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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 28 February 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].

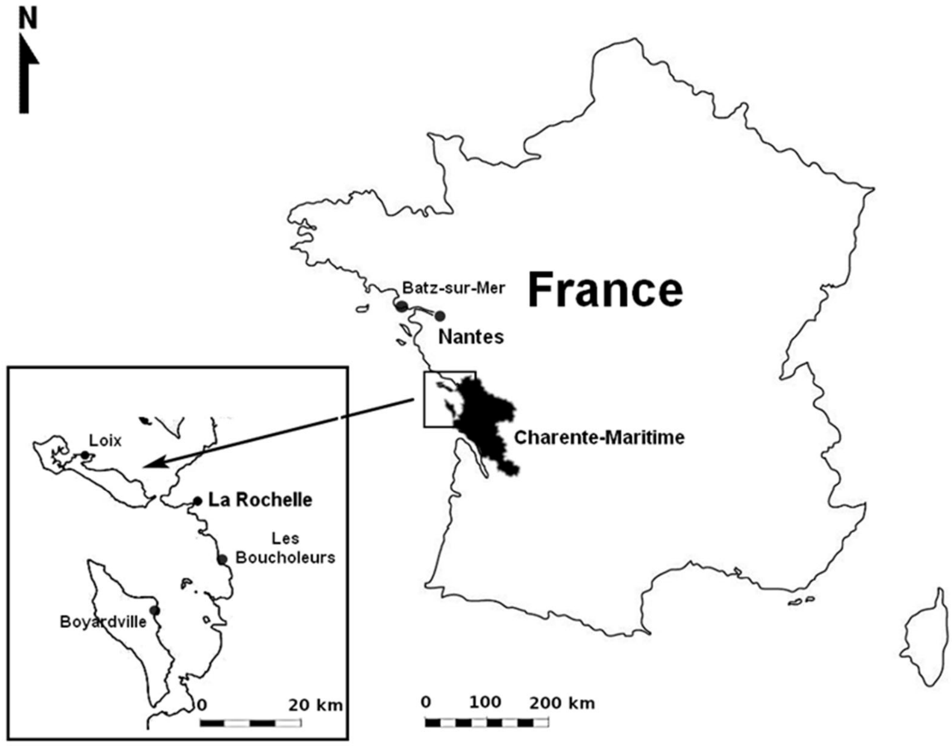


Figure 1. Locations of the four sites used to develop the methodology [48].

This article is an adaptation of an article [50] originally written in French.

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.

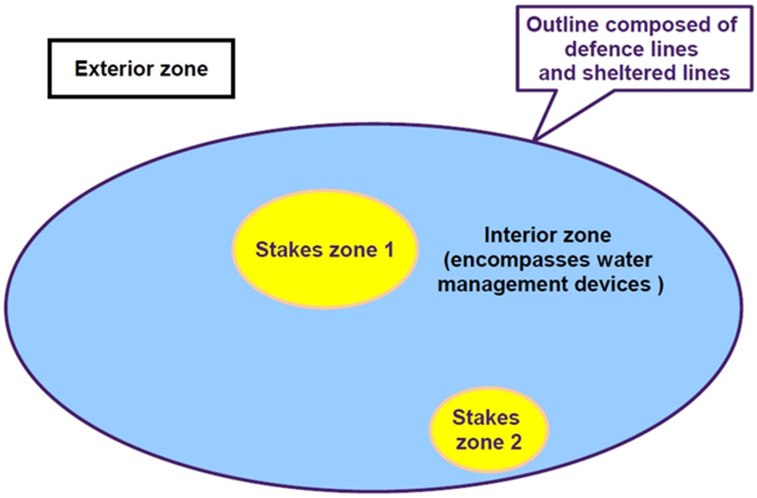


Figure 2. Demarcation of a protection system.

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.

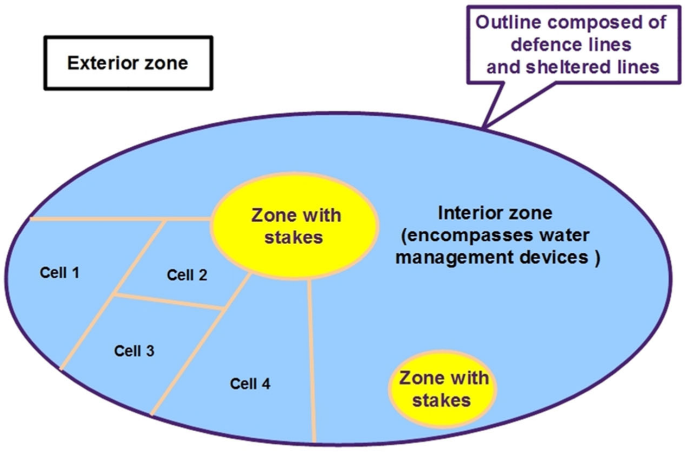


Figure 3. Schematic representation of cells within a protection system.

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.

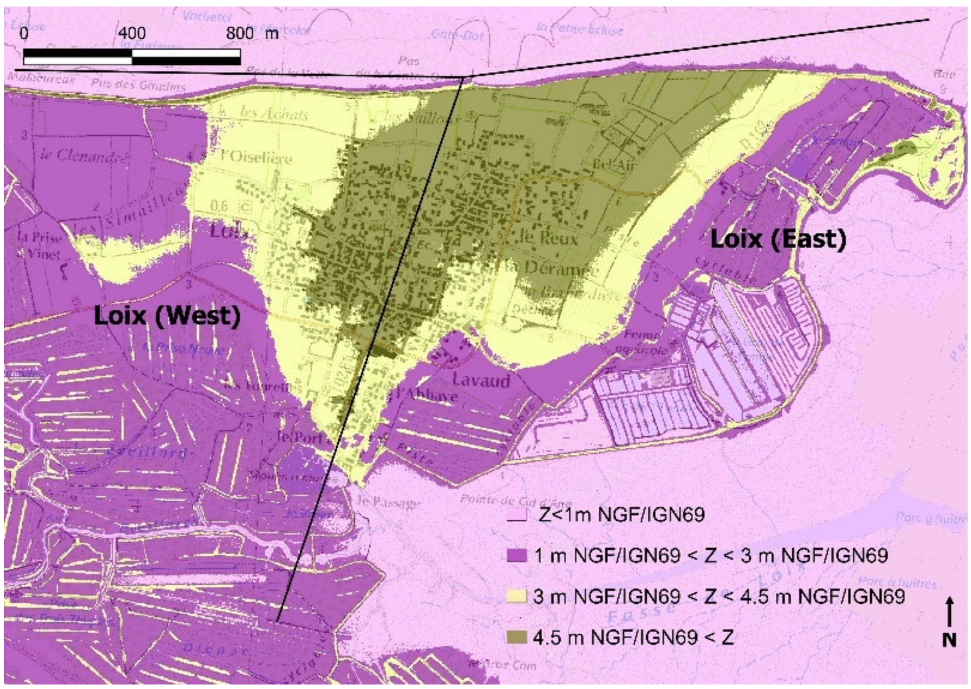


Figure 4. Synthetic topographic map. Altitudes are given using the NGF/IGN69 (French reference system).

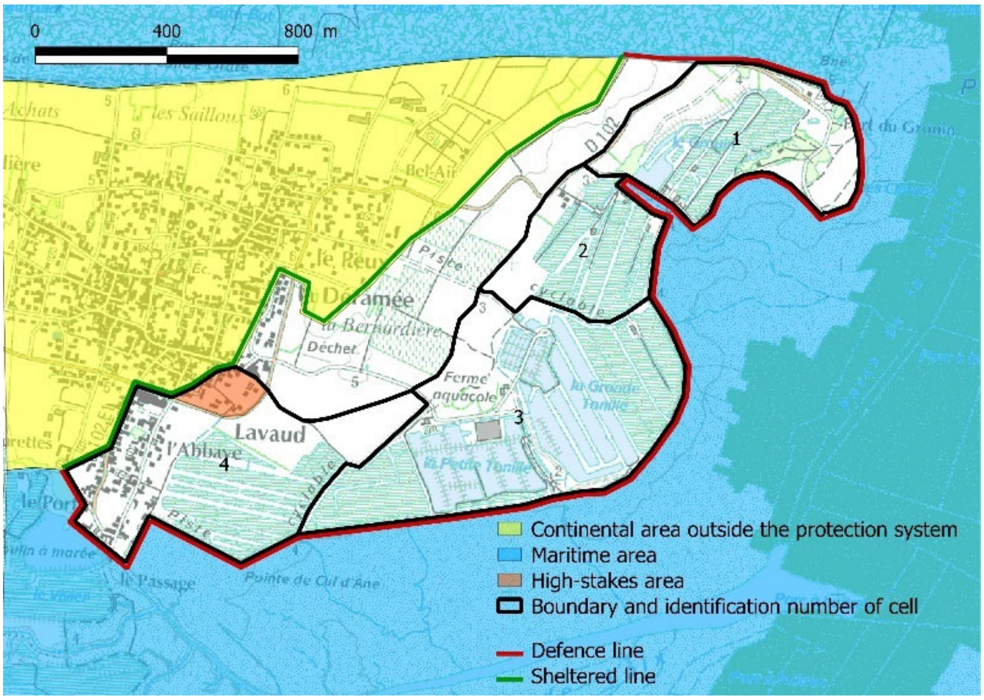


Figure 5. Schematic representation of the Loix protection system.

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.

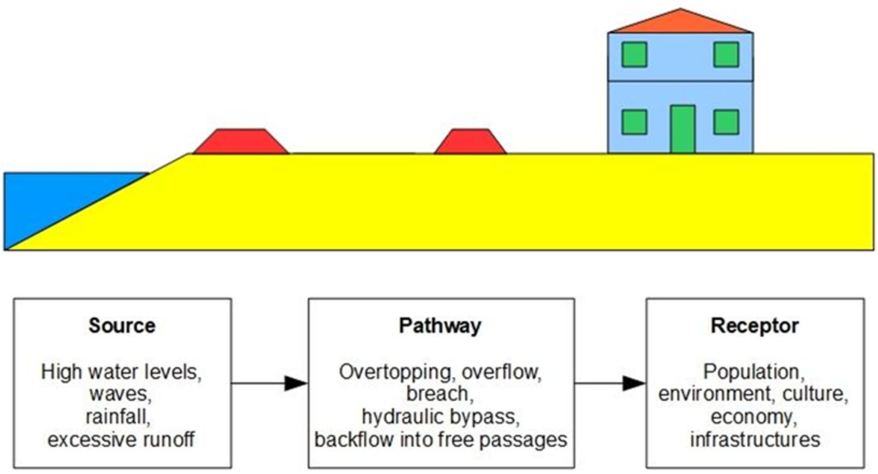


Figure 6. Representation of the SPR model.

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.

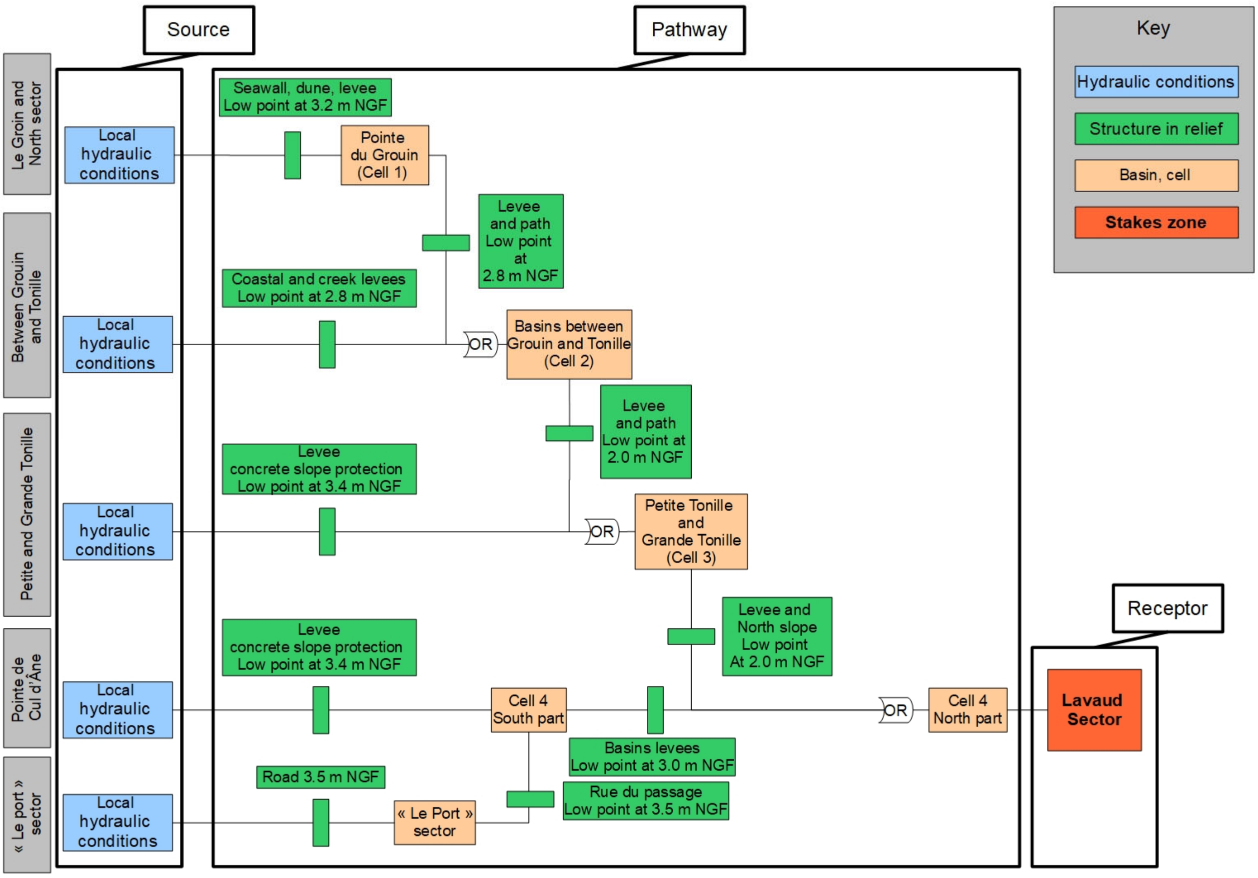


Figure 7. Synthetic flowchart of the Loix system. Altitudes are given using the NGF/IGN69 (French reference system).

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

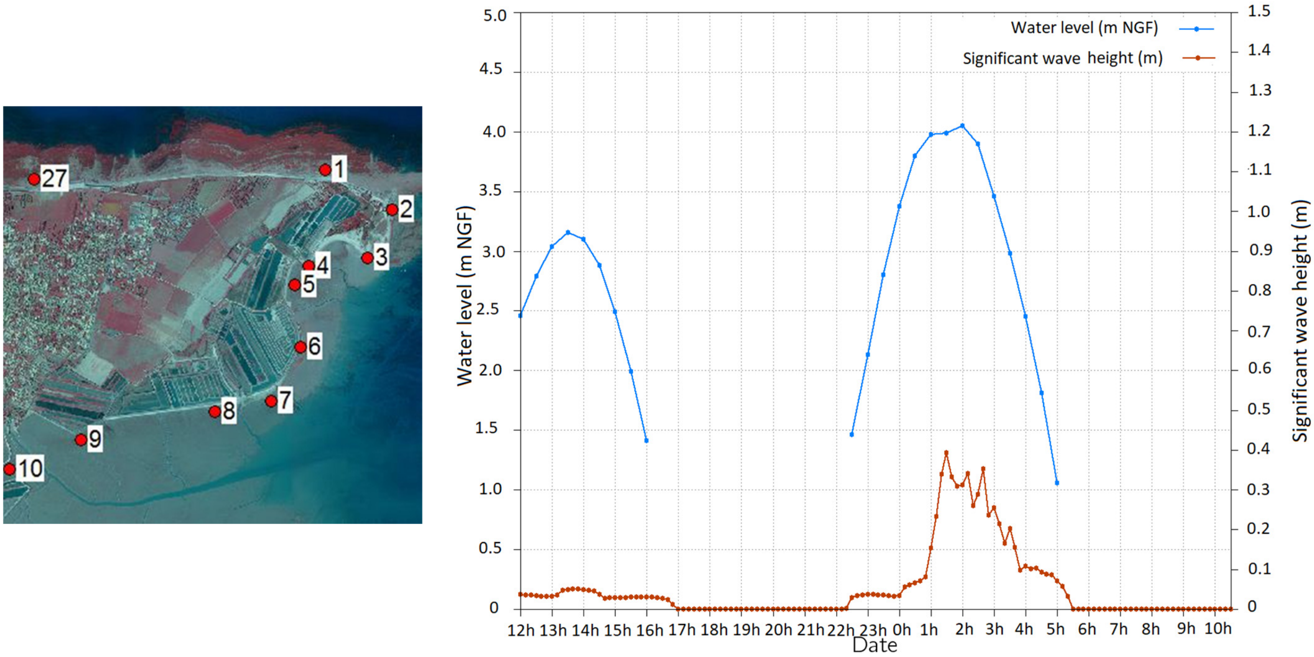
Physical phenomena that produce a flood are generally multiple and occur on wide temporal and spatial scales.

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.



(**a**) (**b**)

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).

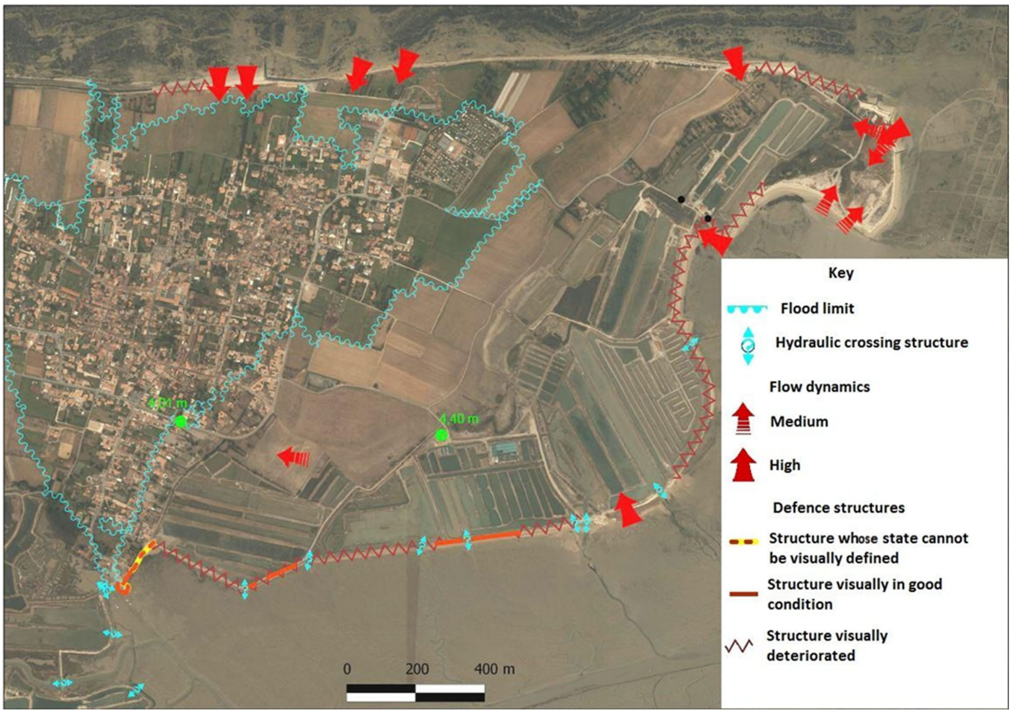
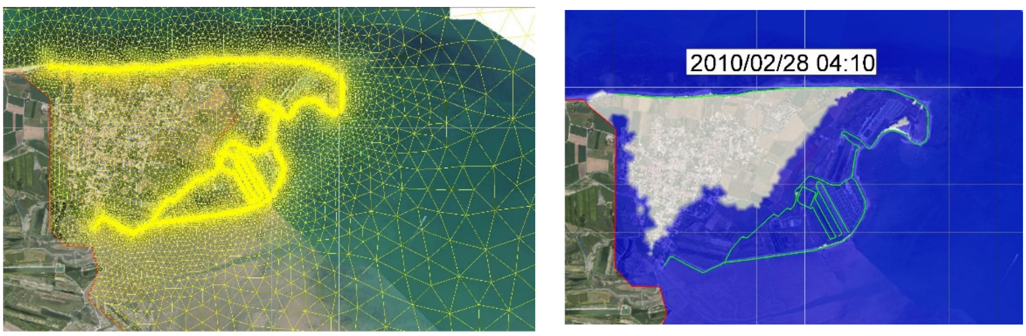


Figure 9. Synthesis map of Xynthia event.

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).



(**a**) (**b**)

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.

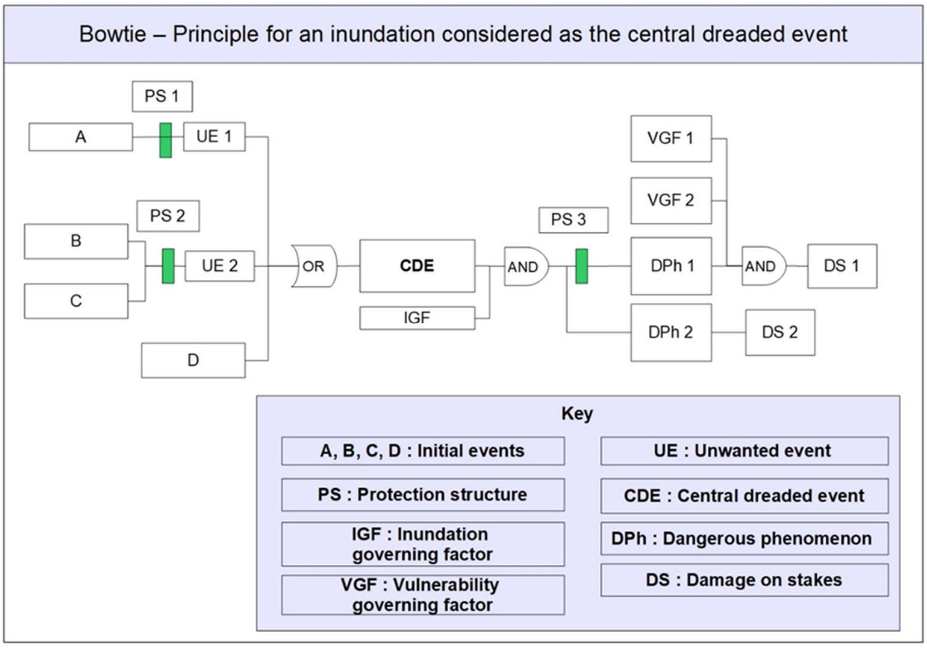


Figure 11. Generic representation of a bowtie tree.

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.

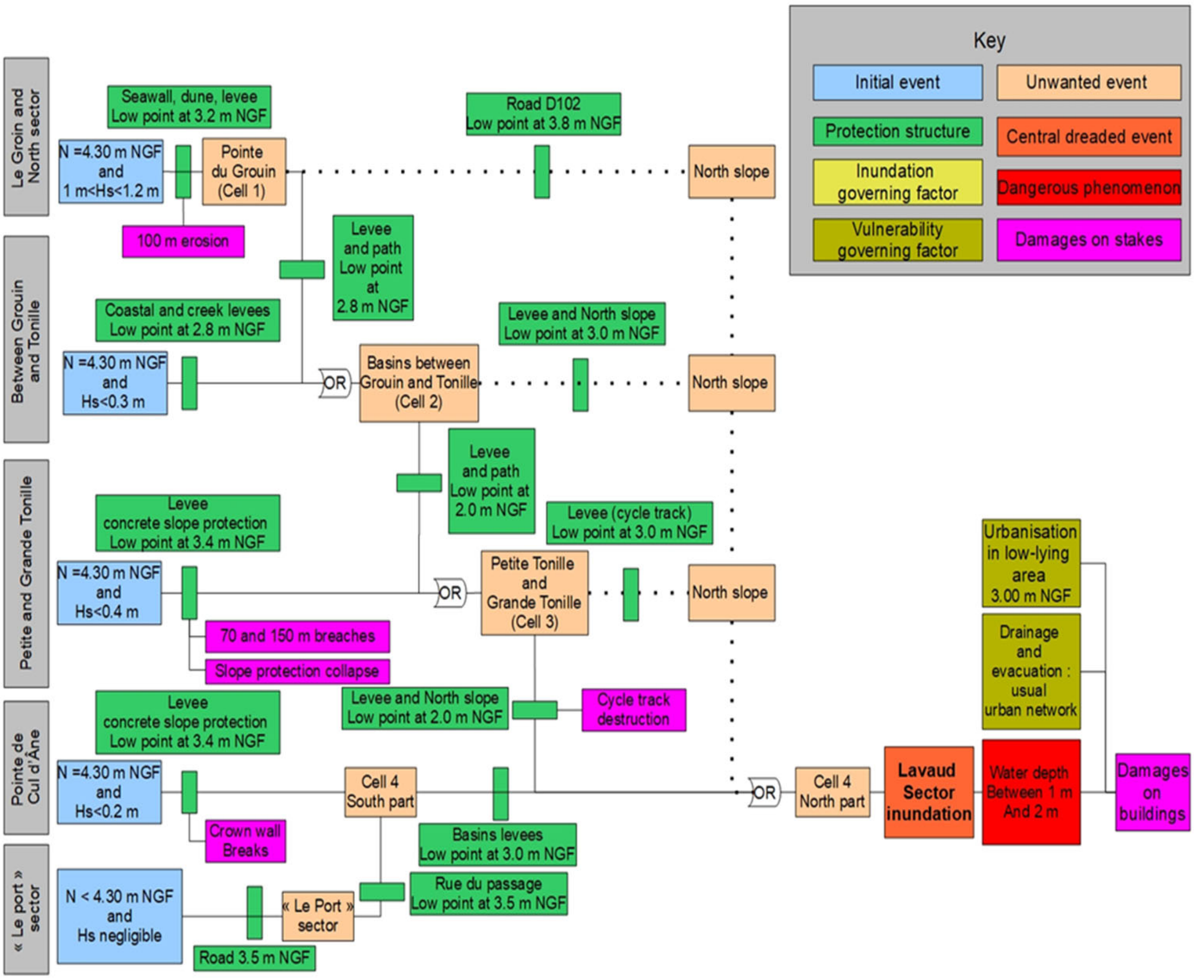


Figure 12. Bowtie tree of the Loix protection system (Xynthia feedback). Altitudes are given using the NGF/IGN69 (French reference system).

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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