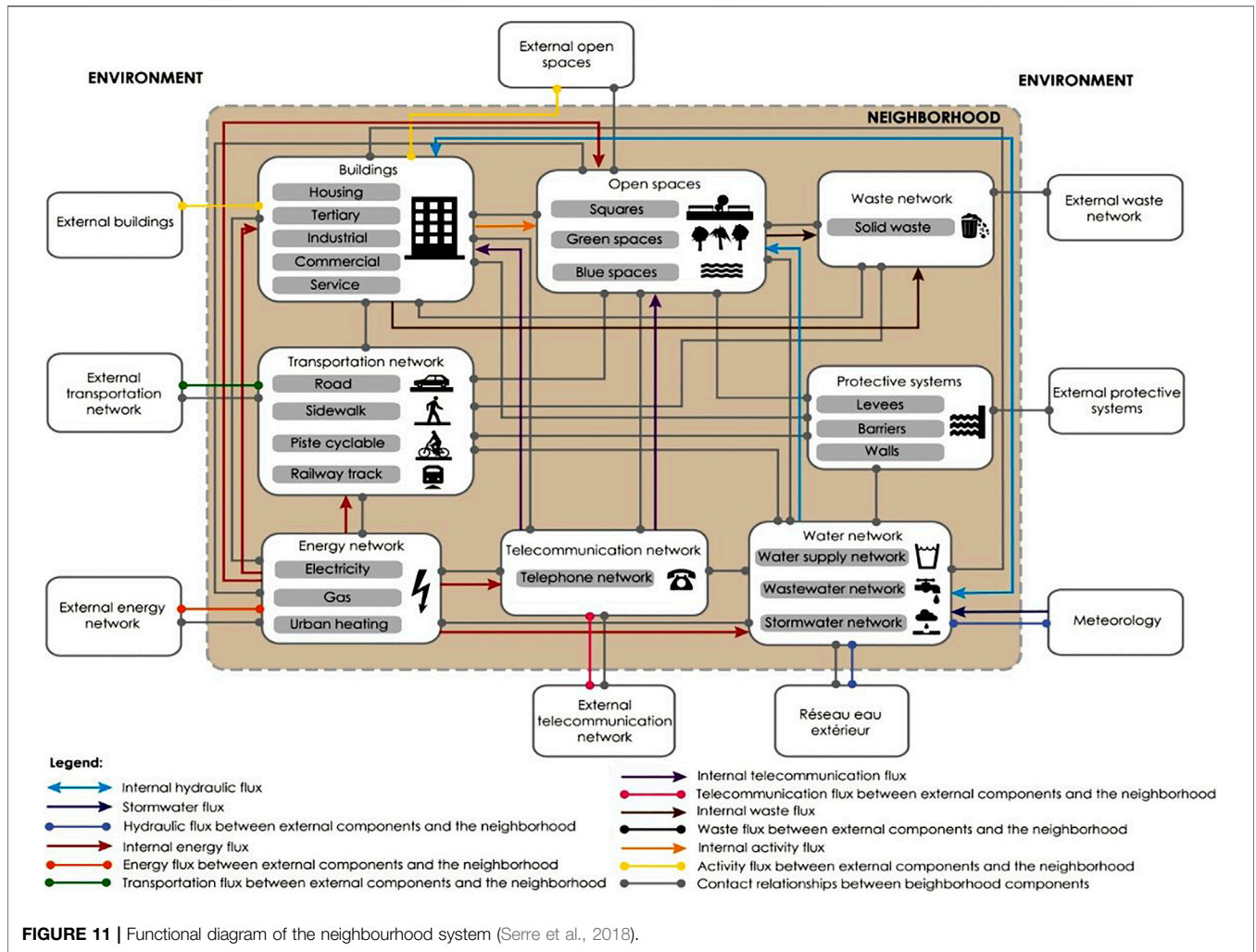
3.1.4 Risk Assessment at the Level of a Territory

Risk assessment methods at the level of a territory focus on urban environments, where flood protection stakes are most prevalent. The scale of the urban district is especially important because it is

at this scale that cities carry out their adaptation, transformation and/or development operations (Serre et al., 2018). These approaches are selected for their overall operational character, as well as for the links established with flood protection systems. However, there are other models or approaches (Barroca et al., 2013; The Rockefeller Foundation, 2015) aimed at the analysis or assessment of urban resilience from a more general point of view.

The methods used to study an urban system consist of a double characterisation of its structural and functional aspects. The structural aspect corresponds to the spatial organisation of the system whereas through functional analysis, it is essential to characterise the temporal phenomena, such as flows, exchanges, and feedback. The understanding of risk at the scale of a territory can therefore be engaged by successively defining the limits of the system, its environment, its components, and finally by associating functions (Serre et al., 2018). In an urban system, this method shows the interdependence of the networks and critical infrastructures of the studied area, and hence, the domino effects and impact chains (Bourlier et al., 2020).

The **Figure 11** shows the application of a functional analysis at the neighbourhood level. It indicates contact and normal operational flow relationships between a



neighbourhood’s individual components and its external environment factors.

The predominance of the systems approach is marked by the focus of the study, which is mainly on the relationships between the elements, and avoids analysing the resilience of a territory through a sectoral approach based on specializations (e.g., flood protection, energy and transport). It should be noted that analytical approaches can be efficient only if the limitations of the system—determining what is internal and what is external—have been well delineated and the internal organisation of the system has been well described. Risk analysis can be continued by studying failure mechanisms for each function (Balsells et al., 2012). In applying these methods, the relations within the territory in question (the neighbourhood) and with the external environment of that territory should be well identified, particularly in regards to the structures performing a protection function. The interdependence plays the role of a risk diffusion factor. And as Lhomme et al. (2013) stated, networks then act as vectors of risk propagation. These analysis principles have

been implemented by several authors, for example, by studying the effects of Hurricane Katrina (Heinzl et al., 2019) and New Orleans’ recovery (Balsells et al., 2012) after this event.

Although for Serre et al. (2018), a neighbourhood is considered a social, economic, and physical/technical system, the above-mentioned authors generally placed more emphasis on the physical/technical dimension. In addition, other authors address:

- The human aspect of the management of the urban system. For example, Zevenbergen et al. (2015) presented a pragmatic screening procedure, referred to as a « Quick Scan methodology ». Its purpose is « to provide guidance for network operators and decision makers on identifying and rating those critical infrastructure networks and hot spot buildings that may be at risk from flooding, and assessing where intervention will be most feasible and cost beneficial—the so-called quick wins »;



FIGURE 12 | Brushwood dams in the Dutch Wadden Sea, which create artificial shelter for salt marsh vegetation from waves and currents. The levee is visible in the background (Photo: V. Vuik).

- Social and urban aspects in addition to technical aspects. For example, Heinzlef et al. (2019) defined a resilient hierarchical index (Tate, 2012) constructed on the basis of three indicators of urban, social, and technical resilience. Within this framework, urban resilience is defined by the proactive capacities that the urban system must develop in order to (re)act in the face of the disaster, thereby developing learning and anticipation skills.
- Estimating flows across embankments exposed to swell under either emerged (e.g., Suzuki et al., 2017) or submerged (e.g., Formentin and Zanuttigh, 2018) conditions. Note that in the latter case, the calculation of the flow through a breach can also be considered.

3.1.5 Risk Assessment at the Level of a Protection System

The multiple natural and anthropogenic actions to which the levees are exposed, as well as the heterogeneity of the structures and their very long length, requires the consideration of significant margins of uncertainty of the structure's behaviour. The protection provided by levee systems is therefore always limited, and must be considered as such: when natural phenomena exceed a certain intensity, the structures allow water to pass through, either by overflowing or wave overtopping, or through a breach in the event of an accidental rupture. In either case, the risk may increase, in particular by an acceleration of hydraulic phenomena. Since the positive effect of reducing flood frequency is more immediately apparent than its potential negative effects, levee systems often produce a false sense of security (CIRIA MEDDE USACE, 2013).

This has led to an extensive literature on:

- Modelling and assessing the risk of levee failure (e.g., Stanczak and Oumeraci, 2012; Wu and Li, 2017; Zhang et al., 2017). The effect of transitions, whether in the geometric design of the structure or in materials used, should not be overlooked in assessments as shown for example by van Bergeijk et al. (2019) and Simm et al. (2019);

Chapter 8 of the International Levee Handbook (CIRIA MEDDE USACE, 2013) reviews good engineering practices for structural dimensioning by combining hydraulic and geotechnical approaches. It can also be used to analyse the risk of failure.

Nevertheless, the problem of performance limits and the increase in risk in the case of an event exceeding the nominal operating conditions should be tackled within a broader framework than that of a single structure with only the protection function. On this topic, Marijnissen et al. (2021) assessed the safety of a double-levee system (**Supplementary Figure S2**).

In the more general case of a system with a front and a rear defense (e.g., a storm surge barrier and levees), the front defense can improve the reliability of the rear defense by reducing the load on this rear defense (Dupuits et al., 2017). Other studies also show the effectiveness of hybrid solutions combining land-based structure (for example a dike) with the effect of a natural formation such as coastal wetlands and mangroves (Vuik et al., 2018; Vuik et al., 2019). Similarly, the construction of brushwood dams is often a relevant solution: at exposed coasts, strong waves and currents may impede the settling of fine sediments and the establishment of salt marsh vegetation or mangroves (Winterwerp et al., 2013). Construction of a system with brushwood dams (**Figure 12**) creates shelter, facilitates sedimentation, and prevents erosion. Combining these dams with drainage ditches improves consolidation of the settled sediment. This method has successfully been applied for

centuries, and has led to artificial salt marshes along 450 km of the Dutch, German, and Danish Wadden Sea coastline (Bakker et al., 2002; Hofstede, 2003).

Risk assessment approaches for protection systems are hybrid in nature. The diversity of natural structures and formations, as well as the diversity of the environments in which these components are placed, require the adoption of systemic approaches. However, the objectives of performance and rationalization of the resources employed, also force the adoption of analytical approaches. In particular, this is done in order to evaluate their reaction to various demands, or to determine quantitatively the human, financial, and material requirements for the management and adaptation of the protection system. Framing analytical approaches through systemic approaches is an ongoing challenge for managers of protection systems.

The structure performance assessment is crucial since this process provides input for the evaluation of the residual risk in a leveed area. In addition, the results of the evaluation of the structures will determine, along with the results of the risk attribution at the scale of the system, the priorities for action: if the risk attributed to a structure is high, then the requirements on its structural state will also be high, which will give it a better ranking in the intervention priorities of the levee manager. The main difficulty therefore lies in evaluating the performance of each component of the system. To meet this challenge, the concept of the fragility curve was explored. In the context of flood risk assessment, a fragility curve represents the probability of breach of the defence given a set of loading conditions and therefore represents (along with the probability of overflowing and wave overtopping) part of the likelihood of water flowing from source to receptor in the SPRC model. This analytical approach can be either deterministic or probabilistic, as shown in the **Supplementary Figure S3**. In the deterministic design, the assumption is made that the probability of failure is zero until the design load event is reached, at which point the probability switches to 1. In reality, as the load rises above the design condition, the probability of failure rises and only after considerable extra load has been applied does it actually approach 1. Similarly, there is a small but significant probability of failure at conditions below the design loading. This is what probabilistic approaches represent (Simm et al., 2008).

While these modes of representation are interesting for understanding the complexity of levee behaviour, the associated methods are difficult to apply due to the geotechnical heterogeneity, uncertainties about hydraulic loads, —even more so on coastlines exposed to waves—, and the multiple failure modes. In fact, since levees commonly extend over several tens or even hundreds of kilometres, their management can benefit from computer assistance in terms of data organisation, management, and representation (spatial representation and evolution over time), but will always require expertise for their diagnosis. For example, the system designed by Serre et al. (2009) has two components:

- A geographic information system (GIS) application that allows collecting data necessary for managing a levee portfolio;
- A Spatial Decision Support System (SDSS) which uses performance indicators to assist levee managers in prioritizing maintenance activities.

This type of operating mode led Hathout et al. (2019) to question the validity of human judgment. These authors presented approaches of elicitation, calibration and aggregation of expert opinions to evaluate the reliability of river levees. Applying the proposed weighting and aggregation procedure reduces variability in the probability of failure estimate and provides a better probabilistic distribution of aggregated expert opinion than that of individual expert opinions. The results allowed for the identification of a trend of aggregated expert opinions indicating over or lack of confidence.

This review of the state-of-the-art shows that it is dangerous to seek « automation » of risk assessment at the level of a structure and, *a fortiori*, at the level of a protection system. The methods of evaluation which combine human expertise and the advantages of data management by computer means should indeed be sought. Since each structure is unique, monitoring its behaviour over time is essential, especially during major events through feedback. However, it should be considered in the application of this principle that in a future affected by multiple changes, decisions based solely on past events will no longer necessarily be relevant and that more anticipation will be required in the application of risk analysis methods and also in the definition of adaptation strategies.

3.2 Methods for Defining Adaptation Strategy and Changing System Governance

As a follow-up to the study of methods for understanding risk, this section deals with methods for defining adaptation strategies for territories and their protection systems. Since changes in governance patterns are generally necessary for the effective implementation of adaptation strategies, this issue will also be addressed.

Drafting an adaptation policy requires thorough insight into the precise type and magnitude of future problems, the possibilities to counteract or reduce these in terms of strategic alternatives composed of physical measures and policy instruments. These strategic alternatives must be evaluated on performance, cost and side effects and opportunity criteria (Klijn et al., 2015). As such, scenario planning and the recent concept of Climate Resilient Development Pathways (CRDP) deserve to be highlighted, because they represent methods of governance and management of SESs essential to operationalize the concepts of adaptability and transformability. This section is devoted to the study of these methods and their governance implications.

3.2.1 Scenario Planning and Pathways for Building Resilience to Climate Change

The definition of strategies for the adaptation and *a fortiori* the transformation of SESs can be based on the establishment of

scenarios. Scenario planning is a systemic method for thinking creatively about possible complex and uncertain futures. The central idea of scenario planning is to consider a variety of possible futures that include many of the important uncertainties in the system rather than to focus on the accurate prediction of a single outcome (Peterson et al., 2003). Scenarios can help overcome fundamental problems about transformation by organising thinking in a coherent way. With so many changes happening simultaneously, the very complexity of the situation can become a barrier to understanding and action. The scenarios can organise information about transformation in a comprehensible way that facilitates discussion and action (Walker et al., 2004).

The definition of adaptation strategies largely depends on the dynamic nature of the SESs, which requires considering several time horizons and assessing uncertainties. The study of several scenarios helps to achieve these two objectives. To this end, it is possible to use general data, although transposition across territories is often difficult:

- For climate change scenarios, the use of climate model projections (Moss, 2008; Moss et al., 2010; van Vuuren et al., 2011) is recommended. However, the further down the chain of effects, the larger the uncertainties about the degree of an effect (Haasnoot, 2013), and sometimes even about the direction. Moreover, when climate changes beyond the range historically observed, unforeseen shifts may occur which complicate the downscaling of global climate scenarios to the national or regional level (Klijn et al., 2015);
- For socio-economic development scenarios (O'Neill et al., 2017), Klijn et al. (2015) stated that the autonomous developments in the socio-economic subsystem are even more uncertain than climate change scenarios because of the global scale of economic developments and their dependency on very dynamic geo-political changes. Nevertheless, for demographic, economic, and land-use developments, a scenario approach may be applied.

The use of scenarios may also involve analytical techniques, including:

- The policy tipping points (Kwadijk et al., 2010). A tipping point is reached if the magnitude of change is such that the current management strategy can no longer meet its objectives. Beyond the tipping point, an alternative adaptive strategy is needed. By applying this approach, the following basic questions of decision makers are answered: what are the first issues that we will face as a result of climate change and when can we expect this. In the west of the Netherlands, the results show, for instance, that climate change and the RSL rise are more likely to cause a threat to the fresh water supply than flooding; and
- The adaptation pathways (Haasnoot et al., 2013). This method relates to an analytical approach for exploring and sequencing a set of possible actions based on alternative external developments over time. The authors

tested this concept by producing an adaptive plan for long-term water management of the Rhine Delta in the Netherlands that considers the deep uncertainties about the future arising from social, political, technological, economic, and climate changes. The **Supplementary Figure S4** provides a representation of this approach.

Addressing the major challenge of climate change adaptation and in order to take into account the Sustainable Development and Poverty Eradication Goals, it is also possible to use the concept of Climate-resilient development pathway (CRDP), represented by the **Supplementary Figure S5** (Kainuma, 2018; Roy et al., 2018).

CRDPs are increasingly being explored as an approach for combining scientific assessments, stakeholder participation, and forward-looking development planning, acknowledging that pursuing CRDP is not only a technical challenge of risk management but also a social and political process (Roy et al., 2018). This implies an organisation of the process by the institutions in charge of the governance of the territories. CRDPs aim to establish narratives of hope and opportunity that can extend beyond risk reduction and coping—in particular integrating the fight against climate change (Amundsen, 2018)—and are critical in driving motivation, creative thinking and behavioural changes in response to climate change (Myers et al., 2012; Prescott and Logan, 2018). The definition of the scenarios should be based on general strategies for enhancing social-ecological resilience. These principles, on which CRDPs are based, were the subject of an integrative presentation by Bigg et al. (2012) on the basis of a review of the scientific literature (**Supplementary Figure S6**).

According to Bigg et al. (2012), the principles of resilience management fall into two levels:

- Principles that relate to generic SES properties to be managed; and
- Principles that relate to key attributes of SESs governance.

The implications for coastal flood protection systems of these principles are presented below. Issues related to the adaptation of governance are presented in this section. Issues related to adaptation strategies will be addressed in the next section.

3.2.2 Adaptation of Governance

A territory subject to coastal flooding should be considered a CAS and the issue of protection against this risk can, as such, be dealt with in conjunction with other issues including freshwater management. In the context of adaptation to the effects of climate change, this is particularly relevant when one of the main threats to coastal territories is the salinisation of freshwater bodies and soils. « Understanding an SES as a CAS » involves a paradigm shift. This paradigm shift in particular implies a change in the mode of governance. The **Supplementary Figure S7** shows how the evolution of mental perceptions and representations on this subject of fresh water, through the transition from an analytical to a systemic way of thinking, may result in a change in governance and improved flood resilience. The

standard perception of freshwater management leads to inflexible, and often ineffective, command-and-control approaches, whereas accounting for ecological complexity opens avenues to adaptability, which builds better resilience to events such as flooding (Moberg and Galaz, 2005). One such pathway may be to assess the role of wetlands in flood mitigation and to anticipate across several scales (including those of the region and of the territory) increases in capacity that may be required in response to climate change (e.g., changes in precipitation patterns and changes in thermal regulation by glaciers) and land-use changes (e.g., increases in runoff caused by deforestation and urbanization).

The framework established by Bigg et al. (2012) calls for governance that intends to bridge two approaches:

- Adaptive management, which focuses on “learning by doing” as a strategy to deal with uncertainty in CASS; and
- Co-management, which builds on the idea of participatory resource management and community–government linkages.

These two approaches are often grouped under the same term « adaptive co-management » since the research of Ruitenbeek and Cartier (2001). Adaptive co-management combines « the iterative learning dimension of adaptive management and the linkage dimension of collaborative management in which rights and responsibilities are jointly shared » (Armitage et al., 2007).

The participatory nature of adaptive co-management enables sharing and reflecting on experiences, ideas, and values with others, which builds trust and relationships and facilitates social learning as well as collective action (Olsson et al., 2004). Participatory learning processes can help actors learn about each other’s mental models, which builds social capital, in turn supporting institutional change and conflict resolution (Biggs et al., 2011).

On « coastal territory » SESs, the utilisation of an expanded circle of actors can be sought in different ways, for example:

- In the definition of town planning rules, a consultation phase may involve all stakeholders in the decision-making process. Perherin (2017) described in detail how the debate between the actors can be organised around the production of hazard maps carried out as part of the elaboration of coastal risk prevention plans;
- Citizen participation in data collection and analysis can reduce the vulnerability of urban areas to rainfall flooding, as shown by the European FloodCitiSense research programme (McCroory and Veeckman, 2017), which had study sites at Birmingham, Brussels, and Rotterdam;
- In urban flood management strategies, the use of flood risk as a design parameter for spatial planning increases flood risk awareness and improves the development of practical strategies to cope with and communicate the residual risk (Zevenbergen et al., 2008). Following this principle, an applied scientific research project was executed by a learning network nested across multiple scale levels, from the national level to the local planning

and street/building level in the city of Dordrecht (Netherlands).

The evolution of modes of governance is a necessary condition for change when a profound transformation is envisaged. This is supported by three studies realised in China (Jiang et al., 2018), in Australia (Hurlimann et al., 2014) and in Italia (Vitale et al., 2020). In the three cases, it appears that the change in governance should also be accompanied by institutional changes, and administrative reorganisation. The governance implications of the adaptive co-management principles should therefore be well understood methodologically. Olsson et al. (2004) showed that the self-organising process of adaptive co-management development, facilitated by rules and incentives of higher levels, has the potential to expand desirable stability domains of a region and make SESs more resistant to change. The European Flood Risk Directive (Directive 2007/60/EC) is in line with this principle by encouraging the participation of local stakeholders in the development of flood risk management plans. Its application has indeed led to an institutional and administrative restructuring of governance, by developing more integrated visions of land use planning by combining the issues of risk prevention and management of aquatic environments. The refocusing of institutions on the geographical perimeters of emerging risk (e.g., river basins) is another notable advance (Cerema, 2020).

While a review of the modes of governance can be initiated by a top-down process as is the case for the implementation of the European directive, which can lead to real progress, this observation should not, however, obscure the fact that all regions of the world do not benefit from a national or supra-national organisation that encourages changes in the modes of governance. To initiate a change in governance, Termeer et al. (2017) proposed a methodological framework to clarify how governance can be improved through bottom-up initiatives and how this change can be initiated. In complement, Cundill and Fabricius (2010) identified system attributes and key variables that could form the basis for monitoring the governance dimension of adaptive co-management.

3.3 Adaptation Methods (Simplified Approach Based on RSL Rise)

The increase in RSL triggers multiple adverse effects (Supplementary Figure S8) and often appears, rightly or wrongly, as the most important factor in the appearance of risk. Moreover, the monitoring of a single parameter has a practical advantage for the establishment and implementation of a strategy. For these two reasons, the adaptation options in response to this factor alone have a high visibility in the scientific literature.

The various types of response are addressed below, both technically and economically.

3.3.1 Different Types of Responses

Building on previous research (Wong, 2014), the IPCC report (2019) describes, in addition to the option of no response, five

main modes of adaptation to mean and extreme sea level rise: advance, protect, retreat, accommodate, and ecosystem-based adaptation. These options are shown in the **Supplementary Figure S9**.

The IPCC report (2019) in Chapter 4 provides a comprehensive analysis for each of these options based on six criteria: observed responses, projected responses, cost of responses, effectiveness of responses, co-benefits and drawbacks of responses, governance challenges (or barriers), and economic efficiency.

Nevertheless, the typology of adaptation options with reference to sea level rise is based on strong implicit assumptions that are not justified in many cases. Thus, the options described are only applicable if the following assumptions are, either completely or partially, verified:

- The coastal strip must have a significant slope, and therefore the possibility of reducing the exposure of the stakes by providing a zone for retreat at a short distance from the coast. The reality of territories is often quite different: the deltas are very flat areas (Syvitski and Saito, 2007) and many small islands do not have an area allowing for retreat;
- The territory must have a topography maintained at an altimeter level sufficiently high over time. In many territories (such as deltas, small islands, and arctic territories), the observed phenomena and long-term projections indicate that this topography is likely to vary under the effects of subsidence or erosion of coastal features;
- The territory must have sufficient environmental stability. Most territories experience major disturbances in their natural environment [e.g., acidification, rising ocean temperatures (Gattuso et al., 2018), and the degradation of wetlands] and the built environment (particularly as a result of population growth). The simplified approaches consider the issues separately and propose adaptation solutions for each of them. However, these issues belong to a territory, i.e., an SES that should be considered as a CAS, and solutions should be defined at the level of the system in order to take into account the interrelationships between its components.

The main interest of the approach focused on RSL rise is to provide spatio-temporal benchmarks in the definition of protection strategies. This parameter is also used in global studies to identify, under several scenarios, the exposed territories, the associated demographics, and economic issues in order to determine the benefits that could be expected from effective protection. Nevertheless, the results of these studies appear to be fragile when it comes to assessing the real possibilities for adaptation of territories and their protection systems. This fragility naturally increases over longer-term projections (Hallegatte et al., 2013; Tiggeloven et al., 2020).

3.3.2 Economic Evaluation of the Different Types of Responses

As for the technical aspects, it is important to avoid approaching coastal flood protection from an economic perspective with overly simplified approaches. As coastal flood protection systems consist of a set of structures such as levees (sometimes layered in several rows), breakwaters, seawalls, which are possibly supplemented by storm barriers and natural features, the economic assessment should be based on:

- The length of the structures and not the length of the coastline. Where possible, consideration should also be given to the height of the structures as proposed by Lenk et al. (2017) on coastal dikes;
- The search for protection structure combinations, with the aim of optimising costs. In particular, coupling natural features with artificial structures, which in turn strengthen the natural features, is a good way to limit long-term spending. Ideally the economic study should cover an even wider spectrum, encompassing the natural environment, the protection system, and the built environment. This was proposed by Aerts (2018).

The studies of Lenk et al. (2017) and Aerts (2018) provided interesting theoretical contributions to cost assessment. However, the results obtained remain fragmented, and the uncertainties on unit costs are far too high for a construction manager to utilise for cost estimates for a particular project (a rapid estimate on the basis of the unit costs appearing in the current public work contracts would be more accurate). The main reason is that the initial data used for these studies comes from bibliographic reviews, with data of multiple international origins. In reality, estimates can only be made on the basis of costs observed currently in the given context (which therefore presupposes the availability of recent national or regional studies), because the availability of resources and the general economic context are decisive.

The international state-of-the-art on this issue should therefore progress, not by seeking cost estimates, but by supplementing and refining the methodology for observing costs on a territory.

3.3.3 Conclusion on Simplified Approaches

In conclusion, decisions on a territory cannot be made by considering the various issues separately and by seeking solutions of only modifying the coastline, as might be suggested by the simplified schemes presenting adaptation options. On the contrary, the issues should be considered globally and should take into account the physical, human, and biological dynamics of the territory envisaged in its three spatial dimensions. The use of methods that make it possible to understand these developments is therefore necessary to give meaning to adaptation decision-making. Ultimately, if simplified approaches are not devoid of interest, they are analytical approaches that should be supplemented with a comprehensive systemic approach.

3.4 Adaptation Methods (Comprehensive Approach)

To avoid maladaptation risks, adaptation strategies should be integrated into a comprehensive scheme, as represented on the **Supplementary Figure S10**. This scheme comprises:

- Mitigation, which refers to human actions to limit climate change by reducing emissions and enhancing the sinks of greenhouse gases;
- Adaptation, which refers to processes of adjustment by natural or human systems to actual or expected climate and its effects, intended to moderate harm or exploit beneficial opportunities.

Synergies can be developed between climate action, risk prevention, and sustainability (Hackmann et al., 2014). It is therefore important to identify these synergies when they relate to coastal flood protection systems.

In general, the principles of traditional development using civil engineering for the construction of levees and drainage systems lead inevitably to a degradation of the ESs of protection, and therefore to an increase in risk following processes that correspond to:

- Increased dependence on technologies such as levees (Wong, 2014; Welch et al., 2017), pumping and drainage systems (Bloetscher et al., 2011; Aerts, 2018), and storm barriers in estuaries (Burdick and Roman, 2012). In the future, it will be necessary to develop ecosystem-based solutions, including in urban context where the term for these solutions is « green infrastructure » (Culwick and Bobbins, 2016);
- Unsustainable resource management. Fresh water, sand, armourstone, and wood are multiple-use resources. Clarification is needed on the status of these resources (Renaud et al., 2013; Day, 2016; Brakenridge et al., 2017) and the uses (Peduzzi, 2014; Torres et al., 2017) to which they should be allocated. It would seem more relevant in the context of climate change and RSL rise to direct these resources preferentially towards the protection of threatened territories than towards the construction of new buildings on exposed sectors.

Ultimately, as the protection system is nested in the territory, proactive actions are required at the level of the community. These actions fall into three categories:

- The preservation or restoration of ecosystems that play a protective role and their support in the face of the effects of climate change. However, in the long term, such adaptation does assume that the climate can be stabilised. Under changing climatic conditions, there are limits to the effectiveness of ecosystem-based adaptation, and these limits are currently difficult to determine (IPCC, 2019);
- The reduction of hazard exposure by controlling urbanization: water management primarily involves the management of space and in particular, the liberation of

low-lying areas where water could be oriented without negative consequences (Angel et al., 2005; Zevenbergen et al., 2008);

- The reduction of the vulnerability of infrastructure (Zhu et al., 2010; Mikami et al., 2015; Hatzikyriakou and Lin, 2018; Duy et al., 2019; Singh et al., 2021), buildings (Zhu et al., 2010; Scussolini et al., 2017), and other assets: on this point, it is more of a question of coordinating actions over time.

The search for nature-based solutions should also be encouraged in flood protection (Culwick and Bobbins, 2016; Alves et al., 2020; United States Environmental Protection Agency US EPA, 2020). The other ESs to which these solutions are likely to contribute to (in particular water purification, climate regulation, and reduction of air pollution) can thus be integrated into the review (Gersonius, 2016; van der Nat et al., 2016; McPhillips et al., 2020).

Other accommodation measures exist, including protection structures. Nevertheless, these measures should be considered as temporary measures, given the increase in hazard: economic challenges to hard protection increase with higher sea levels and will make adaptation unaffordable before technical limits are reached (IPCC, 2019). Therefore, investing in levee systems not knowing the extent to which such systems can protect against future events is only acceptable if it does not impede upon the implementation of other actions contributing to risk protection with more long-term assurance. In this sense, short-term benefits should be sought, only if the cost of the transitional measures is low enough, so that it does not penalize investment in longer-term strategies.

Adaptation strategies can be defined at the level of a country, city and neighbourhood, as shown by the following examples:

- In the Netherlands, on the deltas of the Rhine, the Meuse and the Scheldt, an integrated strategy for multiple issues (including flood protection, water resource management, and sanitation), defined at the national level, is implemented locally (Klijn et al., 2015; Bloemen et al., 2018);
- In Dublin, Ireland, the development of the city's resilience to floods is undertaken on the basis of a diagnosis considering the interrelationships of technical networks and the impact of their malfunctions on vital services (Lhomme et al., 2021);
- In a neighbourhood in Beira, Mozambique, an action programme integrates civil engineering operations, nature-based solutions, and warning and evacuation measures (Van Berchum et al., 2020).

Where the increase in risk is significant, restructuring and urban transformation operations may be necessary. In this case, it is not a question of adapting the existing system, but of rebuilding a new system. As the strategies can be very different in rural and urban contexts, it is necessary to give at least two examples:

- New Orleans, U.S.A. This example shows the significant transformation challenge for coastal megacities facing subsidence, disturbance of sedimentary fluxes, and the effects of climate change (Constanza et al., 2006; Fischetti, 2015);
- The Mekong Delta, Vietnam. This territory represents an example of transformation in the rural context which is characterised by an evolution of economic activities. The smaller spatial constraints in the rural environment allow significant processing capacities (Ha et al., 2012; Renaud et al., 2015; Kruse et al., 2020).

Unfortunately, in practice, the process of transformation is generally undertaken under the constraint of difficulties which may arise on a daily basis (for example, due to a large subsidence or the rise of the RSL leading to a marine transgression), or during a major meteo-oceanic event. In response to the latter case, the Build Back Better initiative (Clinton, 2006) has been promoted in post-disaster recovery to encourage communities and stakeholders to rebuild beyond the pre-disaster state for safer, more sustainable and resilient communities.

4 DISCUSSION

The literature review leads to general conclusions on the concept of a coastal flood protection system as well as specific conclusions on approaches to risk understanding and adaptation strategies. In each case, certain shortcomings have appeared in the state-of-the-art, which makes it possible to identify new avenues of research.

4.1 Conclusions on the Protection System Concept

The bibliographical analysis was carried out by considering a system of protection against coastal flooding as a socio-ecological system, a complex adaptive system, integrating components of the natural environment, of the built environment, and the social and institutional environment. If this hypothesis has made it possible to define the scope of the analysis and to define its structure, it is clear that the methods identified address the various aspects (ecological, technical, social and economic) of the various components of the environment (natural, constructed, social and institutional), but without attaching them to this central concept of socio-ecological system. In order to seek unity and coherence, the concept of a system of protection as an SES should therefore be described precisely, and in this way the relations between these systems and the territories in which they are situated should be formally deciphered.

As a follow-up to this conceptual work, methods for defining and characterizing existing protection systems should be further developed. Work has already been completed as part of marine submersion experience feedbacks (Iggigabel, 2016; Iggigabel et al., 2022). This work should be continued to consider multiple hazards, including several types of events. These methodologies should in particular specify the links between the protection structures and the other structural elements of

the territory (both the stakes to be protected and the infrastructure or natural), while offering operational tools for the development of supply chains for strategic material resources [e.g., sand and armourstone (Le Turdu et al., 2016)].

In a more general way, the methodologies, together with governance and expertise, should foster the integration of strategies for adapting protection systems into land use planning, resource management, and environmental conservation policies. Improving the overall efficiency and effectiveness of the system could be achieved through the coordinated development of information management systems, methodologies, and operational tools.

In relation to these general objectives, two types of approaches should be the subject of new methodological developments: ecosystem approaches and socio-economic approaches.

4.2 Development of Ecosystem Approaches

Ecosystem-based analysis should be conducted on SESs consistent with the multiple themes that an adaptation project must address:

- The watershed is a territory relevant for the consideration of global and local changes, especially when they affect the management of water, sediments, and other materials that may be utilised for protection against coastal flooding (for example, armourstone, and wood);
- The territory in which the protection system is established makes it possible to consider the changes in the natural environment and the built environment and to plan for adaptations of the protection systems in a coordinated manner with these changes.

Concerning the coastal flood protection ES, it should be noted that the rate of soil sealing, the RSL, sedimentary transit, and other processes influencing erosion phenomena (sea states, including wave climate and marine currents) are slow variables whose monitoring is necessary to understand the system evolution and the associated risks. Thus, one important response for preparing for RSL rise is to improve observational systems (including tide gauges, wave buoys, and remote sensing techniques), because in many places around the world, current frequencies and intensities of ESL events are not well understood due to a lack of observational data (IPCC, 2019).

4.3 Development of Socio-Economic Approaches

The bibliographic review shows that:

- In urban contexts, adaptation strategies will certainly have greater financial resources, but they will also be subject to greater constraints, the rigidity imposed by the urban fabric, and the conflicts of interest which can arise in response to a change in the levels of protection or the appropriation of the areas necessary for the adaptation of the system. Stable institutions with strong prerogatives will be necessary to carry out these projects with

sufficient anticipation and involvement of the community according to the principles of adaptive co-management. Given the scale of the challenge, additional methodological developments should certainly be sought on this subject;

- Relevant forms of adaptation can only be achieved through adequate knowledge of the system in place including all of its anthropogenic and natural components. The comparison of several options for adaptation at various time horizons can be carried out by economic evaluations. However, the cost of adapting and maintaining the structures can only be estimated in the regional economic context. Therefore, it is more important to look for methodological frameworks that can be applied in different contexts on the basis of local cost observation, than to seek unit costs at the international level, which cannot be applied universally (Iggabel and Yates, 2018).

5 CONCLUSION

The emergence of the concept of resilience, by opening up a range of additional modes of analysis provides an opportunity to redefine a more relevant methodological framework in a period marked by the effects of climate change and other environmental disturbances.

While definitions of this concept may vary depending on the types of systems, resilience development in all cases involves adopting systemic approaches that contrast with analytical approaches that founded most protection strategies in the 20th century. From the study of the methods, it appears in particular that the observation and analysis of SESs should be carried out first as part of a systemic approach considering the possibility of multiple risks. After this global analysis, which integrates the multiple issues of the territory and is inclusive with regard to its actors, analytical approaches can be led, dedicated to specific points relating to quantitative evaluations and dimensioning.

Understanding the risks in a territory provides a basis on which adaptation scenarios can be built. Analytical techniques exist to decide over time between the different options offered by these scenarios. Furthermore, the idea that improving resilience increases the chances of sustainable development in a changing and uncertain environment is reflected in the relatively recent concept of the CRDP. With this perspective, risk management should not be seen as a constraint only, but as an opportunity for sustainable development. Regardless of the projection technique chosen, the SESs should be considered as CASs which should lead to the emphasis on the substantial uncertainties surrounding these systems, and therefore, the need to continually learn and experiment, and adaptively manage uncertainty, disturbance, and surprise rather than attempt to eliminate them. This principle, coupled with that of participatory management of resources and links between communities and governments, forms the basis of a recommended mode of

governance, which includes engaging transformational forms of adaptation: adaptive co-management.

Using these analytical techniques, adaptation or transformation strategies can be considered using two joint approaches:

- Considering territories and their coastal flood protection systems as CASs, in relation to the observed and projected responses of the natural and built environment;
- Considering the RSL rise as a major parameter in the evolution of coastal hazards, including coastal flooding or salinisation of inland waters and soils.

In practice, these two approaches should be coordinated. In all cases, assessing the real possibilities of adaptation at various times requires considering all the components of protection (the natural environment, the built environment, and the levee system), and seeking the optimization of performance coupled to the reduction of expenditures over the long term. The definition of these strategies should be integrated into a territorial project in order to avoid forms of maladaptation which invariably result in environmental degradation and higher risks due to processes of increasing dependence on technologies and inappropriate resource management. Only long-term planning, consisting of a redevelopment of territories to preserve or restore the protection ESs, and limiting exposure to hazards will make it possible to gradually reduce dependence on containment technologies and to progress in implementing the principles of adaptive co-management. Whatever the SES considered, the existence of stable institutions capable of carrying out and financing projects over their entire duration is an essential condition for the effective implementation of the strategies.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

This article is a synthesis of a bibliographic analysis by MI, under the direction of YD and MY. All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/feart.2021.756936/full#supplementary-material>

Supplementary Figure S1 | A breach in the Wilnis levee due to drought. Credit: STOWA.

Supplementary Figure S2 | Double dike system (Marijnissen et al., 2021)

Supplementary Figure S3 | The true fragility curve compared with the deterministic design (Sayers and Meadowcroft, 2005).

Supplementary Figure S4 | An example of an adaptation pathways map (left) and a scorecard presenting the costs and benefits of the nine possible pathways presented in the map (right). The colors in the scorecard refer to the actions A (red), B (orange), C (green), and D (blue) (Haasnoot et al., 2013).

Supplementary Figure S5 | Climate-resilient development pathway. From Hock, R., G. Rasul, C. Adler, B. Cáceres, S. Gruber, Y. Hirabayashi, M. Jackson, A. Kääb, S. Kang, S. Kutuzov, Al. Milner, U. Molau, S. Morin, B. Orlove, and H. Steltzer. In: IPCC, 2019, Figure CB2.2.

Supplementary Figure S6 | The seven principles for managing the resilience of an SES (Bigg et al., 2012).

Supplementary Figure S7 | A comparison of analytical thinking and systemic thinking (Moberg and Galaz, 2005). Illustration by Henrik Ernstson.

Supplementary Figure S8 | Overview of the main cascading effects of sea level rise. From Oppenheimer, M., B. C. Glavovic, J. Hinkel, R. van de Wal, A. K. Magnan, A. Abd-Elgawad, R. Cai, M. Cifuentes-Jara, R. M. DeConto, T. Ghosh, J. Hay, F. Isla, B. Marzeion, B. Meyssignac, and Z. Sebesvari. In: IPCC, 2019: Sea Level Rise and Implications for Low-Lying Islands, Coasts and Communities, Figure 4.13.

Supplementary Figure S9 | Different types of responses to coastal risks and sea level rise. From Oppenheimer, M., B. C. Glavovic, J. Hinkel, R. van de Wal, A.K. Magnan, A. Abd-Elgawad, R. Cai, M. Cifuentes-Jara, R.M. DeConto, T. Ghosh, J. Hay, F. Isla, B. Marzeion, B. Meyssignac, and Z. Sebesvari. In: IPCC, 2019: Sea Level Rise and Implications for Low-Lying Islands, Coasts and Communities, Box 4.3, **Figure 1**.

Supplementary Figure S10 | Overview of the main mitigation and adaptation measures (from Abram, N., J.-P. Gattuso, A. Prakash, L. Cheng, M.P. Chidichimo, S. Crate, H. Enomoto, M. Garschagen, N. Gruber, S. Harper, E. Holland, R.M. Kudela, J. Rice, K. Steffen, and K. von Schuckmann. In: IPCC, 2019, Framing and Context of the Report, Figure 1.2).

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Guidelines for Analysing Coastal Flood Protection Systems After a Submersion

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Abstract: Storm Xynthia, which hit the French Atlantic coast on February 28th, 2010, flooded vast territories despite coastal defences. This disaster highlighted the need to further study the behaviour of the coastal flood protection systems at an adapted geographical scale by considering the kinematics of the events. This objective has been achieved through a combination of conceptual input on the definition of protection systems, significant breakthroughs in the knowledge of the mechanisms governing the flooding, and via the improvement of strategies and methods dedicated to flood analysis and representation. The developed methodology was successfully tested on four sites submerged during Xynthia (Loix, Les Boucholeurs, and Boyardville, located in Charente-Maritime, and Batz-sur-Mer, located in Loire-Atlantique). This work is intended to guide the diagnosis of sites prone to marine flooding from the first investigations until the delivery of study reports. Beyond the usual focus on hydraulic structures, it provides guidelines to better analyse the interactions with the natural environment (sea, soil, dune, wetlands, etc.) and with the built environment (roads and urban networks, ponds used for fish farming, buildings, etc.). This systemic approach, which is applied to a territory considered as a complex adaptive system, is fundamental to understanding the reaction of a territory during a marine submersion event and subsequently developing adaptation or transformation strategies.

Keywords: flood protection system; submersion; methodology; analysis; feedback

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1. Introduction

In the field of coastal flooding and, more generally, coastal hazards, many factors lead to an increase in risk or the emergence of new risks: climate change, demographic change, unplanned and rapid urbanization, poor land management, unsustainable uses of natural resources, and declining ecosystems [1]. The low elevation zone (classified as having land less than 10 m above sea level), where people and infrastructure are most exposed to coastal hazards, is currently home to around 11% of the global population (around 680 million people). By the year 2050, the population in this zone is projected to grow to more than one billion under all socio-economic scenarios [2]. Depending on the sector, coastal hazards can vary. Nevertheless, on a global scale, there are three cases of particular concern: deltas, low-lying islands, and arctic regions [3]. Global technical and economic studies [4–6] on the value of the stakes exposed and the damage they are likely

to suffer in the absence of adaptation conclude that it is imperative to anticipate in order to reduce the risk of disaster. This situation requires redoubled efforts in the observation of territories, in analysing feedback experiences, and in the development of prediction and anticipation systems in order to adapt the decision support tools.

Methodological developments and operational tools are already numerous, both on the understanding of risks and on strategies for coastal adaptation. In particular:

- there are methods and operational tools for the assessment of levee performance using geographic information systems [7–9]; methods also exist to assess the degradation of ecosystems and the services they provide [10–12], particularly flood protection services;
- the modes of adaptation have been extensively studied through alternative options covering both protection structures and vulnerable stakes. Thus, building on previous research [13,14], the IPCC report [3] describes, in addition to the option of no response, five main modes of adaptation to mean and extreme sea level rise: advance, protect, retreat, accommodate, and ecosystem-based adaptation

Numerical modelling is now widely used to understand and represent tsunamis [15], weather-marine phenomena, such as storms and hurricanes [16,17], as well as river floods [18]. Similarly, the models make it possible to understand morphodynamic evolutions, especially on beaches [19].

The multiple natural and anthropogenic actions to which the protection structures are exposed, as well as the heterogeneity of these structures and their very long lengths, require the consideration of significant margins of uncertainty of the structure's behaviour. This has led to an extensive body of literature on:

- modelling and assessing the risk of levee failure (e.g., [20–22]);
- estimating flows across embankments exposed to swell under either emerged (e.g., [23,24]) or submerged (e.g., [25]) conditions.

In addition, since the protection against coastal hazards is organised through systems with, in general, multiple structures, the issue of performance limits and risk of failure was also addressed by considering the combined effect of several structures. On this topic, previous research [26] has assessed the safety of a double-levee system. Other authors investigated the effectiveness of two anthropogenic works (e.g., a storm surge barrier and levees [27]) or the effectiveness of hybrid solutions combining a land-based structure (e.g., a dike) with the effects of natural formations, such as coastal wetlands and mangroves [28,29].

Despite all these methodological developments, the state-of-the-art relative to risk understanding and adaptation strategies remains incomplete. The main reason is that the state of the art is largely dominated by sectoral approaches, mobilizing a small number of disciplines (for example, hydraulics and geotechnics [30], possibly combined with statistics [31]), whereas territories and their protection systems are complex, adaptive systems [32] that need to be addressed through systemic approaches to understand their “architecture” [33]. Then, if necessary, analytical approaches (deterministic or probabilistic) are appropriate to evaluate quantitatively the performance of the system or to finalise the design of its structures.

There are, of course, systemic methods for understanding multiple risks [34–37] while paying attention to spatiotemporal scales [38]. The desire to develop the resilience of territories also leads to the establishment of risk observatories [39,40]. However, these methods are either very general and based on a narrow set of indicators [41,42], relate to infrastructure and urban networks [43–47], or relate to protection structures without establishing a link with the rest of the territory, as previously established. A method has, therefore, been developed with the objective of comprehensively understanding the reaction of a territory to a marine submersion event, with particular attention to the relations between the protection system and its natural and built environment. Such a method is particularly useful when an area has just been affected by an event, its protection system has shown its limits and is damaged, and its restoration or adaptation must be considered.

Rapid knowledge of the system is expected so that the work carried out can quickly become part of a long-term strategy, ensuring the safety of the population, while ensuring that the environment is not disturbed, which often contributes sustainably to the protection of the territory.

This paper presents a methodology developed in the aftermath of storm Xynthia, which affected the French Atlantic coast in February, 2010. Without entering all the developments of the reference study [48], it aims at underlining some essential aspects: concepts for geographic analysis, functions, performance limits and failure modes, and, finally, analysis strategies and methods. Although these aspects will be presented sequentially, it is necessary in practice to implement them jointly throughout a study.

The data collected from four sites (see Figure 1), selected for their diversity and their representativeness of situations met during this storm, were used to build and test this methodology so that the developed analysis methods could be considered as applicable to most geographic configurations for similar events. In this paper, principles will be illustrated with their application in the case study of Loix, a site that is situated on Île de Ré in Charente-Maritime, France. In addition, for more information, the results obtained on all four sites (Loix, Boyardville, Les Boucholeurs, and Batz-sur-Mer) are presented in the article [49].

This article is an adaptation of an article [50] originally written in French.

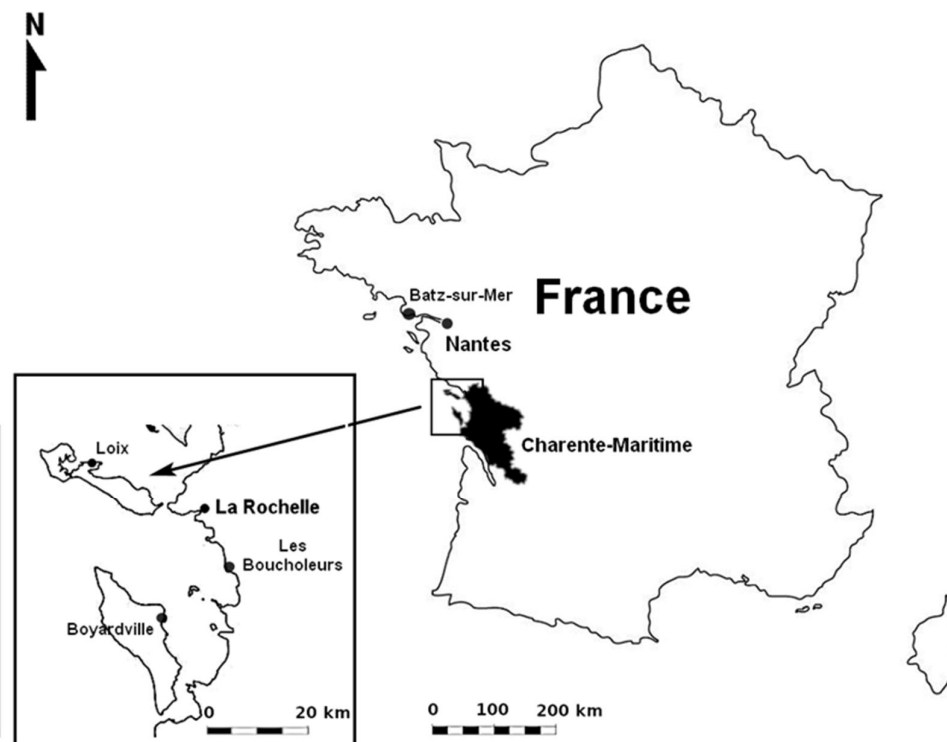


Figure 1. Locations of the four sites used to develop the methodology [48].

2. Concepts for Geographic Analysis

The definition of a methodology and its associated methods requires having a conceptual framework to deal with the complexity of the reality through representative models. This chapter aims at specifying appropriate concepts and definitions to describe and understand these systems using a geographical approach. The topography and the natural features, as well as all anthropogenic structures, influence the sequence of events during a flood. Thus, we need conceptual plans to organize and to understand the functioning of the

territory in relation to the risk management. The “protection system” and “hydraulic cells” concepts and the “source–pathway–receptor” model are intended to provide these marks.

2.1. Protection System

The definition of a protection system requires drawing an outline that separates the system interior and the exterior environment with which the system interacts. This outline must be continuous and closed. This operation, simple in theory, is represented by Figure 2. Generally, the outline will include:

- lines representing the limit of lands that are not submerged under normal circumstances. These lines can be called “defence lines”. During a stormy event, important exchanges of water can take place through these lines;
- lines drawn on grounds that are not prone to flooding thanks to their elevation or to their distance from the source of the flood. These lines can be called “sheltered lines”. No noticeable exchange takes place through these lines during a flood event.

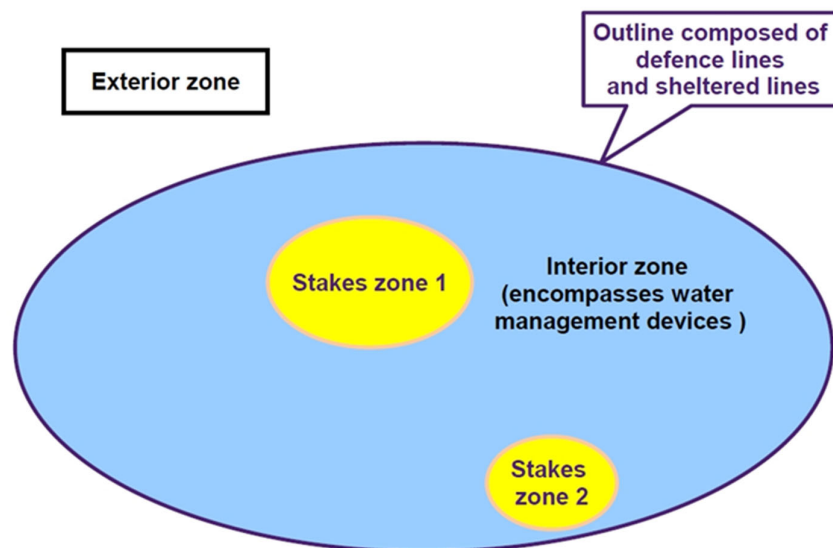


Figure 2. Demarcation of a protection system.

As defined, this outline represents an object that is geographically closed but hydraulically opened: controlled or uncontrolled water exchanges exist with the exterior environment (only through defence lines). Moreover, the word “lines” is used here to illustrate a concept and to facilitate the schematic representation. Nevertheless, some lines have, in reality, a thickness. Defence lines can represent a single work (a levee, for example) as well as a set of natural and anthropogenic features, such as a foreshore and a dune on which seawalls, groynes, or breakwaters were implanted.

The entirety of the zone inside the outline can be referred to in unambiguous terms as the “interior zone”. The stakes vulnerable to flooding are not uniformly distributed in this zone: they are sometimes locally, even widely, absent. In the interior zone, the characteristics of the hazard are also variable. To lead analyses with more precision, restricted geographical areas must be delimited in the interior zone. As these outlines aim at indicating the stakes location, each delimited area can be called, in unambiguous terms, a “stakes zone”. In the same way as for the demarcation of the system, these outlines are geographical objects that shall in no way prejudge the hydraulic phenomena that can occur in their location.

2.2. Hydraulic Cells

It ensues from previous definitions that a protection system contains two types of components, whose roles are well differentiated:

- defence elements against water entrances situated on the system outline;
- water management elements situated in the interior zone.

This observation leads us to introduce the concept of the hydraulic cell represented by Figure 3.

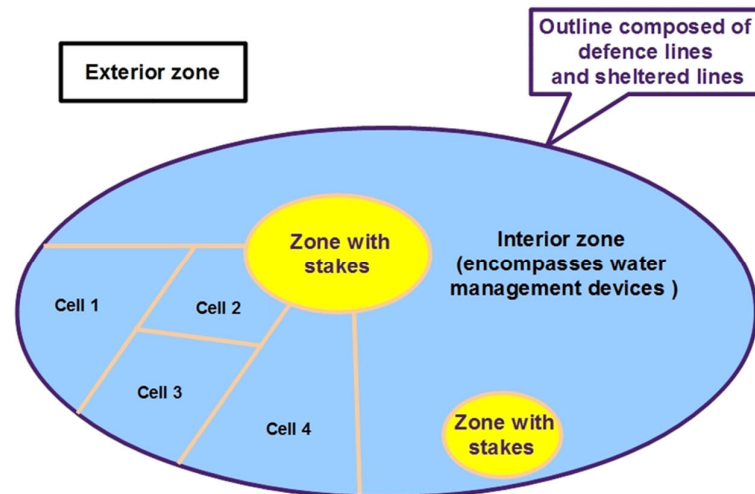


Figure 3. Schematic representation of cells within a protection system.

In order to correctly analyse the hydraulic phenomena within a territory that can extend over several square kilometres, it is necessary to determine the scale that is the most appropriate to study the main phenomena. For this purpose, a classic choice for hydraulic studies consists in defining “hydraulic cells”, which, visually, can be likened to a container whose edges fit relief elements: defence structures, internal levees, infrastructures, etc., or the natural topography if it reaches sufficient elevation. In plan view, these edges form a continuous and closed line.

Note that Figure 3 represents cells inside a system in the frequent case where relief elements are only marked on certain parts of the interior zone.

Illustration of the concepts of defining a protection system and hydraulic cells using the case study of Loix, France

The topography analysis makes the most important reliefs of the territory appear and correspond to the main means to determine the outlines of a protection system and its cells. Figures 4 and 5 show the implementation of this method on the site of Loix.

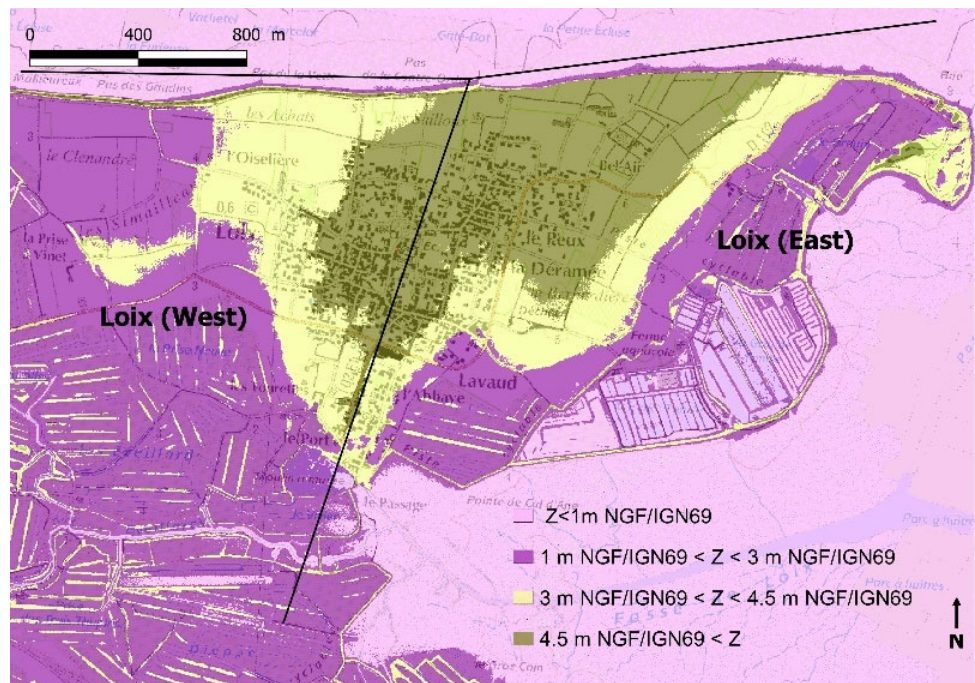


Figure 4. Synthetic topographic map. Altitudes are given using the NGF/IGN69 (French reference system).

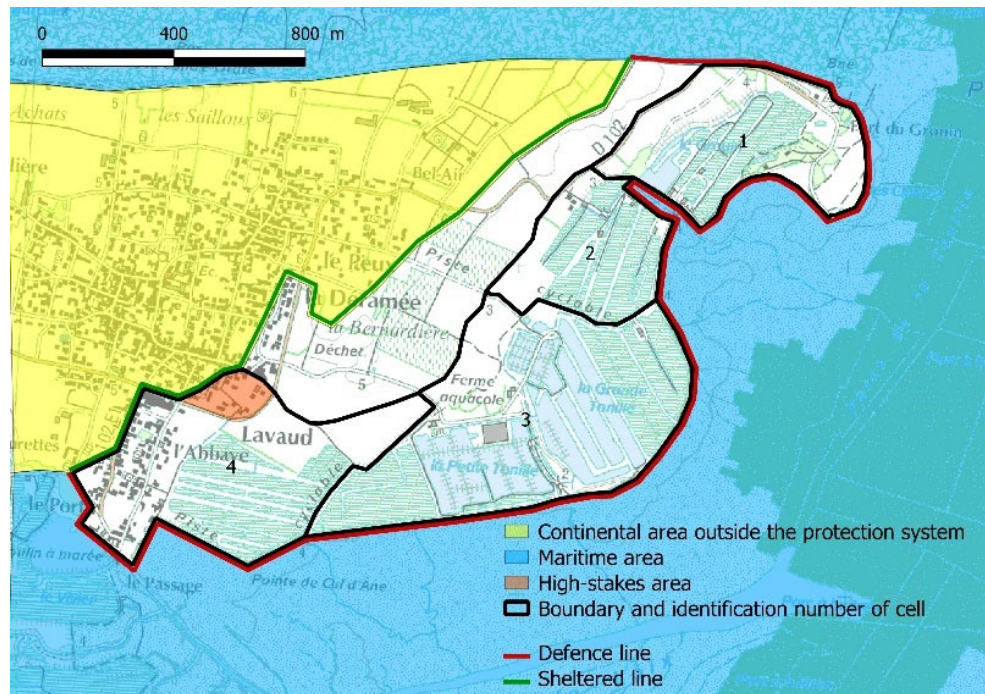


Figure 5. Schematic representation of the Loix protection system.

2.3. “Source–Pathway–Receptor”

In addition to the previously explained approaches, flood risk analysis can use the “source–pathway–receptor (SPR)” model [51]. This model represents interactions between the environment and the protection system. It helps identify the links between:

- natural phenomena that initiate the event (sources);

- zones with vulnerable stakes (receptors);
- flood routes from the exterior environment towards the receptor (pathways).

A schematic representation of the SPR model is shown in Figure 6.

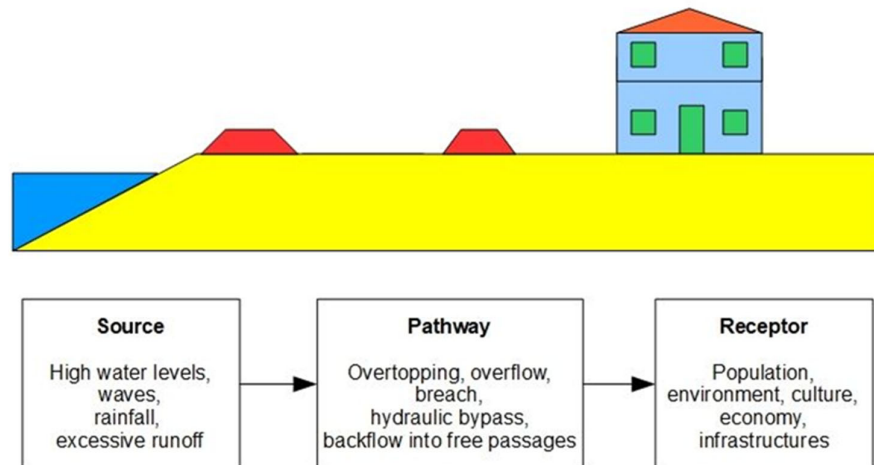


Figure 6. Representation of the SPR model.

Illustration of the SPR model using the case study of Loix

On the basis of the outline of the system and its cells, a flowchart can be established to represent the potential hydraulic pathways that connect the sea front (and possibly other “sources”) with the stakes zone. Figure 7 shows the implementation of this method on the site of Loix. The elements of the SPR model are annotated.

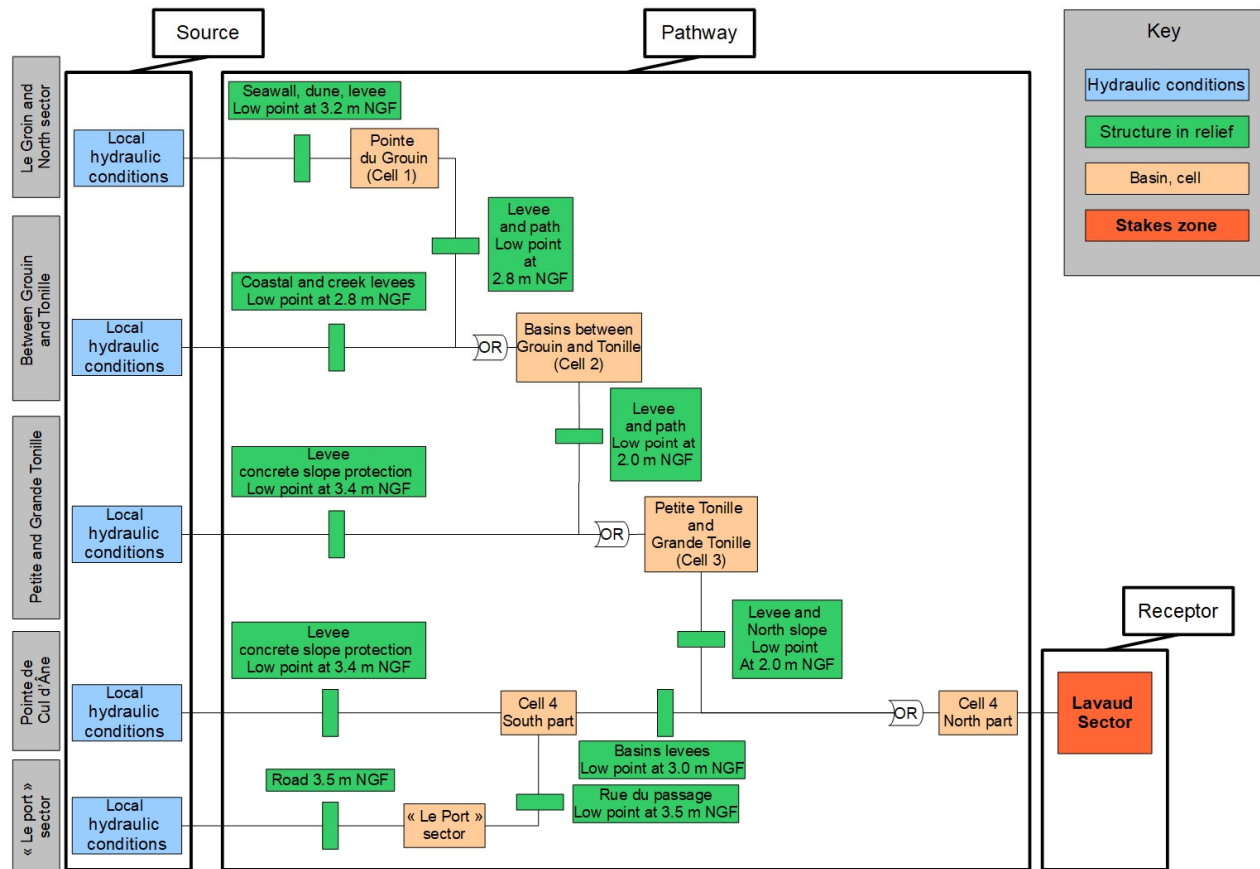


Figure 7. Synthetic flowchart of the Loix system. Altitudes are given using the NGF/IGN69 (French reference system).

3. Function, Performance Limits, and Failure Modes of a System

The study of a system, led within the framework of an experience feedback, aims at understanding the mechanisms that determine the performance limits and failure modes and how they relate to the protection objectives and the predicted functioning. In this part, we consider successively:

- the natural phenomena at the origin of the flood;
- the behaviour of the protection system facing these phenomena.

3.1. Natural Phenomena at the Origin of the Flood

Physical phenomena that produce a flood are generally multiple and occur on wide temporal and spatial scales.

The analysis of an event requires a comprehensive study of:

- the meteorological phenomena;
- the evolution of water levels during the event with consideration of their components (e.g., astronomical tide, storm surge, dynamic effects due to the propagation of this surge, effects of the local wind);
- sea states (direction, significant height, period) and currents;
- where necessary, the flow characteristics of rivers (water levels, discharges, speeds);
- the morphological evolutions.

Hydraulic phenomena observed on the Loix coast

2D hydraulic modelling of the ocean during Xynthia was performed by the laboratory UMR 7266 LIENSs, CNRS-University (National Center for Scientific Research-University) of La Rochelle [17]. The results of these works supply the water level and significant wave height value variations across diverse points of Loix coasts (see Figure 8). The graph of the point 6 is presented as an example.

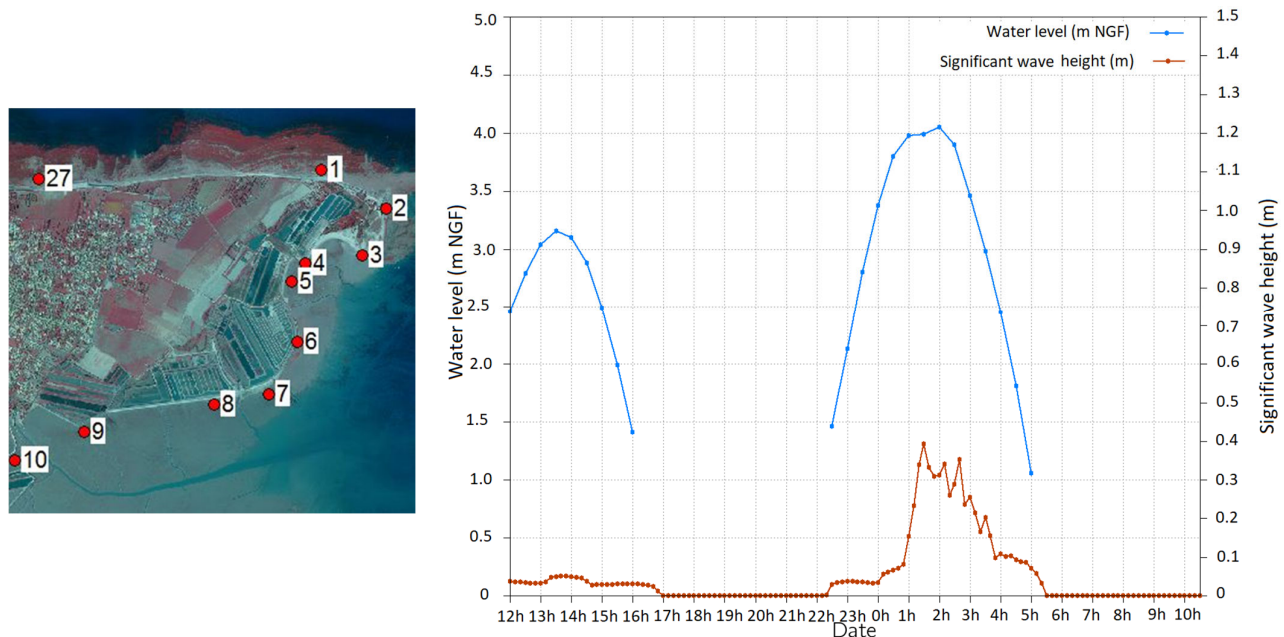


Figure 8. Water level and significant wave height on the Loix coast (a) localization of temporal series; (b) representation of values collected from point 6. Altitudes are given using the NGF/IGN69 (French reference system).

Numerous sites are exposed to several dependent or independent natural phenomena: river flooding, water table rise, and runoff can occur in conjunction with extreme marine levels. The swell and wind waves can accompany these extreme levels. An analysis of the combinations and interactions between these forces may be necessary.

3.2. System Behaviour During the Event

System performance limits and failure modes can often be explained by inadequate stakes zones protection due to the absence of analysis at the global scale. As a result, the system design is inadequate for the stakes zones protection. Typically, the main issues include:

- a discontinuity in the defence line, either by a hydraulic bypassing of existing structures, by water entrances through openings in coastal structures (e.g., via a staircase, slipway, or through gates), or by overtopping or overflowing of structures whose dimensions were not sufficient;
- no coordination between the defence function (around the system) and the water management function (inside the system). A global plan should make water management capacities and defence protection levels consistent for the entire system. Normal conditions and breaches in the defence line should be considered.

Failures are also often a matter of inadequacies in the maintenance or the operational management of the system.

For a stakes zone, the performance of a system can be estimated according to the characteristics of the hazard resulting from a given natural phenomenon: maximum water heights, flow speeds, water level rise speeds, flood duration, etc. Performance criteria can be defined for each of these characteristic values. If these criteria are established, for example, according to the vulnerability of the people, it is possible to adopt values such as (values given for information purposes):

- maximum water height should not exceed 0.5 m;
- flood duration should not exceed a tide cycle;
- flow speed should not exceed 0.25 m/s;
- overtopping should not exceed an average discharge of 0.1 l/s.

Behaviour of the Loix system—Photointerpretation and hydraulic modelling

To better understand the flood dynamics, aerial photographs were analysed to identify the diverse hydraulic (referring to flow dynamics and submersion) and mechanical (referring to damages and breaches on levees) phenomena appearing after the storm Xynthia, as shown in Figure 9. In this document, two high water marks were indicated that were found in the report [52] (in green: 4.01 m NGF in the Lavaud district and 4.40 m NGF in the North of Petite Tonille).

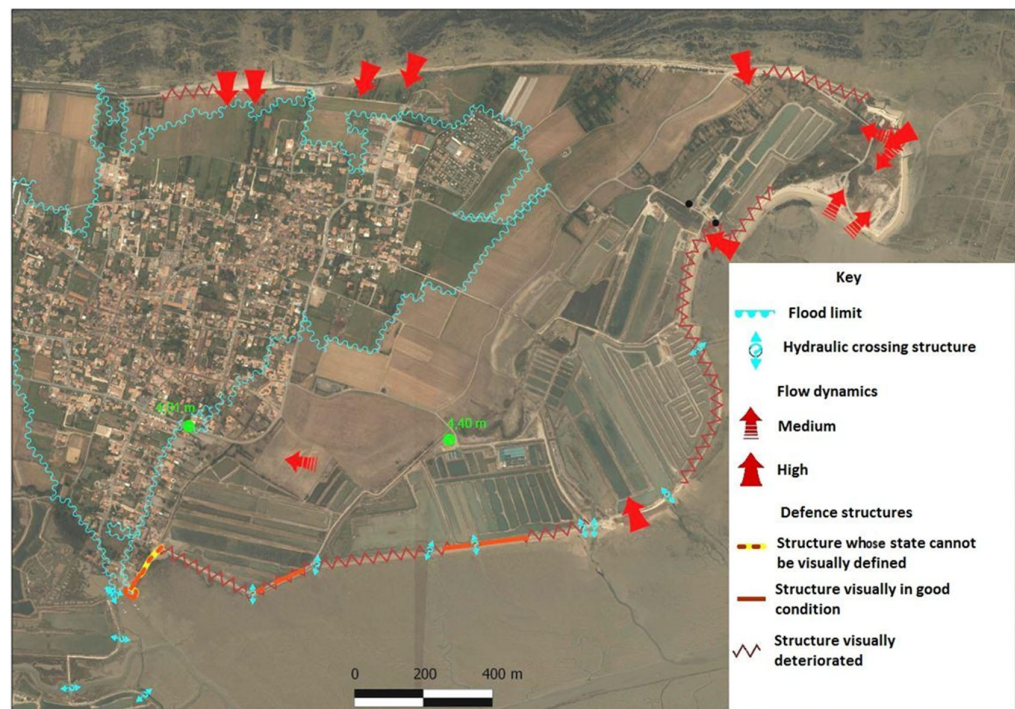


Figure 9. Synthesis map of Xynthia event.

A hydraulic model has been developed (see Figure 10). An overall consistency was sought in the representation of the data previously described (and other data).

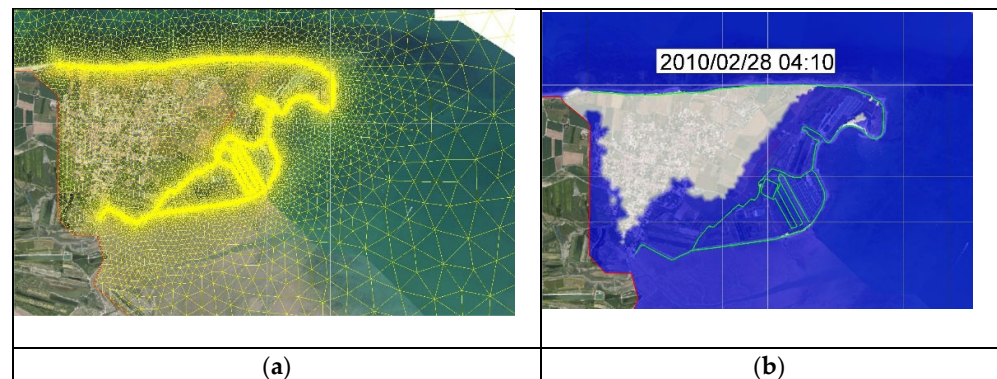


Figure 10. Loix hydraulic model (a) model grid; (b) output result of the model at a given time.

4. Study Strategy and Analysis Methods

To study the functioning of a system within the framework of an experience feedback requires developing strategies and adapting analysis methods. These two points are successively discussed.

4.1. Strategy and Organisation of a Study

The analysis of the functioning of a site is based on numerous and diverse data, and, before formalising the analysis through the production of a report, important preliminary work is necessary. This work consists of the collection and the analysis of data. To ensure efficiency and precision, data should also be listed and linked to geographical landmarks. This need for classification and localisation can be satisfied by producing preliminary maps, plans (representations of the system outlines, stakes zones, hydraulic cells), and flowcharts.

A risk analysis can be very time-consuming if tasks are performed without anticipating their final utility. It is thus advisable to adopt a tiered approach so that the efforts are produced based on the prerequisite that results can actually be achieved. The efforts should also be proportionate to the interest of expected results. Analysis tools (flowcharts in connection with plans) can be useful in the definition of this strategy because they allow the review of the mechanisms that generate the risks and aid in the decision of continuing the investigations on a case-by-case basis. Thanks to these “visual aids”, the analysis can be both more relevant and more systematic. By means of plans and flowcharts, the need to continue investigation can be regularly estimated on each component of the system. An appropriate strategy tailored to the study can be developed. In addition, when modelling of the hydraulic phenomena is developed, the model sensitivity to input data can also be studied to evaluate the necessity of specifying hypotheses.

The analysis of protection systems is subjected both to the natural variability of phenomena and to the uncertainties linked to their observation and to their understanding. It is thus advisable to identify not only the information that will be useful but also the associated degree of precision. Multiple information sources can exist locally on a site. For example, the analysis of punctual information utilizing both photographs and LIDAR data interpretation will increase the reliability of the results and can be usefully systematized if these data are available and relevant. The development and the use of a model is also a way to ensure the overall consistency of data.

The precision of data is not a characteristic that alone justifies its relevance. For example, when a flood occurs, sites quickly evolve, on the one hand, under the influence of hydraulic actions and, on the other hand, under the influence of the emergency interventions that are led. It is thus necessary to verify that the available data effectively meet the need and are not outdated with regard to the studied situation. A site visit is often very useful to better understand the evolutions.

4.2. Analysis Methods

Analysis methods can be implemented to perform an exhaustive search for the causes of a failure (in the case of the feedback of a past event) or to examine the reaction of a system to variable actions. In any case, these methods consider the protection structures as components of a system and claim to be exhaustive. Three flowchart types, whose objectives are different, are presented in the reference study [48]:

- the fault tree,
- the event tree,
- a combination of both trees called the “bowtie tree” because of its general shape

In this paper, we will focus on the adaptation of the third type of flowchart (the bowtie tree) to coastal floods. Nevertheless, it is advisable to use the first two flowcharts to give the definitions necessary for the understanding of the third:

- fault tree: for a given failure, this flowchart allows for the identification of all the intermediate events and the initial causes,
- event tree: for a given event, this flowchart identifies all the scenarios that can lead to a variety of negative consequences.

The bowtie tree was initially developed to deal with “loss of containment” in the field of industrial risks [53]. As illustrated in Figure 11, it allows for the representation of both parts of this analysis:

- the fault tree, which establishes the events chain until the stakes zone flooding (central dreaded event);
- the event tree, which considers this flooding and determines all of the potential consequences.

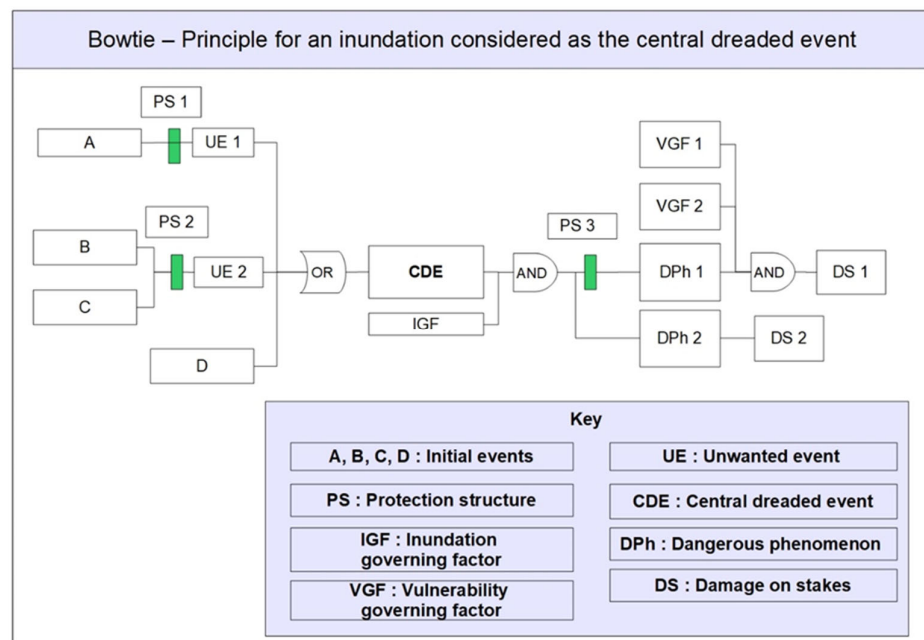


Figure 11. Generic representation of a bowtie tree.

The construction of this flowchart requires the identification of the flood protection system, of the interior zone, and of the stakes zone, which must be sufficiently well delimited.

The construction of the flowchart is widely determined by the determination of the central dreaded event (CDE). Within the framework of our study, the CDE is the flooding

of the stakes zone (and not the flooding of the interior zone). This option considers the flooding of the stakes zone as the CDE allows the construction of the part of the bowtie tree relative to the protection system dysfunction by considering, in a global approach, all of its components (defence functions and water management functions that aim jointly at preventing or at limiting water entrances in the stakes zone).

It is recommended to model the construction of the fault tree on the geographical configuration of the system in order to facilitate the dialogue between the flowchart and the plan. Hydraulic cells are used to identify the subsets of the bowtie tree. Then, the construction of the part relative to the event tree concentrates on:

- dangerous phenomena that can occur in the stakes zone depending on the action of the protection barriers that can exist in this perimeter. In addition, factors influencing the flood propagation in the stakes zone (those that cannot be considered as barriers) can be indicated;
- the damage to the stakes. In addition, the exposure factors of the stakes can be indicated.

Synthesis of the functioning (and dysfunctioning) of the Loix protection system

The functioning of the Loix protection system can be synthesized by a bowtie tree as shown in Figure 12. In this flowchart, the hydraulic pathways appearing in the first phases of the event are represented by the black, unbroken lines. The hydraulic pathways appearing on the “north slope” after the filling of the cells are represented by dotted lines.

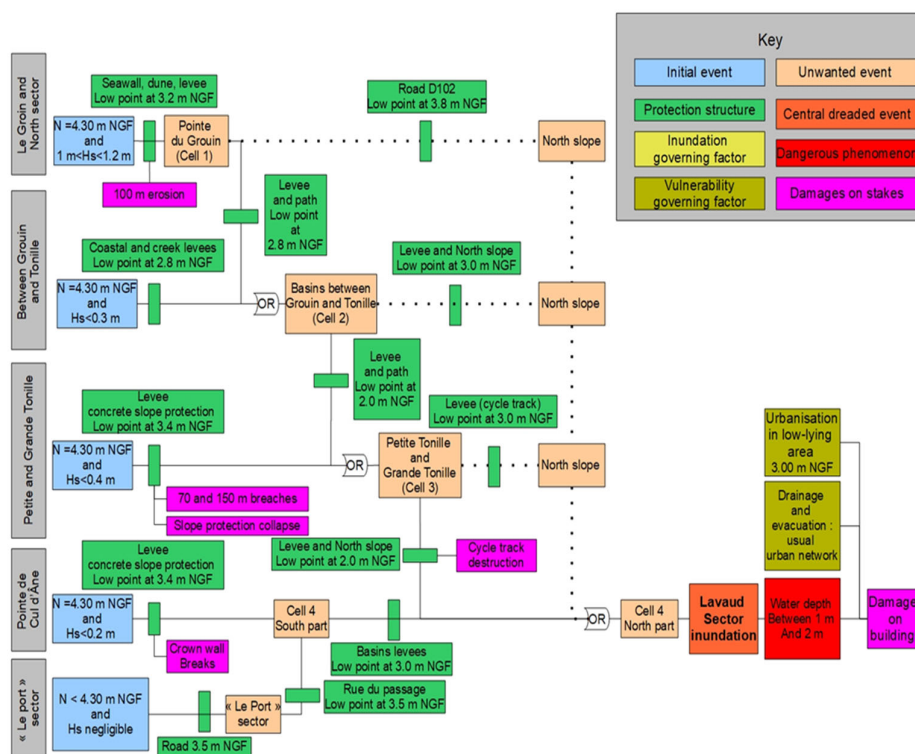


Figure 12. Bowtie tree of the Loix protection system (Xynthia feedback). Altitudes are given using the NGF/IGN69 (French reference system).

5. Conclusions

Flood risk management on a site is made by the implementation of a coherent programme of measures. For coastal sites, the definition of these measures requires specifying

the geographical area in which the approach must be led and defining a global functional plan within this perimeter, which includes:

- the delimitation of the system, understanding of its functioning, understanding the conditions in which flooding can occur;
- the definition of measures for the maintenance and inspection of the structures and the definition of adequate operations for measuring and forecasting water levels and sea states;
- the comparison of this functional plan to the reality: when an event occurs, the way the system reacts should be compared to the way it was predicted to react according to the global functional plan.

The study of past events plays a fundamental role in the implementation of this approach. The precise knowledge of the functioning of a system during a major event such as Xynthia allows for the better understanding of the functioning of the system for other events.

This article highlights the guidelines of a methodology developed for studying protection systems within the framework of an experience feedback. Emphasis was placed on the concepts, the study strategies, and the analysis methods.

The concept of a protection system in connection with the SPR model paved the way for the development of a schematic cartographic representation of the system composition. This schematic cartographic representation can be completed by a flowchart representing the structure of the system.

The schematization under this double shape (mapping and flowchart) is pertinent for the representation of flood scenarios. It allows for the establishment of precise relationships between the three levels of the SPR model: natural phenomena (primarily outside the system for marine submersions), flood propagation (particularly through hydraulic cells), and damages on main stakes (on sectors well delimited inside the system).

This double representation makes analyses more systematic and also makes investigations more efficient. Ultimately, we can obtain a clear vision of the global functioning of a system, of its performance limits, and of its failure modes.

The implementation of these guidelines also requires:

- mastering the fundamental notions of flood risk management (i.e., natural phenomena, events, hazards, stakes, and vulnerability);
- understanding the physical phenomena that occur in these coastal environments, both at the global scale of the system and at the scale of the structures (including the coastal natural features);
- implementing multiple scientific and technical disciplines for the investigation and modelling.

For further information about these subjects, the reader is invited to consult the methodological part of the reference study [48], as well as case studies that present concrete examples of implementation [49].

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Coastal flood protection systems Xynthia feedback experience. Case studies conclusion

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Abstract:

The determination of the borders and the internal structure of a coastal flood protection system, then the understanding of its behavior during past events contribute widely to determine actions to improve its performance. To set up in this domain a proven methodology, transposable in other places prone to episodes of marine floods, four sites with contrasted configurations were chosen for case studies. These sites are representative of most of the situations met during the storm Xynthia which hit the French Atlantic coast in February, 2010:

- Loix is a peninsula surrounded by a set of basins and marshes,
- Les Boucholeurs extends in border of a vast bay and presents houses on the sea front directly exposed to waves as well as setback constructions on the location of former leveed marshes,
- Boyardville-La Perrotine is an urbanized zone crossed by a leveed canal connecting the sea front with a vast zone of swamp and a marina,
- Batz-sur-Mer is characterized by salterns along which urbanization developed.

These sites are structured by a network of natural features, levees, canals and ditches, road and railway infrastructures, involving many actors for their management.

This paper presents case studies conclusions. It focuses on the way the main identifiable stakes were actually protected during the passage of the storm Xynthia.

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3. Les Boucholeurs

Les Boucholeurs site is a large area fairly densely urbanized. The analysis focuses on the inhabited sector of Les Boucholeurs (see figure 2). During Xynthia, the following protection failures appeared:

- North, sea walls did not protect enough against overtopping. Wave breaking caused two deaths,
 - South, dunes were very fragile and the swamp storage capacity was widely exceeded.
- At rising tide, only water from cell 2 could join cell 1. If road and railway infrastructures partially orientated water from cell 2 to the stakes zone, they also let a part of the volume spill in cell 3. Water entering in cell 4 overflowed the cell 3 without reaching cells 1 and 2.



Figure 2. Les Boucholeurs system schematization.

Port Punay canal, that crosses the urbanized zone, provoked its flooding by orientating flows in this low-lying sector. At its outlet, low discharge didn't contribute significantly to the inundation but after the storm the discharge was also too low to evacuate the water. This led to a detrimental inundation for many days.

4. Boyardville-La Perrotine

Boyardville-La Perrotine is an urbanized sector crossed by a leveed canal connecting the sea front with a vast area of swamp (see figure 3). This site is analyzed considering one single protection system because the canal allows hydraulic exchanges on one hand between the sea front and the swamp, and on the other hand, between its two banks. The analysis focuses on Boyardville sector.

Potential hydraulic pathways leading to cell 1 (Boyardville) are:

- between the downstream part of the canal and Boyardville (the most direct path),
- between the swamp and Boyardville, from cell 3 to cell 1 (by the West),
- and between the swamp and Boyardville, from cell 3 to cell 1 through cell 4 (passing North widely).

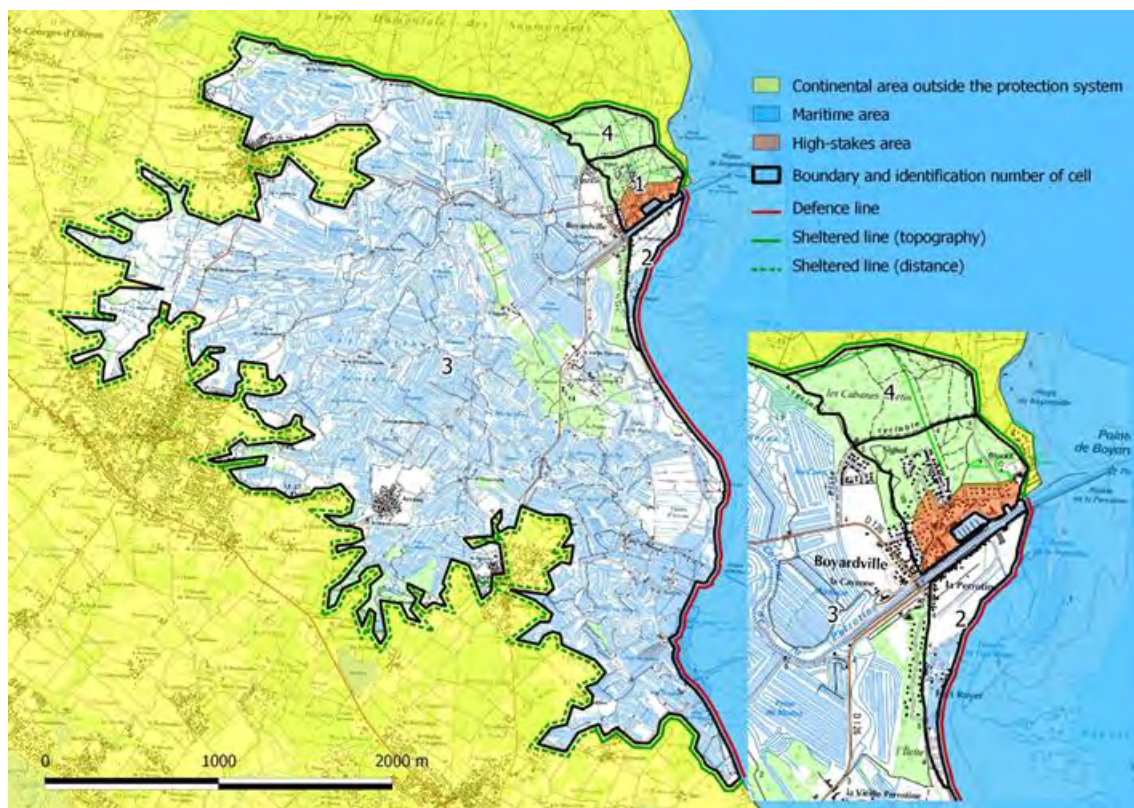


Figure 3. Boyardville system schematization.

During Xynthia, because of the exceptional sea level, the functioning of the canal was perturbed: shortly before the peak of tide, an additional water flow crossed La Perrotine (Cell 2). The main flow in Boyardville occurred downstream to the canal where the head loss was least important and where the flow from La Perrotine came out. Boyardville basin flooding, although it was partial (water depths between 1.40 and 1.65 m), caused a death. A 0.15 m higher sea water level would have engendered water depths between 1.75 and 2.00 m.

5. Batz-sur-Mer

Batz-sur-Mer (see figure 4) is characterized by salterns along which urbanization developed. The analysis focuses on the urbanized La Herpe sector. The system is constituted of:

- four cells along the sea front that are separated by inlets,
- a back area where La Herpe sector is situated.

This position behind cells results of the fact that its altitude is higher than the low points of the defense line constituted by the maritime dike. It means that for this district, the maritime dike does not retain water and that La Herpe district is not prone to fast floods engendered by a breach or the overflow of the sea dike.

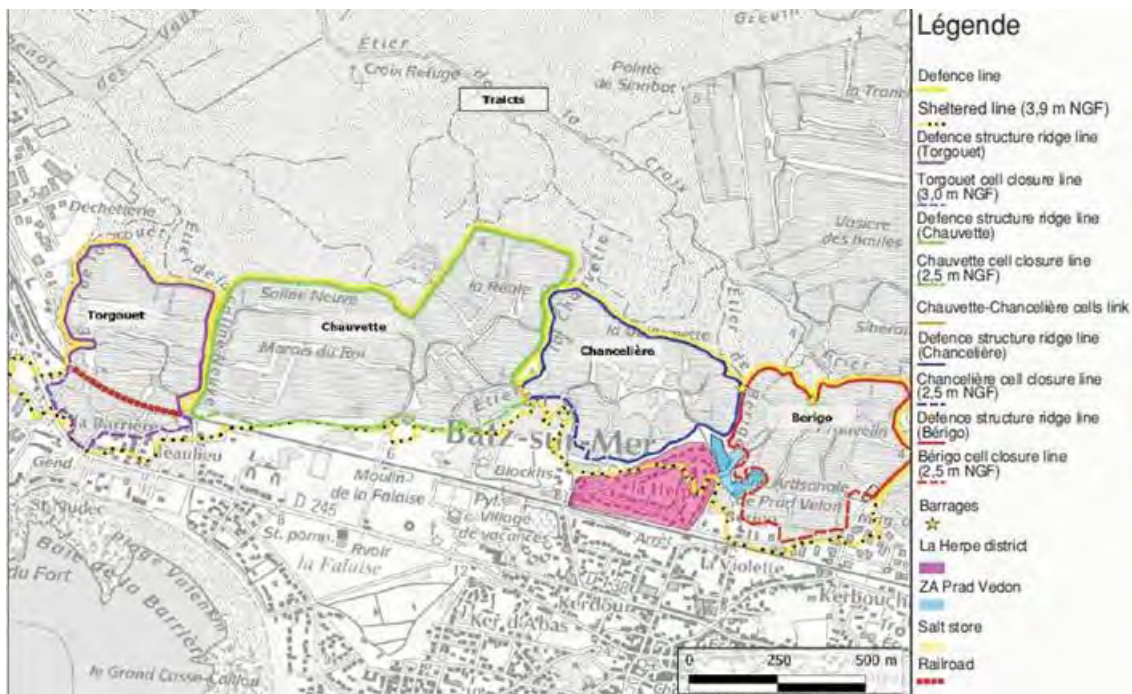


Figure 4. Batz-sur-Mer system schematization.

During Xynthia, basins filled quickly enough to consider that the system doesn't slow down the flooding on this stakes zone. Inlets, although some of them are equipped with dams represents preferential flow paths. Thus levees and basins have a neutral effect on water levels that appear on La Herpe sector. Nevertheless, this device keeps a positive effect by offering a good protection against waves propagation.

6. Conclusion

Studied sites show diverse configurations which engendered during Xynthia diverse flooding mechanisms.

- In Loix, the position of Lavaud district is particular: far from the sea front, it is potentially at the place where flows from all cells meet and can store their water. Breaches and the saturation of basins provoked a very fast flood in this district just before the peak of tide.
- In Les Boucholeurs, the urbanized zone has undergone both, north, overtopping on the sea front (the strong exposure to waves caused two deaths) and, south, water entrances on a very large linear due to levees and dunes overflowing. The canal that crosses the urbanized area contributed to store the water in the high stakes zone. However, the permeability of road and railway infrastructures allowed a part of the water to spread outside the most vulnerable areas.
- In Boyardville-La Perrotine, the flooding of Boyardville basin depends on the water level of the canal that crosses the site. In addition to its normal supply from the sea front, the canal received water crossing La Perrotine sector. Although Boyardville basin was not completely filled, its flooding caused one death.
- In Batz-sur-mer, la Herpe district is separated from the sea front by a series of basins. This district is located at a higher altitude than the crest of the dike. For this reason, there is no risk of fast flood.

The most dangerous configurations are the ones which engender fast floods. Some are easy to identify:

- basins positioned immediately at the back of a dike (Boyardville, whose situation is comparable to La Faute-sur-Mer where Xynthia caused 29 deaths),
- sectors exposed to waves (sea front of Les Boucholeurs).

Others are more difficult to reveal:

- basins positioned at the back of basins (case of Lavaud district in Loix),
- low areas crossed by a canal without levee (case of Les Boucholeurs).

A long distance from the coast does not necessarily protect against fast floods.

Finally, some areas can be flooded but the risk for the life of their occupants is limited thanks to their situations out of dike influence zones and out of basins (case of La Herpe district in Batz-sur-Mer). If these areas are flooded, the water will raise slowly (at the speed of the sea water level at the peak of tide).

7. References

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COST STUDY OF COASTAL PROTECTION

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A better definition of the long term protection strategies against littoral hazards requires evaluating investment, management, and maintenance costs of various interventions on levees and other civil engineering structures, as well as on beaches and dunes. The cost study of coastal protections (Cerema 2018) aims at providing the assessment of the project global cost. Based on the study of a large number of projects completed in France, estimations were produced to enhance the reliability of these calculations at the scale of a site in the littoral zone or of an individual natural or artificial structure. For each structure type, the obtained results are essentially linear, surface, volume or mass costs (initial costs or annual average costs), as well as lifetime and intervention frequency. To obtain this information, the analysis mainly consisted of:

- the creation of a typology which crosses « structure type » and « intervention type » which allows establishing homogeneous groups of characteristic operations;
- the identification, for every group, of physical parameters influencing the associated costs, which allows the user of the manual to evaluate better the difference between the observed high and low values.

This paper presents the context of the study, its methodological process, the progress of the investigations and the analyses, the obtained results, and finally the generic lessons learned.

Keywords: cost, protection, defense, sea, flood, erosion, levee, dune, beach

INTRODUCTION

The traditional techniques of « sea defenses » are frequently used on the French coast, showing mixed results of their efficiency. Moreover, the use of these techniques is often controversial because of the artificialisation of the landscapes and the impacts on the environment. This has led to an evolution of public policies and to the emergence of new protection strategies.

Coastal features vary significantly (beaches and dunes, polders and swamps, estuaries and deltas) but all have in common a dynamic mobility that causes their evolution in time. This instability strongly questions the sustainability of hard structures. In spite of the impression of robustness that materials such as armourstone, concrete and steel provide, these structures are fragile when subjected to storms. New evidence of this fragility was shown during the recent storms in France. On February 28th, 2010, the Xynthia storm highlighted the necessity of improving levee systems to protect against marine floods, and a series of storms in the winter 2013-2014 was a reminder of the sensitivity of our coasts to erosion.

Natural features (consisting of mud, sand or pebbles), as well as certain types of vegetation, are often the best way to dissipate wave energy. The implementation of traditional protection structures modifies the complex sediment transport balances existing on coasts. In particular, foreshore erosion can be caused by:

- the reflection of waves on concrete or steel seawalls;
- the interruption of the sediment transport when groynes are placed along beach profiles.

In spite of high construction, maintenance and repair costs, traditional works generate strong impacts on the environment and on landscapes, and may offer only limited protection against littoral hazards.

Based on these limitations, alternative solutions have been developed that disrupt less the complex dynamics existing on the coast. If these solutions are already implemented at numerous sites, protection strategies against littoral hazards must still be questioned at an even greater number of sites, and in most cases, redefined. Yet, long-term project funding often represents the main barrier to this evolution. It was thus advisable to produce a methodological handbook assembling useful information and pertinent recommendations to compare in the long term the protection scenarios of projects employing these techniques. In particular, the goal is to calculate the global cost, summing the investment, management, and maintenance costs. This is the scope of the handbook produced by the Cerema (2018) on the basis of the observation of a wide variety of projects completed during the last fifteen years in France. The present article presents this study, focusing more particularly on information relevant not only in France, but on an international scale. The flowchart in Figure 1 gives an overview of the contents of the study and is a recommended outline to follow for similar studies.

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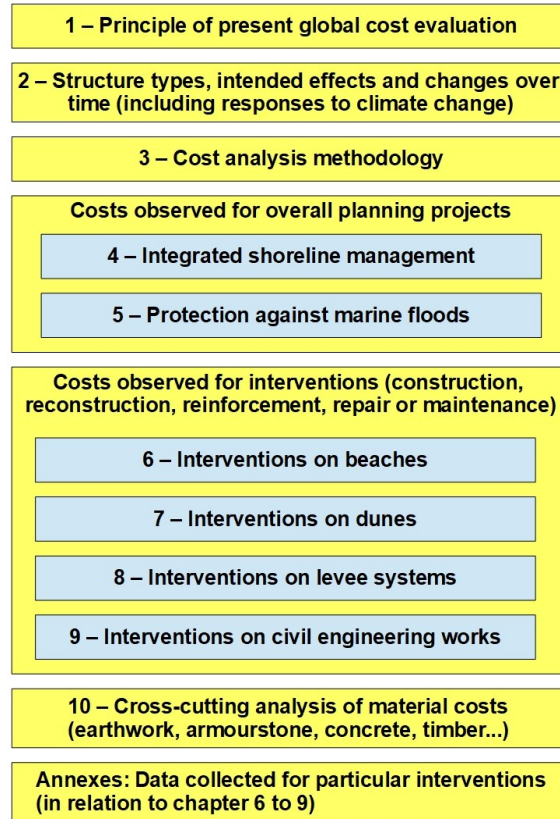


Figure 1. Flowchart of the study

CONTEXT OF THE STUDY

The study (Cerema 2018) is based on the observation of past projects. To appreciate the possibility to conduct this type of study, it is necessary:

- first, to have a sufficient understanding of the protection strategies that these projects are fulfilling;
- secondly, to make sure that the geographical perimeter of investigations and the nature of the concerned coast, in connection with the historic context of the studied period, guarantees favourable conditions to obtain sufficient data for the establishment of reliable estimations of unit costs and other researched data.

Protection strategies against coastal hazards

For certain sites, the main problem is the management of beaches and dunes in connection with the sediment transport. Other sites are more concerned by the protection against coastal flooding. To deal with these two problems, projects will inevitably refer to:

- the shoreline position, which marks the limit between land and sea. This limit moves depending on erosion and accretion processes, under the influence of hydro-sedimentary and aerial processes, as well as changes in sea level. Generally, the main objective is to avoid that erosion causes shoreward movement of the shoreline position, ultimately threatening coastal infrastructure and populations;
- levee systems, whose function is to protect against marine flooding. These systems consist of levees and hydraulic structures assuring the flow regulation between the various sections of the system and between the land and the sea.

The position of levee system structures does not coincide *a priori* with the shoreline: setback levees, canals, or retaining basins are positioned land-side. Nevertheless, a variety of means to manage the shoreline position and to protect against marine flooding are common: in many cases, the preservation of the sedimentary stock, as well as structures positioned on the foreshore to absorb wave energy, are deemed necessary to reach these two objectives.

Historical background and geographic scope of the study

The study (Cerema 2018) was conducted in France. The coastline of metropolitan France extends nearly 6200 km, excluding estuaries and ports (MEEM 2015), and every coastal type is represented (IGN 2007):

- 2200 km of sandy coast (35%);
- 1500 km of marshes and tidal reservoirs (24%);
- 2500 km of rocky coasts (41% with 13% cliffs).

The evolution of public policies during the studied period 2002-2017 led to the implementation in France of a wide variety of protection strategies against coastal hazards. The most pronounced examples are the restorations of lidos (strips of land made of sand that close lagoons) in the Mediterranean Sea and the large-scale works on the Atlantic coast conducted after the Xynthia storm. These projects are defined in action plans that can be classified in three categories:

1. projects designed to protect against littoral hazards taking into account the hydro-sedimentary functioning of sites, but constrained by the strong public policy issues (which explains that the use of civil engineering structures is still frequent);
2. restoration of the coastal zone intended to return to a more natural functioning of the environment ;
3. management and maintenance on sites at which the natural character was widely protected (beaches and dunes, coastal marshes), or on the contrary, at sites marked by a strong human activity.

In the first two categories, all in all 173 projects were taken into account in the study (Cerema 2018). The location of these projects is shown in Figure 2, but the figure does not include the maintenance interventions on natural sites of the third category (especially dunes), which were also considered on the basis of the annual activity reports.

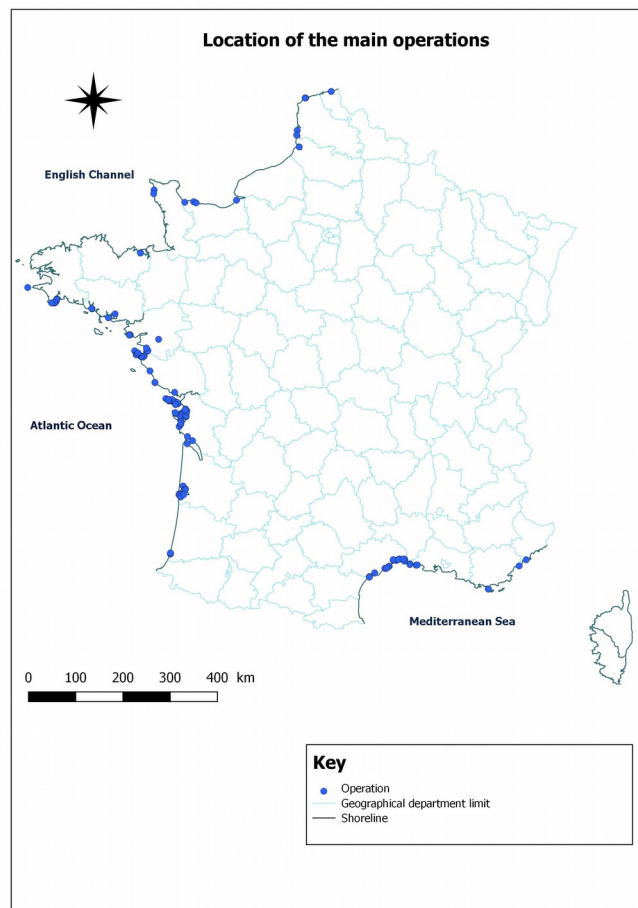


Figure 2. Location of main studied projects

To give a sense of scale of expenditures dedicated to these objectives in France:

- over the period 2007-2013, on the West part of the Mediterranean coast (Occitanie), the investment over 7 years for the rehabilitation of the coastal zone represents 120 M€ (value updated in 2014);
- over the period 2011-2016, on sectors affected by the storm Xynthia (center of the Atlantic facade), expenditures over 6 years amounted to 300 M€ (CGEDD 2013).

CALCULATION OF THE GLOBAL COST AND COMPARISON OF PROTECTION SCENARIOS

To define and estimate the cost of the projects protecting against littoral hazards requires having a relevant calculation method of the global cost. This method applies normally within the framework of the comparison of scenarios ending in the adoption of a strategy. Each scenario can concern several natural features or structures. Thus, the principle is, for each scenario, to calculate the global cost of each component. The global cost of a scenario is thus the sum of the global costs of its components.

Comparison of protection scenarios

Every project should be designed considering the geographical scope and time scales adapted to the stakes that must be protected. The approach consists mainly of:

- defining exactly the objectives of protection against littoral hazards;
- defining scenarios of protection and identifying for each of them the outline of the project and the planned techniques;
- estimating the investment, maintenance, and management costs (global cost) of the project for each of the scenarios.

On the basis of these elements, detailed below, and by taking into account the level of funding, it is possible to determine the most adapted strategy to reach the objectives.

Definition of objectives

It is essential:

- to identify the stakes that must be protected;
- to know the reference events (storm, flood) against which protection is necessary;
- to determine a lifetime of the project.

On this last point, it is important to underline that estimations must be made in a temporal perspective which is intrinsic to each project and should be explicitly defined:

- if the project aims only at maintaining a level of protection, the estimations can, for example, be established over a 30-year horizon (considering that it is about the life expectancy of the structures);
- if the issue of the protection objectives is raised and a comparison with the value of the stakes must be established, it can then be preferable to consider a duration of 100 years, while taking into account climate change effects.

Definition and study of protection scenarios

The outline of the project must be well defined by integrating the intellectual services, possible land acquisitions, and, especially, associated elements (corresponding to a function other than the protection against littoral hazards: public road networks, access to the foreshore, buildings...) that are created or impacted by the works. Costs of interventions on these associated elements can be equivalent or even superior to those of the hydraulic works. In particular, these associated elements can have a significant impact on long-term costs.

Whenever possible, the comparison should take into account all of this information, both for the calculation of initial costs and for the calculation of management and maintenance costs. However, in the rest of this paper, the subject will be restricted to the structures and natural features that have a protection function.

Before any economic comparison, it is essential to evaluate the long-term behavior of these elements. The most important part of their global cost can, most of the time, also be attributed to their management and maintenance.

Consequently, it is recommended to study two types of measures:

- measures requiring small annual interventions (beaches, dunes equipped with fences made of wooden slats or covered with oyat plants, levees covered with grass, groynes made of timber piles);
- measures requiring irregular, but more extensive, repair and maintenance interventions (reinforced concrete structures, sheet piling or armourstone).

Measures of the first type present numerous advantages:

- better control of the level of protection due to regular monitoring of the structure and the site, and the possibility to add materials, if need be;
- better environmental balance by the use of natural materials, generally present near the project site;
- better control of the costs, which are more regularly spread out in time.

Once the qualitative study is completed, the comparison between solutions can be achieved by a quantitative approach evaluating the global cost.

Method of calculation of the present global cost

The present global cost of a structure is defined as the sum of the initial investment cost and the management and maintenance costs during the life of the project. Within the framework of cost-benefit analyses, its calculation is based on costs without the value-added tax (taxes are transfers, and not net losses or gains). In theory, the global cost of a project is equal to the difference between:

- the global cost of the reference scenario excluding the implementation of the project. The initial cost of investment is then zero and the management and maintenance expenditures follow their « natural trend »;
- the global cost resulting from the project, namely the sum of the initial investment cost and the management and maintenance costs.

For each term of this difference, the global cost for an n-year time horizon is:

$$C_{Global} = C_0 + \sum_{i=0}^n \frac{C_i}{(1+r_i)^i}$$

With:

C_0 the initial investment cost without value-added tax ;

C_i the cost of the management and maintenance expenditures occurring in year i

r_i the discount rate in the year i . France Stratégie (2013) recommends a 2,5 % discount rate until 2070 and then a 1,5 % discount rate within the framework of risk management investments.

Note that the calculation of cumulative management and maintenance expenditures is very sensitive to the discount rates. The calculation can be completed by following the three stages described in Figure 3.

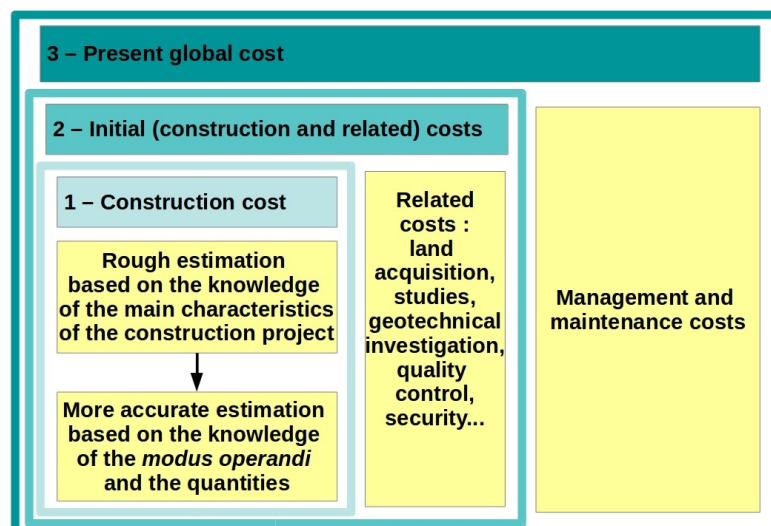


Figure 3. Calculation method of the present global cost

STUDY PROTOCOL

The handbook (Cerema 2018) contains analyses at two different spatial scales:

- the analysis on the scale of the coastal sites. This analysis gives a global vision of the composition of large investment programs and of the spending associated with the various types of projects. At this scale, it was not possible at the time of the study to collect real management and maintenance costs data and to derive annual mean values. This analysis remains however very interesting to develop knowledge on the composition of multiple coastal projects and on the corresponding initial costs. The global project cost is calculated by considering each natural feature and structure (considered in detail in the following section), and this fortunately does not reduce the operational reach of the handbook;
- the analysis at the scale of natural features and structures, extended by additional analyses at the scale of structure components or individual devices installed on natural features. Fundamentally, this part aims to classify the recorded operations and, for each operation type, to identify the information (mainly unit costs, but also life expectancy and intervention frequency), which will be necessary to calculate the global costs of protection scenarios, to compare these global costs, and to aide in decision-making.

To appreciate the extent of the estimations, this section provides insight on the study protocol which allowed obtaining the necessary data at the two spatial scales.

Analysis frames at the scale of coastal sites

To complete the first phase of observation and analysis, two strategy types were studied, which apply, separately or jointly, to coastal zones:

- strategies of shoreline management;
- strategies of protection against marine flooding.

The interventions relative to these two strategies correspond to two sets that overlap partially. Nevertheless, in coherence with the current organization of the public policies, a first estimate of linear investment costs can be acquired by this approach.

Analysis of shoreline management projects

The shoreline management projects benefited from an adapted analysis frame. In investment programs, the following expenditure types were listed:

- studies in preparatory and operational phases (environmental assessment, planning, project management, topography, safety, and protection of the health);
- land acquisitions;
- works on the various types on natural and artificial structures (distinguishing beaches, dunes, and civil engineering structures);
- road works, service connections, and buildings (for projects including a land component).

This analysis provided a better knowledge of the percentage represented by each of these expenditures in investment programs.

Analysis of the operations of protection against marine flooding

As well as for shoreline management projects, the projects of protection against marine flooding benefited from an adapted analysis frame. Besides intellectual services and land acquisitions, the following expenditure types were listed:

- levee construction, reconstruction, reinforcement and increase;
- works on seawalls and groynes, beach and dune nourishment;
- works on setback levees;
- interventions on hydraulic works (tidal gate and drying devices).

The case comparison highlights a highly variable orientation of expenditures depending on site configurations and strategies.

Analysis at the scale of natural features and civil engineering works

To extend the analysis at the scale of natural features and civil engineering works, particular attention should be paid to structure life cycles because these cycles imply different expenditure rhythms that strongly influence the calculation of present global costs.

The handbook therefore integrates the costs of diverse intervention types, which can be completed independently or jointly within the context of a larger-scale project including:

- beach nourishment, as well as hydraulic bypass systems and beach drains favoring sedimentation ;
- dune creation, rehabilitation, or maintenance ;
- levee construction, reinforcement, and maintenance ;
- civil engineering construction, reinforcement, and maintenance (seawalls, walls and supporting structures, groynes, breakwaters, abutments).

This analysis thus required crossing the typology of the natural features and civil engineering works (beaches, dunes, levees and other structures) and the typology of the interventions (construction, reconstruction, rehabilitation, reinforcement or maintenance). Estimations obtained in this part result from the analysis of construction and intellectual service contracts, and of operating and maintenance budgets.

The outcome values are mainly:

- linear costs (values estimated for the whole project or for separated structures based on investment expenditures) ;
- annual average costs (values estimated especially for levees, dunes and some beach nourishment interventions, on the basis of operating and maintenance budgets) ;
- linear, surface, volume or mass costs (values estimated for different techniques based on the total cost and the prices observed on particular interventions).

In this last case, the cost study of particular interventions, based on construction contracts, requires cautious interpretation regarding protocol and countable conventions to develop reliable estimations.

Desired values on particular interventions

Whatever the intervention type, this analysis aims at determining:

- the total cost. Based on this cost and on the length of the structure, a linear cost is determined;
- the cost of different techniques by aggregating relative prices.

In the second case, appropriate unit costs for considered techniques are wanted: cost per cubic meter of the sand, cost per ton for armourstone, cost per cubic meter of concrete, etc. Where necessary, a cost per linear meter or per square meter can be determined, in particular in the case of revetments or screens (for example for seawalls or floodwalls projects).

Countable conventions on unit costs associated to techniques

Unit costs integrate all the costs that are intrinsic to the technique, which implies certain countable conventions. For example:

- « For sheetpile, the cost takes into account the following actions: to supply, to position, to beat and to cut »;
- « For the concrete, the coffering, supply and implementation of the concrete are taken into account. In particular, for reinforced concrete, the supply, shaping of the steel, and wedging in the coffering will be added ».

For these two techniques, the determination of quantities taken into account is relatively obvious because most of the time the construction uses exclusively imported materials. But for intervention types involving the re-use of materials in the reconstruction or rehabilitation operations, calculation rules must be refined.

For example, two special cases are:

- armourstone: the cost depended initially on the quantity of imported materials, but finally it was decided that the quantity of materials integrated into the structure should instead be taken into account;
- earthwork: the cost depended more on the excavation and filling costs than on the quantity of the materials in the structure, and it was considered that the amount of earth movement should be taken into account.

OUTCOMES OBTAINED

In coherence with the progress of the study, the results obtained at the spatial scales of the site and the structure (natural feature or civil engineering work) are presented, provided that at the second scale, the analysis was completed on the cost of the various techniques.

To the extent possible, the study presents the observed costs with three values: low, average and high. In certain cases, cost ranges are large, and the factors determining the variations are studied. The knowledge of the conditions of project completion allows refining the assessment in this manner.

In the general case, the composition of the structures and its dimensions can be mentioned to explain the linear costs variations. However, it is naturally desirable to enrich the analyses with other considerations. Thus, the identification of the physical parameters influencing the costs must be led with a certain rigor to avoid biases in the analysis.

For example, the exposure of the coast to waves will influence the dimensions and the composition of structures (in particular for the protection of slopes by armourstone or other covers resistant to hydraulic actions) and thus their costs. On the other hand, it is not certain that the tidal range has, in the general case, a significant effect on the project cost:

- the implantation and the dimensions of the structures are defined with regard to the level reached by the maximum tide and not with regard to the tidal range;
- except in the case of seas with a small tidal range (for example the Mediterranean Sea) where structures can be subject to permanent hydraulic actions for several days (and not a few hours), the composition of the structures does not vary substantially in function of the tidal range height.

Although it is not possible in this paper to detail all the results obtained for every intervention type, significant results are presented concerning:

- the high and low estimations of unit costs;
- the identification of the physical parameters influencing the costs.

Some additional information is also provided relative to project life expectancy and maintenance frequency.

Results obtained on the scale of sites

At the scale of a coastal site, two determining parameters appeared during the analysis of past projects:

- the first one, situated on the sea side, was already evoked in the general case: wave exposure;
- the second one is situated on the land side: the stakes that must be protected, which represent a determining parameter for expenditures recorded at the level of global action plans.

If the value of the stakes that must be protected is high enough, an additional financial effort may be accepted to increase the dimensions of a structure and to strengthen them with facings likely to resist swell.

The study (Cerema, 2018) provides a synthesis of investment costs as a function of the coastal length for shoreline management operations and for operations protecting against marine flooding. Table 1 shows the synthesis for coastal flood protection.

Tableau 1. Linear cost (low, medium, and high) for operations of protection against marine flooding		
Exposure to waves	Stakes to protect	Linear cost HT (M€/km)
Sheltered levee system (canals, estuaries)	Mean natural and human stakes	0,5<0,6<0,7
	High natural and human stakes	0,7<0,85<1,0
Levee system exposed to wave (open waterfront)	Mean natural and human stakes	1,0<1,5<2,0
	High natural and human stakes	2,0<3,0<7,5

Results obtained at the scale of natural features and civil engineering structures

For the various intervention types affecting beaches, dunes, levees and other civil engineering works, the study (Cerema, 2018) offers a synthesis of the total costs as a function of the structure length. In addition, the surface, volume or mass costs relative to the various techniques are specified. If possible, the annual linear mean values for investment, maintenance, and management expenditures are also estimated by considering, for long durations, long structures.

The determining physical parameters can theoretically be of all kinds. In addition to the wave exposure evoked previously, the following parameters are also important:

- material quantities and equipment used (for example, for beach nourishment from the sea, the quantity of transported sand determines the dredge type, which induces strong disparities in the volume costs);
- material supply distance (earth or armourstone for levees, sand for beach or dune nourishment) and accessibility of the site;
- weather conditions, to which most of the structures are very sensitive. In the case of dunes, if the rainfall intensity is sufficient and the wind orientation is favorable relative to the available foreshore sand stock, management and maintenance costs will be nearly zero. If one of these parameters is unfavorable, the preservation of the dune may require expensive interventions;
- construction modes: according to the mode of implementation, the same material will not present the same unit cost, nor the same life expectancy. For example, concrete blocks poured without iron bars will last much longer than reinforced concrete with a beam or plate shape.

The geotechnical and morphological constraints are also very important, but these complex parameters were only taken into account implicitly in the study through the technical choices of the project manager.

To illustrate the content of the study, two examples are shown here:

- levees with facing (exposed to swell), for which table 2 synthesizes the information relative to the construction, reconstruction or repair operations;

Technique	Number of recorded operations	Linear cost (€/m)	Surface cost (€/m ²)	Volume cost (€/m ³)	Mass cost (€/t)
Earthwork and armourstone	2	2000<2500<3100 (height between 2 and 3m)	N/A	19<32<45 (earthwork)	17<21<24 (armourstone)
Armourstone and concrete superstructure	2	5600<5800<6000 (height about 8m)	N/A	N/A	29<31<33 (armourstone)
Masonry and concrete injection	2	1400<2300<3200 (height between 2 to 3,5m)	160<200<230 (masonry)	580 (concrete injection and anchors)	N/A
Earthwork and gabions	1	1500 (height about 2m)	N/A	N/A	N/A
Reinforced concrete and sheetpile	1	14300 (height about 8m)	N/A	N/A	N/A

- timber groynes, for which detailed information are given in table 3. (Large volume cost differences emerge between simple piles and assemblies.)

Technique	Volume cost (€/m ³)
Assemblies of poling boards, sheetings and walings	1700
Pile alignment	660

Life expectancy and maintenance frequency

Structure life expectancy and maintenance frequency is very important for the calculation of the global cost of a project. Based on a bibliographical study and on ground observations, values presented in table 4 are recommended for the structure types that are the most frequently used.

Tableau 4. Mean values for life expectancy and maintenance frequency		
Structure type	Life expectancy (or duration between two major repairs)	Maintenance frequency
Levees covered with grass	100 years	Annual
Concrete or rock structures	50 to 100 years	every 15 years
Sheetpile structures	50 years with cathodic protection 100 ans without cathodic protection	20 years (replacement of sacrificial anodes)
Masonry structures	100 years	5 to 10 years
Timber groynes	until 100 ans	every 15 years
Geotextile structures immersed or protected with sand	40 years	Annual (Repair of accidental tears or replacement of deteriorated elements)
Geotextile structures exposed to meteomarine conditions	15 years	Annual (Repair of accidental tears or replacement of deteriorated elements)

GENERIC LESSONS

Based on unit costs observed during past projects and on the mean life expectancy and maintenance frequency, some general conclusions can be drawn. These conclusions are supported by the contents of the last part of the study, which presents a transverse analysis of the cost of techniques used on various types of civil engineering structures or natural features. The same techniques can be used in different conditions, and comparisons are instructive. (In the same way as in the previous sections of the handbook, comparisons can be established between different techniques used for the same purpose and under equivalent conditions.)

The study suggests strongly the importance of considering systematically alternative protection modes, instead of restricting the design process solely to traditional civil engineering techniques. In the medium term, at sites where strong stakes must be protected, the combination of several techniques (traditional or alternative) can be optimal to reach performance goals while optimizing global costs. If we consider very long timescales (duration equal or superior to 100 years), alternative techniques seem more adapted to respond to the challenges posed by sea level rise and increased wave power.

Alternative protection modes to consider

To protect against coastal hazards, several technical options are generally possible, with strong disparities regarding the environmental impacts but also regarding investment, maintenance, and management costs. In every case, it is advisable to study and compare the different options and the various possible combinations, in the littoral zone (integrating at the same time the foreshore and the land situated at the back of the sea front).

To prevent erosion, the alternative solutions to the traditional techniques consist in restoring the natural balance by:

- beach nourishment and dune reconstruction;
- timber groyne implantation;
- the implantation of geotextiles filled with sand that act as a breakwater;
- the implementation of beach drainage systems.

This set of measures can also contribute to maintain a sufficient sedimentary stock, thus assuring a better response of the coast exposed to the hydraulic forces (waves and storm surge) that cause flooding.

To prevent marine flooding, and as supplementary measures to techniques limiting erosion, better control of the flow may allow avoiding the construction or increase of levees. The precise evaluation of storage capacity in « buffer zones » at the back of the sea front, and good management of levees and hydraulic structures often allows defining less expensive protection strategies.

From an economic point of view, every technical approach generates a particular expenditure rhythm. In most cases, it appears that:

- traditional techniques engender high investment costs, followed by management and maintenance costs that are irregular but also high;
- the use of natural materials (earth, sand, timber) involves, on the contrary, regular management and maintenance costs, but a lower global cost, even more so if these materials are available near the site that must be protected.

The necessity at sites with high stakes to combine approaches

There exist a wide variety of protection techniques, which can be combined, sometimes along the extent of the littoral zone. In particular, it should be noted that the height of a protection structure can be reduced when it is coupled with another structure placed seaward (breakwaters or groynes) or landward (setback levees).

One example of this strategy is the repair of the protection structures in Sangatte, illustrated in Figure 3. At this site, a civil engineering structure is associated with timber groynes. Groynes establish a first curtain that dissipates part of the wave energy and stabilizes the level of the foreshore, whereas the levee, covered with armourstone absorbs the remaining energy. This combination limits strongly wave reflection and nearshore erosion.



Figure 3. Construction site of Sangatte: implementation of armourstone on the levee (on the left) and of piles (on the right) - Source: DDTM 62

The strategies implemented recently in France show a wide range of solutions, as well as the necessity to take into account, from the beginning of the project, the structure management and maintenance costs.

To the extent possible, when developing the project strategy, it is strongly advised to consider the techniques used at nearby sites. Nevertheless currents, wave exposure, and sediment transport vary substantially depending on the site. Thus, additional investigations are necessary to ensure the relevance of a technique for a considered site.

Climate change adaptation

The study (Cerema, 2018) presents for every structure type the desired effects regarding the protection against littoral hazards and the way the effects of climate change, and more particularly sea level rise, could reduce the performance of these structures. From this point of view, a big disparity appears, with a much higher adaptation capacity of the natural features compared to civil engineering structures. Structures using natural materials and integrating natural processes generally present better resilience and lower global costs.

On long timescales, adaptation to climate change of levee systems requires good shoreline management (to increase sedimentary stocks) and adaptation of the flow management (using setback levees, retaining basins...).

CONCLUSIONS

The cost study of coastal protections (Cerema, 2018) presents, for a wide range of protection scenarios, reliable data stemming from the observation of projects undertaken in France during the last fifteen years. Completed with the cooperation of the ministry of ecology and numerous local authorities, this handbook is designed to provide assistance in cost assessment at various stages of project development.

Beyond the data necessary for the calculation of the global project cost, the handbook gives a perspective on the multiple interventions that these protection systems require. Each of the components follows its own life cycle, and the project expenditures depend of these cycles. It also provides information about the behavior of the structures in a future impacted by the effects (sea level rise, changing wave conditions) of climate change. For all of these reasons, this study can also contribute to adjust national strategies regarding the protection against littoral hazards.

Based on projects observed during the same period and in the same country, all of the estimations benefit from a certain uniformity in the economic environment, which thus enables comparisons of the cost of the various techniques or their use in various environmental conditions. The generalization of the conclusions of this study to other countries must take into account differences in context that can exist, in particular concerning public policy strategies, and more concrete issues such as the availability of materials.

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Inventory of armourstone

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Abstract. Natural armourstone is widely used for hydraulic works, both in the coastal domain and in border of rivers and torrents, especially to protect against flood and the effects of waves and currents. To meet the expectations associated with this resource, an inventory of armourstone quarries was realized on a national scale in France. This inventory informs not only about the localization of quarries but also about the quality and the availability of materials. To fully optimize this inventory in a dynamic format, the association of all actors of the sector was preferred to archival research. This partnership approach led to project deliverables that can constitute durably a shared reference. The database can indeed be updated regularly thanks to the contacts established with the professionals of quarries. The access to this database is offered to a wide public: maritime and fluvial ports, local authorities in charge of planning and managing structures that protect against flood and other hydraulic hazards. This new database was organized considering its importance on the operational plan. This led to a hierarchical organization at two levels for each quarry face: first level, a synthesis sheet brings the essential information to realize choices upstream to the operational phases. Second level, a detailed specification sheet presents the technical characteristics observed in the past on the considered face. The atlas has two information broadcasting formats: a pdf file with browsing functions and a geographical information system that allows remote request of the database. These two media have their own updating rhythms, annual for the first and continue for the second.

1 Introduction

In recent years, a number of situations exist where the knowledge of armourstone resource was insufficient. It is not uncommon that these materials with a rough appearance, which seems to be easily accessible in many landscapes, appear finally, when projects are launched, to be the main source of difficulty for the conduct of operations. Either to localise quarries that may produce armourstone or to know more precisely characteristics of materials, knowledges of project owners and project managers are often very patchy and lead in design to technical and economic choices that are not optimized. In addition contexts in which armourstone are used also require to appreciate fairly accurately their availability: the conduct of operations in crisis following a major flood and the implementation of development projects cannot tolerate such uncertainties on the condition under which materials can be delivered.

One common reason for this lack of information is that armourstones are often a by-product for quarries, the

main products being either aggregates or ornamental stones. Ordinarily, quarries operating mode is therefore turned to research specific characteristics for armourstone on well-defined periods, in response to specific requests. When answering to a tender request, two options are possible for quarries, sometimes in combination:

- operating an armourstone stock built up over time by blocks that did not fit in the manufacturing process of the main product,
- operating walls of a quarry with suitable extraction methods, in order to generate blocks that meet the criteria of desired size and integrity for the tender.

In the first case, armourstones are available relatively quickly, with the sorting and control operations. In the second case, the drilling and blasting will lengthen significantly the time required.

It was very crucial for us when we designed the database and the front-end Atlas to make sure we were taking in account the knowledge of this types of operational constraints at the scale of the quarry to manage in a better way the expectations of people in

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charge of the structure design and conducting operations, especially in an emergency context.

To produce a useful, shared and lasting Atlas in a dynamic format, the association of all the actors of the sector was preferred to an archival research. This desire to create a shared and sustainable reference founded the partnership approach adopted by Cerema and CNR (Rhône river National Company with quarries professional and the associations that represent them: UNPG (National Union of Aggregates Manufacturers) and CIGO (union of Independents Quarries from Great West) in particular.

2 Objectives of the atlas

The atlas (Figure 1) is designed to provide operational support to the optimal selection of armourstone.

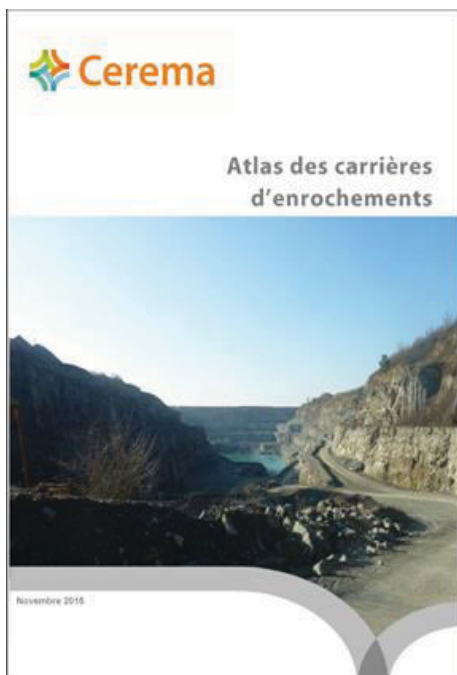


Figure 1. Cover page of armourstone quarries Atlas (Photo credit: the Lombardieres quarry Mousset (85)).

To this end, the atlas has two information levels that correspond to the preliminary study and to the project phase and the preparation of tender documents:

- first, the atlas localises armourstone quarries and it also indicates their production capacity and the potentially available stocks (based on historical data at 2 years and 10 years),
- secondly, the atlas aims at providing armourstone characteristics following criteria required by the standard specifications of NF EN 13383-1 (Table ZA.1). Nevertheless, we must be aware that these detailed specifications may vary depending on the state of operation in the quarry and therefore additional testing should generally be made on the already extracted material or on the working face before acceptance of armourstone. (this requires a quarry study to recognize the

different facies and the delimitation of areas suitable for the production of armourstone).

In addition, the atlas of armourstone quarries takes advantage of the certification process by mobilizing auditors from Cerema. Inversely, the atlas is a way to encourage the certification, insofar as the publication can highlight this certification.

3 Figures and tables

3.1 Principles

Although the State decentralized services and the Cerema already had information about most of the quarries, these data had a good "degree update" only if they dealt with the petrographic nature of rocks or their intrinsic characteristics, that vary slowly. Conversely the information on the grading and integrity of armourstone and on the availability of blocks and the production capacity was insufficient, because more dependent on the progress in working faces. To update the information more regularly, the principle adopted was to get the information directly from quarries.

3.2 Study protocol

The objectives, methodology and funding plan of the study have been defined by Cerema in collaboration with the Ministry of Environment, Energy and Sea.

Cerema (laboratory of Angers) was in charge of undertaking the data collection, defining and creating the database structure and producing deliverables.

Workers quarries unions accompanied the project with their advices on the conditions of the partnership with quarries and established contacts. In the case of independent quarries not affiliated with a union, the laboratory of Angers exchanged directly. In all cases, to obtain reliable data, the laboratory of Angers offered to quarries technical assistance by phone. Following the treatment of transmitted information and before their final integration in the database, a validation phase was organized, so that each quarry could verify and approve the publication of its own data.

Over the period 2010-2014, Cerema and its partners engaged the professionals of quarry sector in a series of seven roundtables about armourstone to give the opportunity to learn about standards and, more generally, to discuss the state of the art. These roundtables have been used to gather information from quarry operators.

The organization of these roundtables was provided by the Cerema in partnership with:

- the workers quarries unions: the UNPG (National Union of Aggregates Manufacturers), SN-Roc (National Union of Ornamental Rocks) and CIGO (of Great West Quarries Independent union),
- CNR (Rhône river National Company).

The sites selected for the organization of panel discussions (see Figure 2) were defined to cover the entire metropolitan area and address the main

armourstone use conditions (coastal areas, rivers and streams).

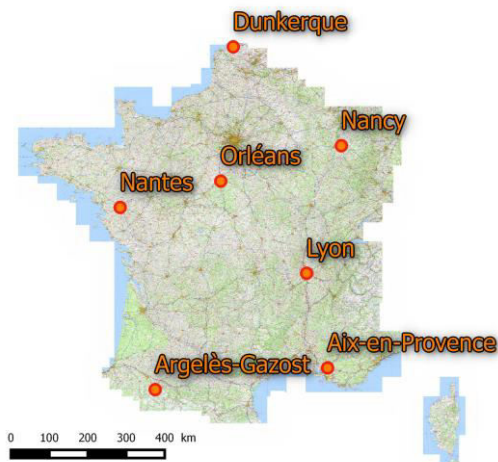


Figure 2. Location of roundtables.

The national conference on armourstone, held on October 27, 2015 in Paris (La Défense) in collaboration with the MEEM served as launch event for the armourstone quarries atlas.

4 The atlas of armourstone quarries: a permanent and lasting link between manufacturers and users of armourstones

4.1. Organization of information: key features and detailed specification

The essential characteristics have been identified and are the subject of sheets for each of the identified quarries (see Figure 3). The possibility is offered to a quarry to have several sheets if this quarry has several facies.

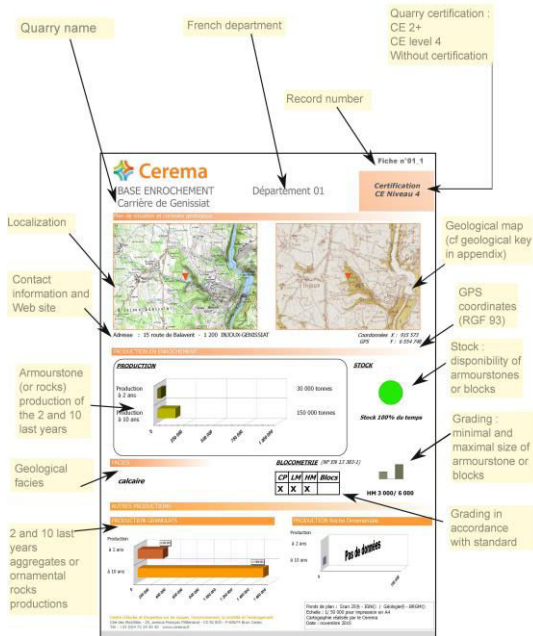


Figure 3. Example of sheet showing the essential characteristics.

Note that the production quantities of granulate or ornamental rock are indicated in the database. Indeed, these quantities give an idea of possible rock productions considering that:

- an aggregate quarry will never produce more than 20% of armourstone in tonnage compared to its production of aggregate. (This percentage may be zero in case of crushing all generated blocks.)
- an ornamental stone quarry can produce armourstone up to 10 times more than the ornamental rock quantity.

Others characteristics can be presented in detailed sheets (see Figure 4).

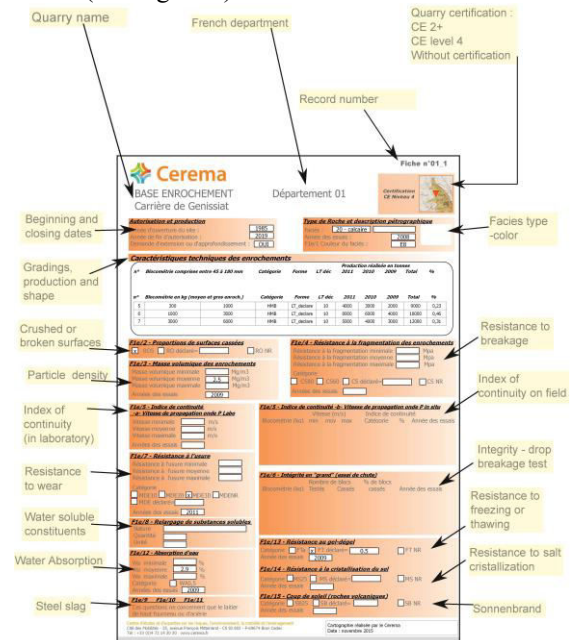


Figure 4. Example of detailed sheet.

This sheet contains characteristics required by the standard specifications (as described in the table ZA.1 of the standard EN 13 383-1):

- simple indication of the petrographic type,
- shape: length to thickness ratio,
- armourstone grading,
- particle density,
- resistance to breakage,
- resistance to attrition (for armourstone used as top layer that will be subject to abrasion due to sediment),
- percentage of crushed or broken surfaces (in the case the presence of rounded rocks could cause instability of the structure),
- water soluble constituents (if appropriate, test results should be judged according to local regulations),
- requirement associated with grouting (if clay or earth exist on the surface of armourstone that need to be sealed with bitumen or mortar),
- durability against freeze/thaw (if applicable, in areas subject to freezing),

- durability against salt crystallization (if applicable, in hot climates and in parts of structures subject to significant variations in the degree of salt water saturation),
- durability against "sonnenbrand" (in case of doubt, where signs of "sonnenbrand" are possible),
- durability against disintegration of air-cooled blastfurnace slag and steel slag (if applicable).

Note that:

- integrity is not required by standard tests (not required quantification) but essential to the sustainability of structures. To account for this parameter, the database includes sections on the index of continuity (based on the measurement of acoustic velocity) and the "great integrity" (based on the drop test),
- the color of the stones has no standardized test. However in some situations (landscape integration in classified site) this criterion can be a determining factor in the selection of armourstone. Therefore, the atlas allows quarries to describe the armourstone color.

Regardless of the data type, it is very important to make sure the date is recorded precisely. The possibility to access a datum at multiple dates is also interesting: it allows to assess the stability of the production.

4.2. The information dissemination media

The database managers decided to make two evolutionary formats coexist:

- a reference book, published periodically (presumably annually), freely downloadable and printable [1],
- a geographic information system that can be updated anytime and on which it is possible to make computing requests [2].

5 Conclusions

The atlas of armourstone quarries, through the historical view on production and stockpiles it provides and by the rapid contact with quarry operators it allows, is a tool designed to help at any time crisis or project manager in decision making:

- at the design stage (adapting the design to the actual available resources),
- in the procurement (a better knowledge of available stocks limits the award of contracts to quarries that cannot supply a sufficient amount of armoustones in compliance with specifications, a situation that constraints to search as a matter of urgency for alternative supply sites).

6 References

1. Atlas download site: <http://www.eau-mer-fleuves.cerema.fr/atlas-des-carrieres-d-enrochements-a1363.html>
2. Consultation Website of the database http://cartelie.application.developpement-durable.gouv.fr/cartelie/voir.do?carte=Carriere_Enrochement&service=CEREMA

7 Acknowledgments

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Adaptation des systèmes de protection contre les inondations côtières

Apports conceptuels et recherche de développements méthodologiques dans les contextes du changement climatique et de l'aménagement des territoires

Résumé : Les littoraux sont sujets à de multiples évolutions liées à l'aménagement des territoires et aux effets du changement climatique, évolutions susceptibles de générer un fort accroissement des risques d'inondation côtière. Cette thèse sur travaux traitant des systèmes de protection contre cet aléa comporte :

- une analyse bibliographique sur les concepts, les méthodes et les stratégies destinés à l'adaptation des systèmes de protection par le renforcement de leur résilience. Cette analyse repose sur l'hypothèse essentielle qu'un système de protection contre les inondations côtières est un système socio-écologique ;
- en relation avec l'état de l'art et dans l'objectif de le compléter, une présentation synthétique des recherches qui ont conduit à :
 - réviser le concept de système de protection contre les inondations côtières ;
 - établir un cadre méthodologique de nature à renforcer la résilience des systèmes de protection.

Mots-clés : inondations côtières, système de protection, résilience, adaptation, transformation, changement climatique, territoires littoraux, concept, méthodologie, système socio-écologique, système adaptatif complexe, cogestion adaptative, gestion durable des ressources.

Abstract: *Coastlines are subject to multiple developments related to land use planning and the effects of climate change, developments likely to generate a strong increase in the risk of coastal flooding. This PhD on published works focuses on systems to protect against this hazard, and presents:*

- *a bibliographical analysis on the concepts, methods and strategies for adapting protection systems through strengthening their resilience. This analysis is based on the essential assumption that a coastal flood protection system is a social-ecological system;*
- *in relation to the state of the art and with the aim of completing it, a summary presentation of the research that led to:*
 - *the revision of the concept of a coastal flood protection system;*
 - *the establishment of a methodological framework to strengthen the resilience of protection systems.*

Key words : *coastal flooding, protection system, resilience, adaptation, transformation, climate change, coastal territories, concept, methodology, social-ecological system, complex adaptive system, adaptive co-management, sustainable resource management.*

Thèse sur travaux préparée au sein du Cerema – Marc IGIGABEL