Scuola Universitaria Superiore IUSS Pavia

Infrastructure for flood risk reduction: parametric cost functions for mitigation measures and correlation of risk mapping with funds distribution. The Italian case.

A Thesis Submitted in Partial Fulfilment of the Requirements
for the Degree of Doctor of Philosophy in

HYDROMETEOROLOGICAL, GEOLOGICAL, CHEMICAL

AND ENVIRONMENTAL RISK

(HYRIS CURRICULUM)

Obtained in the framework of the Doctoral Programme in

Understanding and Managing Extremes

by

Margherita D'Ayala

February, 2024

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ABSTRACT

Floods cause disastrous events worldwide, to communities, infrastructure, and the environment, leading to loss of life and substantial economic damage. Italy is no exception. One fundamental, although often debated, strategy for flood risk reduction is the construction of hydraulic defence infrastructure. In this perspective, this work addresses two main topics: the identification of a cost-function directly dependant from the geometric design parameters which provides a measure of the investments needed to reduce the flood risk in a particular territorial situation, and the actual risk reduction resulting from the implementation of the designed defence intervention, as measured through the analysis of consecutive editions of risk maps.

Regarding the first topic, traditional approaches to hydraulic design often rely on deterministic methods, historical data, and predefined design rules. However, these approaches may fall short in addressing the evolving nature of risks, especially in the context of climate change and population growth. In Italy, the current legislation requires that the design and verification of hydraulic infrastructure should be carried out for events characterized by intensities associated with a fixed return period of 200 years. The need for a change in this design approach is recognized and prescribed at European level through the 2007/60 European Flood Directive. According to it, a methodology primarily based on cost-benefit analysis (CBA) should be employed within the context of hydraulic risk to evaluate the mitigation measures to be included in Flood Risk Management Plans (PGRA). In this context, in the perspective of adopting a new approach for the design phase based on the identification of the best combination between cost for implementation and reduced risk, a cost model is proposed based on project data, wherein efforts are made to restrict the number of independent variables to a maximum of two. This aims to ascertain whether the fluctuation in the cost of a work (comprising three distinct types) can be effectively encapsulated by just two variables. Consequently, the cost function is conceptualized as a bidimensional function, illustrating the dependency of the work's cost on these two parameters.

Following the design and implementation of mitigation measures, this work analyses the correlation between defence infrastructure implementation and flood risk mapping and reduction, using two critical data sources: the first is an open-access database called ReNDiS, in which, since 1999, the Italian Istituto Superiore per la Protezione e la Ricerca Ambientale (ISPRA) has catalogued these defence measures, documenting their location,

characteristics, and costs. The EU Flood Directive (EU_FD, 2007), mandates Members States to update and map flood hazard and risk every six years. The second are the flood risk maps published by few Basin District Authorities in Italy. Hence, the study develops a multi-layered mapping tool that integrates existing hydraulic defences with flood risk maps of two successive cycles of reporting of the EU_FD. Two indicators are introduced to quantify and verify the expected risk reduction: the Risk Score and the Risk Score Variation. These are compared with the projects' associated cost. A modest correlation is identified, between mapped risk class and infrastructure's location, and also between risk reduction benefits and project costs, with a minority of cases showing effectiveness and efficiency. The study is constrained currently by the quality of risk representation in official flood risk maps and the completeness of the ReNDiS database, but it proves the relevance of the methodology, able to determine risk reduction in subsequent cycles of flood risk management, and the corresponding allocation of resources.

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CHAPTER 1 – INTRODUCTION

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Natural disasters, encompassing events such as earthquakes, hurricanes, floods, and wildfires, present a profound and persistent challenge for humanity, disrupting lives, economies, and ecosystems worldwide. These events, influenced by various geological, meteorological, and climatic factors, pose significant threats to societies and their infrastructures (Loveridge et al., 2010). With the escalation of climate change, the frequency and severity of some of these disasters are expected to increase, necessitating a deeper understanding of their mechanisms and the development of effective mitigation and adaptation strategies (Gallina et al., 2020; Olsen, 2015).

The devastating impacts of natural disasters are extensively documented. The escalating trend in the frequency and severity of disasters, as highlighted by the Intergovernmental Panel on Climate Change (H.-O. Pörtner et al., 2022), emphasizes the urgent need to comprehend the intricate interactions between natural processes, human activities, and environmental changes.

Despite significant advancements in science and technology in enhancing the performance of the built environment and urban planning, natural disasters have increasingly led to loss of life, disruption of commerce and financial networks, and the interruption of essential services over the past few decades (G. Tsionis et al., 2019).

In this study, the word *infrastructure* has a dual meaning: active and targeted structures that contribute to risk mitigation, and passive structures scattered throughout the territory that do not directly protect against risk but should be safeguarded due to their provision of essential services.

Within this overarching classification, flood protection infrastructures belong to the first group, and within them hydraulic structures including dams, barriers, levees and embankments, drainage channels, and drainage systems hold significant importance. These structures are engineered to control the flow of surface water, monitor levels of rivers and lakes, and reduce flood risks through effective water resource management. With the ongoing escalation of industrialization and the exacerbation of hydro-meteorological hazards driven by climate change, the vulnerability of technological systems to natural disaster impacts is expected to increase(G. Tsionis et al., 2019).

Furthermore, data from the Emergency Events Database (EEA, n.d.) reveals alarming statistics: between 2000 and 2014, flood events resulted in at least 85,000 fatalities, affecting approximately 1.4 billion individuals and causing around USD 400 billion in damages. This identifies flooding as the most recurrent and profoundly devastating natural calamity globally (EM-DAT, 2024), annually impacting millions worldwide, resulting in loss of life and disruption of numerous essential services. Hence, for pragmatic considerations, this study will concentrate solely on mitigation measures employed for flood risk reduction.

The second group of the above classification relates to infrastructure that is susceptible to damage from various types of hazards, aiming to withstand any event that could disrupt its services. These infrastructures are distributed across the territory and do not shield against risks, but they must be safeguarded as they provide vital services.

This broader category encompasses critical infrastructures such as the energy system, transportation network, water and wastewater facilities, ICT system, and more. These infrastructures are indispensable for society, and their protection is imperative for sustaining vital societal functions, ensuring the health, safety, and economic well-being of individuals (European Commission, 2008).

Past events have demonstrated how the partial or complete disruption of such systems can lead to severe consequences and unexpected impacts elsewhere, owing to global interconnectivity. These repercussions underscore the consequences of an increasingly globalized world, representing a topic that remains incompletely understood and inadequately studied, especially regarding the exposure of infrastructure systems to extreme natural events (Karagiannis et al., 2019). At the territorial scale, the co-location of "passive" critical infrastructure, with its distinctive physical vulnerability, and "active" flood defence infrastructure, designed to meet a given level of hazard intensity, determine the overall quantification of risk and the need for managing mitigation resources.

Furthermore, certain critical infrastructure systems may face new or heightened risks that were previously overlooked (Vamvakeridou-Lyroudia et al., 2020). With the impacts of climate change manifesting locally, individual assets may be exposed to varying degrees of hazard depending on their geographical location (Forzieri et al., 2018).

Quantifying and mitigating risk, as well as understanding how systems perform under critical conditions when subjected to various threats—whether natural or human-made—is crucial for planning resilient infrastructure systems to ensure the functioning of society.

Contemporary society relies on a highly interconnected world comprising diverse yet interconnected systems—environmental, social, economic, technical, political, cultural, and more. Many of these interconnected systems are deemed critical infrastructure, as they constitute essential networks for people's lives (Chopra & Khanna, 2015).

Since the early 21st century, numerous definitions have emerged regarding critical infrastructures (CIs). One of the seminal documents in this field, cited extensively in scientific literature such as (Batista E Silva et al (2019) and (Forzieri et al. (2018), is the European Programme for Critical Infrastructure Protection (European Commission, 2008). This program defines CI systems as those fundamental for maintaining vital societal functions, health, safety, and the economy. Notably, despite its age, this definition continues to be cited and utilized.

A few years later, in 2013, the United States issued Presidential Policy Directive 21, offering a similar definition of CI systems while also acknowledging that such systems can be virtual, underscoring their crucial role in national security (The White House, 2013).

A more recent definition was articulated in 2017 by Japan in the Cybersecurity Policy for Critical Infrastructure Protection document. Japan defines CI systems as "The backbone of national life and economic activities formed by businesses providing services that are extremely difficult to be substituted. If the function of the services is suspended, deteriorates, or becomes unavailable, it could have a significant impact on national life and economic activities" (Government of Japan, 2017).

In essence, all these definitions highlight the significance of CI systems in delivering essential services to society. The disruption or destruction of these systems would have catastrophic consequences for both physical and intangible assets, as well as production systems and networks.

The table below compiles in chronological order, various definitions provided by national authorities and international bodies.

Table 3 Definitions of Critical Infrastructure from several Country or International bodies

Nation or international body	**Reference**	**Year**	**Definition**	**Peculiarity**
OECD Organization for Economic Cooperation and Development	Protection of Critical Infrastructure and the Role of Investment Policies Relating to National Security May 2008 OECD/LEGAL/036	2008	The term “critical” refers to infrastructure that provides an essential support for economic and social well-being, for public safety and for the functioning of key government responsibilities, such that disruption or destruction of the infrastructure would result in catastrophic and far-reaching damage. National definitions of “infrastructure” refer to physical infrastructure and often also intangible assets and/or to production or communications networks. These definitions are very broad, certainly broader than the notion of infrastructure commonly used in other fields of policy (e.g. the “essential facility” notion in competition law) and end up including not only the tangible assets, but also the intangibles that run with them (e.g. software, services, etc.).	intangible assets and production networks
GERMANY	National Strategy for Critical Infrastructure	2009	Critical infrastructures are organizational and physical structures and facilities of such vital importance to a nation’s society and economy that their failure or degradation would result in sustained	Organizational and physical structures

	Protection (CIP Strategy)		supply shortages, significant disruption of public safety and security, or other dramatic consequences.	
EU	European Programme for Critical Infrastructure protection	2011	Asset, system or a part of it located in Member States which is essential for the maintenance of vital societal functions, health, safety, economic or social well-being of people	Vital societal functions
USA	CISA Cibersecurity and Infrastructures security agency)		Critical infrastructure describes the physical and cyber systems and assets that are so vital to the United States that their incapacity or destruction would have a debilitating impact on our physical or economic security or public health or safety. The Nation's critical infrastructure provides the essential services that underpin American society.	Cyber assets – Security of the nation
USA	Presidential Policy Directive 21 (PPD-21)	2013	The term "critical infrastructure" has the meaning provided in section 1016(e) of the USA Patriot Act of 2001 (42 U.S.C. 5195c(e)), namely systems and assets, whether physical or virtual, so vital to the United States that the incapacity or destruction of such systems and assets would have a debilitating impact on security, national economic security, national public health or safety, or any combination of those matters.	Virtual assets
JAPAN	Cybersecurity Policy for Critical Infrastructure Protection	2017	The backbone of national life and economic activities formed by businesses providing services that are extremely difficult to be substituted; If the function of the services is suspended, deteriorates or becomes unavailable, it could have a significant impact on the national life and economic activities.	Economic activities
AUSTRALIA		2017	'those physical facilities, supply chains, information technologies and communication networks which, if destroyed, degraded or rendered unavailable for an extended period, would significantly impact the social or economic well-being of the nation or affect Australia's ability to conduct national defence and ensure national security'.	Damaged for an extended period – defence and national security
CHINA	Regulations on the Security and Protection of Critical Information Infrastructure	2021	Essential network facilities and information systems used in industries such as public communication, information services, energy, transportation, water conservancy, finance, public services, e-government, national defense science and technology, as well as other industries that would seriously endanger national security and public interests if their data was leaked or the systems get	National security and public interests – leaking of data

			damaged. Critical information infrastructure is the central nervous system of economic and social operations, and it is the top priority of network security	

Each nation's approach to defining critical infrastructure is intricately intertwined with its geopolitical context, economic priorities, and perceived security threats. Despite the diversity in how nations define critical infrastructure, there is a universal acknowledgment of the imperative to safeguard essential systems and assets. This shared recognition stems from the understanding that disruptions to critical infrastructure can have far-reaching consequences, jeopardizing not only national security but also public safety, economic stability, and societal well-being. As such, nations collaborate through international forums, information-sharing mechanisms, and joint initiatives to strengthen the resilience of critical infrastructure and mitigate common threats. This collaborative approach underscores a fundamental commitment to upholding national resilience and security in an increasingly interconnected and volatile world.

After providing a global overview of critical infrastructure definitions, shifting focus to the European context is paramount. At the European level, guidelines for identifying and managing critical infrastructures are enshrined in the European Programme for Critical Infrastructure Protection, established by the European Council through Council Directive 2008/114/EC of 8 December in Brussels. This program aims to identify and designate European Critical Infrastructures (ECIs) and mandates the adoption of countermeasures to enhance their protection, thereby contributing to safeguarding people from man-made, technological threats, natural disasters, and terrorism (Article 1).

Critical infrastructures (CI) are defined as assets or systems essential for maintaining vital societal functions, health, safety, economic or social well-being of people, located within Member States. An infrastructure is deemed European CI if its disruption or destruction significantly impacts at least two Member States. CI primarily encompass the energy, transport, and ICT sectors, including electricity, oil, gas, road, rail, air, inland waterways transports, ocean and short-sea shipping, and ports.

The steps for identifying, designating, and protecting ECIs involve:

- Identification of potential ECIs based on sectoral and cross-cutting criteria.
- Designation of ECIs.
- Development of Operator Security Plans, encompassing asset identification, risk assessment, and selection and prioritization of countermeasures and procedures. This involves:

o Identifying important assets.

o Conducting risk analysis considering major threat scenarios, asset vulnerability, and potential impact.

o Selecting and prioritizing countermeasures and procedures, categorized into Permanent Security Measures (employed at all times) and Graduated Security Measures (activated based on varying risk and threat levels).

o Reporting generic data on risk, threat, and vulnerability for each sector to the Commission biennially.

It is worth noting that there is no standardized method in the literature for conducting impact analysis as defined in the European directive, and this issue is not addressed within the directive itself.

Similar to the definition of CI, their classification is subject to ongoing evolution, with more sectors being included. The following table present sectors considered CI by international bodies, countries, and scientific papers.

Table 2 contains the findings derived from the authors' investigation, delineating the critical infrastructural crucial for diverse States. It furnishes a nuanced portrayal of each region's distinctive priorities and imperative developmental needs, thus enriching our understanding of infrastructure planning and management on a global scale.

Table 4 Type of infrastructure considered as critical for several countries.

Type of CI	**EU**	**USA**	**JAPAN**	**UK**	**AUSTRALIA**	**GERMANY**
Energy	X	X	X	X	X	X
Transport	X	X	X	X	X	X
ICT sectors	X	X	X	X	X	X
Finance	X	X	X	X	X	X
Water and Wastewater	X	X	X	X	X	X
Health	X	X	X	X	X	X
Food and Agriculture	X	X		X	X	X
Chemical Services	X	X	X	X		
Defense Industrial Base	X	X		X	X	
Administration services for government		X	X	X		X
Emergency Services		X	X	X		

Nuclear Reactors, Materials, and Waste		X		X		
Logistics			X			
Commercial Facilities		X				
Critical Manufacturing		X				
Dams		X				
Data storage and processing					X	
Higher education and research					X	
Space technology					X	
Credit and services			X			
Media and Culture						X

The recognition of water and wastewater systems as critical infrastructure is directly intertwined with efforts to secure watercourses and mitigate flood risks. Ensuring the resilience of these systems not only safeguards public health and environmental integrity but also plays a pivotal role in enhancing overall community resilience to flooding and water-related disasters. By investing in the protection and sustainable management of water resources, including rivers and streams, societies can effectively reduce vulnerability to flooding, bolstering their capacity to withstand and recover from adverse events. Thus, addressing the criticality of water and wastewater infrastructure is inseparable from comprehensive strategies aimed at mitigating flood risks and promoting sustainable water management practices.

In this study, the focus lies on the analysis of the first category of infrastructure, which actively contributes to the protection of both assets and individuals from flood hazard. Accordingly, analyses primarily centre on flood defence hydraulic structures. Nonetheless, the objective is to extend investigations in the future to encompass the second category of infrastructure, which requires safeguarding due to its critical role in ensuring the sustaining vital societal functions, the health, safety, and economic well-being of individuals.

One fundamental, although often debated, strategy for flood risk reduction is the construction of hydraulic defence infrastructure. In this perspective, this work addresses two main topics: approaches utilized in the hydraulic design phase, and the actual risk reduction resulting from the implementation of the designed defence measures.

Regarding the first topic, traditional approaches to hydraulic design often rely on deterministic methods, historical data, and predefined design rules. However, these approaches may fall short in addressing the evolving nature of risks, especially in the context of climate change and population growth. In Italy, the current legislation requires that the design and verification of hydraulic infrastructure should be carried out for events characterized by intensities associated with a fixed return period of 200 years. The need for a change in this design approach is recognized and prescribed at European level through the 2007/60 European Flood Directive. According to it, a methodology primarily based on cost-benefit analysis (CBA) should be employed within the context of hydraulic risk to evaluate the mitigation measures to be included in Flood Risk Management Plans (PGRA). In this context, in the perspective of adopting a new approach for the design phase based on the identification of the best combination between cost for implementation and reduced risk, a cost model is proposed based on project data, wherein efforts are made to restrict the number of independent variables to a maximum of two. This aims to ascertain whether the fluctuation in the cost of a work (comprising three distinct types) can be effectively encapsulated by just two variables. Consequently, the cost function is conceptualized as a bidimensional function, illustrating the dependency of the work's cost on these two parameters.

Following the design and implementation of mitigation measures, this work analyses the correlation between defence infrastructure implementation and flood risk mapping and reduction, using two critical data sources: the first is an open-access database called ReNDiS, in which, since 1999, the Italian Istituto Superiore per la Protezione e la Ricerca Ambientale (ISPRA) has catalogued these defence measures, documenting their location, characteristics, and costs. The EU Flood Directive (EU_FD, 2007), mandates Members States to update and map flood hazard and risk every six years. The second are the flood risk maps published by few Basin District Authorities in Italy. Hence, the study develops a multi-layered mapping tool that integrates existing hydraulic defences with flood risk maps of two successive cycles of reporting of the EU_FD. Two indicators are introduced to quantify and verify the expected risk reduction: the *Risk Score* and the *Risk Score Variation*, and they are compared with the projects’ associated cost.

Summarizing, the structure of this thesis in organized as follows: besides this introductory chapter, Chapter 2 focuses on the necessary overcoming of the traditional approaches to hydraulic design, aiming at adopt a new approach for the design phase based on the identification of the best combination between cost for implementation and reduced risk, a cost model is proposed based on project data, wherein efforts are made to restrict the number of independent variables to a maximum of two. Chapter 3 includes a scientific article submitted to the International Journal of Disaster Risk Reduction, which is currently under review, and it is devoted to the analysis of efficiency and effectiveness of hydraulic mitigation defences applied for flood risk reduction, using flood risk maps published by basin district authorities in Italy and an open-source database which collects flood risk reduction projects implemented from 1999 to date.

Each Chapter is structured as independent: each of them has an introduction section that provides an overview of the research topic, its significance, outlines the structure of the document, and include also the literature review which critically examines existing theoretical frameworks relevant to the research topic, identifying gaps and establishing the context for the study. Then, the methodology chapter details the research design, data collection methods, and analytical techniques employed in the study, ensuring transparency and replicability of the research process. Later, in the results section, findings from data analysis are presented systematically, supported by tables, figures, or textual descriptions to illustrate key trends, patterns, and relationships uncovered during the investigation. The discussion and conclusion section interprets the results in light of the research questions, synthesizing findings with existing literature, and exploring implications for theory, practice, and future research directions and exploration in the field.

The fourth and final chapter will serve as the conclusion, offering a comprehensive summary of the research and suggestions for future investigations.

CHAPTER 2 – THE ESTIMATION OF COST FUNCTIONS FOR FLOOD RISK MITIGATION MEASURES IMPLEMENTATION

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The estimation of cost functions for flood risk mitigation measures implementation

Abstract: Floods pose significant threats to communities, infrastructure, and the environment, making it essential to adopt a proactive and strategic approach in designing protective measures. Traditional approaches to hydraulic design often rely on deterministic methods, historical data, and predefined design rules. However, these approaches may fall short in addressing the evolving nature of risks, especially in the context of climate change and population growth. In Italy, the current legislation requires that the design and verification of hydraulic infrastructure should be carried out for events characterized by intensities associated with a fixed return period of 200 years. The need for this change in design approach is recognized and prescribed at European level through the 2007/60 European Flood Directive. According to it, a methodology primarily based on cost-benefit analysis (CBA) should be employed within the context of hydraulic risk to evaluate the mitigation measures to be included in Flood Risk Management Plans (PGRA). In this context, in the perspective of adopting a new approach for the design phase based on the identification of the best combination between cost for implementation and reduced risk, a cost model is proposed based on project data, wherein efforts are made to restrict the number of independent variables to a maximum of two. This aims to ascertain whether the fluctuation in the cost of a work (comprising three distinct types) can be effectively encapsulated by just two variables. Consequently, the cost function is conceptualized as a bidimensional function, illustrating the dependency of the work's cost on these two parameters.

1. INTRODUCTION

According to the EM-DAT database floods stand out as the most prevalent natural hazard, constituting almost 40% of all disastrous events caused by natural hazards, recorded in the period between 1998 and 2023 (EM-DAT, 2024). Over the past half-century, the frequency of flood events has markedly escalated, resulting in substantial infrastructural damage and population displacement particularly in fast developing urban contexts where environmental changes occur at a rapid pace (Rana et al., 2021). According to a recent study by the World Bank (Rentschler et al., 2022) 1.81 billion people (23% of world population) are directly exposed to 1-in-100-year floods. The majority of this population resides in low to middle income countries where drainage and flood protection infrastructures tend to be less developed.

However recent flooding events in some of the world's wealthiest and most technologically advanced countries, in the United States (Wing et al., 2022) and in central Europe (Mohr et al., 2023) have underscored the vulnerability and exposure to floods, despite significant investments in flood protection infrastructure, innovation in forecasting, and in preparedness motivated by previous inundations (Cornwall, 2021). The destruction and casualties caused by these events serve as a reminder of the ongoing challenges posed by climate change in even the most developed regions.

Considering also the inherent complexities and uncertainties surrounding flood events, which are influenced by several factors, including climate change (François et al., 2019), land use patterns (Barredo & Engelen, 2010) hydrological variability, and socio-economic dynamics (Ghimire et al., 2015), it is evident that there is a pressing need to improve the criteria for flood risk assessment and its subsequent mitigation and management. All these factors have triggered new discussions on a paradigm shift in the management of floods (Vitale, 2023).

In general, flood risk mitigation can be accomplished by implementing measures to reduce the probability of floods (hazard reduction), enhancing community coping capacity to limit the consequences of flooding events (vulnerability reduction), and restricting occupation of floodplains (exposure reduction) (De Moel et al., 2009; Oosterberg et al., 2005). However, until recently diachronic studies of exposure, considering historic and projected land use models, have been substantially overlooked in strategic planning for flood risk mitigation (Barredo & Engelen, 2010).

Flood risk policies have traditionally prioritized reducing flood probabilities (hazard reduction) through the construction of flood control infrastructure (Vitale et al., 2020). Poorly managed urban development and occupation of floodplains have worsened exposure and vulnerability to floods. Consequently, more recently, efforts have been made to diversify flood risk management strategies and transition towards a risk-based approach (Vitale & Meijerink, 2021).

Traditional methods for flood infrastructure design often rely on deterministic approaches that may not adequately account for the full spectrum of risks posed by floods. The conventional approach used in designing flood risk mitigation measures, is based on the expected peak discharge associated to a given return period of the critical event, which determines the magnitude of the design parameter, while the level of protection (LP) will determine the sizing of the hydraulic structures and their associated costs, ensuring their effectiveness of protection if the critical event occurs (Olsen, 2006; Read & Vogel, 2015). Indeed, in the context of levees design, for example, when evaluating flood-prone areas, it is common practice to consider the scenario of a flood event with medium probability for the definition of the levee' height. Specifically, for the main watercourses, this corresponds to an event intensity with a return period of 200 years (ADBPO, 2016).

Modern flood risk management advocates a paradigm shift from the standards-based approach, which primarily focuses on 'the severity of the load that a particular flood defence is expected to withstand,' to the risk-based approach (Lund, 2002). This alternative methodology aims to comprehensively address both the probability and consequences of floods. By doing so, it offers a more proactive and holistic strategy for effectively managing flood risks in contemporary settings (Sayers et al., 2002; Stakhiv, 2011).

Point 3 of Article 7 of the 2007/60 European Directive (European Union, 2007) require that a methodology primarily based on cost-benefit analysis (CBA) should be employed within the context of hydraulic risk to evaluate the mitigation measures to be included in Flood Risk Management Plans (PGRA).

Assessment of the effectiveness of mitigation measures in avoiding damage and losses and therefore the benefit they bring to the communities they shelter, is usually carried out on the basis of empirical and anecdotal evidence but there are very few systematic studies and methodologies devoted to develop cost benefit analysis tools (Arrighi et al., 2018; Poussin J.K. et al., 2015) to assess the worth of hydraulic defences. This is due to the need to collect extensive data at the individual building level, to determine their vulnerability, insurance records to characterise losses, several high-resolution hydraulic modelling to determine the hazards parameters in the unmitigated and mitigated scenarios, etc. The outcome of such studies is highly dependent on the damage functions, which in turn are highly affected by both vulnerability models for the exposed goods and recovery and replacement costs (Albano et al., 2018), so that loss estimates can fluctuate by as much as one order of magnitude, therefore substantially affecting any cost benefit analysis (Paulik et al., 2023, 2024).

On the other hand, researchers have concentrated on developing risk-based design frameworks rather than hazard probability-based ones. For instance, (Johnson et al., 2022) introduce a procedure for calculating optimal risk informed design heights for levees, based on minimizing at the same time the total system cost and the expected flood losses over 50 years, considering various climate change projections. Applying it to a real case, they show that the procedure delivers significant reductions in residual risk and in cost of the mitigation works. Similarly, Hosseinzadeh et al. (2023) propose a decision-making procedure for the optimal location and sizing of detention ponds as part of urban drainage systems, based on trade-off between cost of the ponds and reduction of the residual risk and economic losses. The pond design is based on few geometric variables, while the multi-criteria decision-making routine identifies optimal solutions based on several sustainability criteria comprising economic, environmental, physiographic and social factors. These studies however are still very few and they do not address the issue of a general framework applicable across different hydrological basins, for diverse mitigation measures, and up to national level.

A risk-based approach emphasizes the importance of considering not only the probability of flooding and its intensity, but also the potential consequences of such event, hence providing a more robust framework for decision-making and infrastructure planning. This shift in perspective encourages stakeholders to prioritize actions that minimize the overall risk, rather than simply focusing on preventing flooding events themselves. In doing so, resources can be allocated more efficiently, maximizing the effectiveness of flood risk mitigation measures.

Within this general framework, a first essential step is to identify and define function for the evaluation of the cost associated to the implementation of diverse typologies of mitigation measures.

Hence this study proposes a generalised approach that allows to use simplified correlations between design variable and mitigation work costs for a number of different mitigations categories. This then allows at the stage of mitigation planning to consider several design alternatives and their cost and evaluate their area of influence and therefore their loss prevention effectiveness. This represents a first step toward the identification of design solutions that strike an optimal balance between intervention costs and the benefits derived from reducing damage caused by flood events.

2. METHODOLOGY AND MATERIALS

As previously stated, the objective of this research is to determine parametrised functions able to easily compute the costs associated with implementing flood risk mitigation measures at an early stage of design. Given the critical importance of mitigating flood risks, understanding the associated costs is paramount for effective planning and decision-making. The first step in this process is the selection of the most commonly used and engineering-relevant mitigation measures at national level, across several Basin District Authorities. Subsequently, efforts were directed towards identifying independent parameters suitable for formulating cost functions, with a direct alignment to the concept of protection level. This meticulous approach ensures that the cost estimations generated are robust and reflective of the diverse factors influencing flood risk mitigation efforts.

In this section, the methodology and materials employed to conduct this study are outlined, providing a comprehensive overview of the procedures, data collection methods, and analytical techniques utilized to address the research objectives.

2.1 METHODOLOGY

The methodology section is dedicated to elucidating the systematic framework employed, as illustrated in Figure 1. In this study, the investigation involved a comprehensive approach, integrating and merging different data sources in order to identify key parameters which are directly related with the cost, and define cost-functions through a regression analysis for the implementation of three types of flood risk mitigation measures.

Firstly, an open-source database called ReNDiS (*National Database of the Soil Defence Interventions*) was consulted to obtain detailed information on Italian projects for hydrological risk mitigation. The consultation highlighted that records were not equally complete for many entries, and therefore the authors proceeded with a thorough integration assigning the correct mitigation measures class to component of projects that were missing. This allowed to consider 2181 mitigation measure for all the Basin Authorities on the Italian territory, which included engineering hydraulic work such as levees and embankments, river flow section adjustments and control storage areas, which are among the most commonly used interventions to mitigate flood risk at national level. Because ReNDiS has not a detailed breakdown of the cost associated to each component of a project, only a subset of the sample above could be used to carry out a first statistical analysis of cost correlation. For this sample of 200 projects, which have only one class of works, corresponding to the ones of interest, cost range and average cost were determined. This approach allowed to associate the project's funding with that specific hydraulic construction, even though the exact funding allocation for the construction phase remains undisclosed, not having a detailed breakdown of costs available.

However, these results could not directly be used to obtain parametric functions correlating cost and dimensions, as the latter are not recorded in ReNDiS, as well as hydrological parameters such as the design return period and level of protection. To overcome these limitations, and to collect detailed information on the individual cost categories that contribute to the final cost of a project work, an internet search has identified approximately fifty projects available on the Regional Authorities' website (referred to in the following as *Regional Authorities projects sample),* which included general report and information on hydraulic and hydrological characteristics, estimated metric calculation, and cost breakdown, to different degree of detail. Hence, an in-depth analysis of the content of the reports, led to the selection of three projects regarding levees and embankments, four project on control storage works, and three projects for river flow section adjustment, as these were the only projects that had all the reports and necessary information for the analysis conducted in this study.

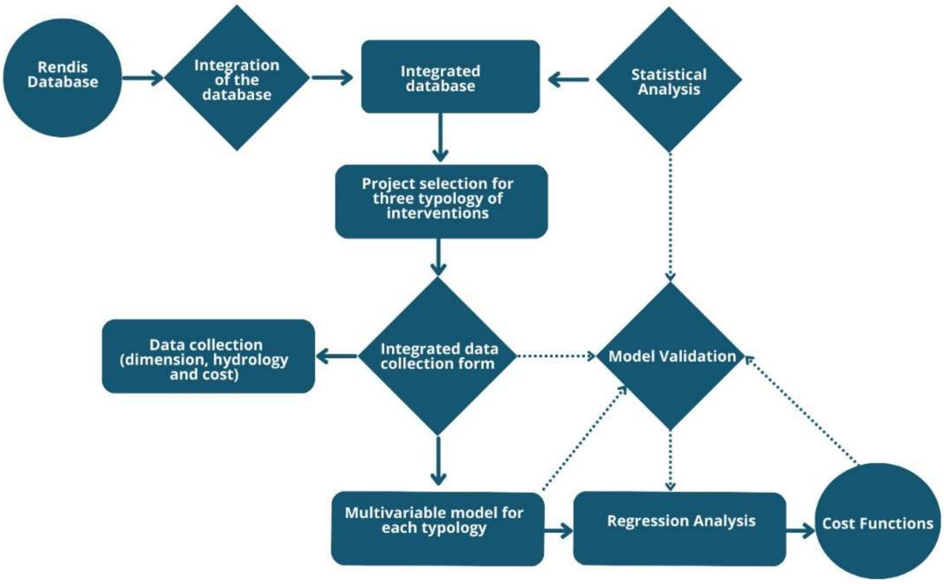

Figure 1 Methodology Flowchart

The information collected during the analysis of these Italian projects, from the project reports, do not all have the same format and therefore it was necessary to identify and interpret the different sources of information. Therefore, they were organized in a datasheet common to the three classes of work, illustrated in Table 1. The first column of the datasheet indicates for which typology of mitigation measure each entry is relevant, and on this basis, an embedded routine automatically selects the cost items contributing to the calculation of the total project cost.

Table 1 Individual Project datasheet. It includes data collected from the general report, the hydraulic and hydrological characteristics report, the bill of quantities report, and the cost breakdown report.

	Typology of mitigation measure	Code			
	Levee and Embankment	L			
	Detention basin	D			
	River flow section adjustment	R			
	Performance Parameter	Symbol	Unit	Quantity	
	Level of protection	LP	years		
	Independent variable	Symbol	Unit	Quantity	
R	Width	W	m		
L, R	Length	L	m		
D, L	Height	H	m		
D	Storage volume	V	m^3		
	Fixed parameter	Symbol	Unit	Quantity	
D, L	Crown width	b	m		
D, L, R	Inclination slope	pi	m		
D, L	Top service road width	Ls	m		
R	Channel depth	d	m		
	Dependent variable	Symbol	Unit	Quantity	
D	Perimeter embankment length	L	m		
D	Inner Area	Ai	m^2		
D, L	Embankment base width	B	m		
D, L	Cross section area	SF	m^2		
D, L, R	Slope length	i	m		
D, L, R	Total lateral area	SL	m^2		
D, L	Volume embankment above ground	V	m^3		
D, L	Volume of excavation for foundation	VS	m^3		
R	Difference between channel bed and surface width	DF	m		
	Construction item cost	Quantity	Unit	Unit cost	Total cost
D,L	Preliminary activities (Excavation, demolition, and landscaping works)		m^3, m^2		

D, L, R	Excavation and demolition		m^3	
D, L	Embankment		m^3	
D	Jett grouting		m^3	
D, R	Lining		m^3	
D	Flow regulation structures		%	
D	Hydraulic system		%	
D	Electromechanical works		%	
D	Riverbed arrangements		%	
D	Roadways and related works		%	
D	Environmental arrangements		%	
L	Supply and transportation		m^3	
L, R	Soil processing and mechanical operations		m^3 - %	
L	Road foundations		m^2	
L	Seeding and bio-mats		m^3	
L	Cementitious conglomerates and steel reinforcements		%	
L	Aqueducts and sewers (channels, etc.)		m	
L	Flap gates and sluice gates		per unit	
L	Metal structures		%	
R	Residual soils for restoring the original riverbed level		m^3	
	Total Construction Cost			
	Additional cost	Quantity	Unit	Total cost
D, L, R	Design, works management, and site safety management		%	
D, L, R	Land acquisition		%	
D, L, R	Inspection/testing		%	
D, L, R	Surveys, assessments, and investigations		%	
D, L, R	Connections to public infrastructures		%	
D, L, R	Provision for price adjustment		%	
D, L, R	Contingencies		%	
D, L, R	Value Added Tax (VAT)		%	
	Additional Cost Total			
	Total Cost			

The first entry of the datasheet in Table 1 is the performance parameter expressed as the level of protection (LP) that the project will ensure for the area of influence associated with it. This is a design parameter which correlates directly with the hydrological intensity measures of the event for a given return period. Therefore, for instance, an embankment will be designed to withstand an event with a peak discharge associated to a given probability of occurrence or the corresponding return period. These hydrological intensity measures determine directly the basic design parameters such as the height and/or length of embankments, which are therefore been chosen as independent variables.

The first part of the datasheet contains three kinds of physical parameters: independent variables, dependent variables and fixed parameters. These dimensional parameters represent physical entities which allow computing the size of the implemented works. All parameters were chosen so that as much as possible they are common to the three types of mitigation work. For each type of mitigation work, only two variables are considered as independent so that a relatively simple cost function could be identified. The review of the *Regional Authorities project sample* highlighted that some physical characteristics, such as the inclination of the riverbanks, crown width, and channel depth, have values which are recurring within a narrow range and therefore it was decided to take their average value as constant. In this way, it was possible to derive all the others geometric parameters for each mitigation work as functions of up to five parameters, so that the geometry of each type of mitigation work can be fully described by a combination of as little as seven to a maximum of thirteen parameters. Indeed, guidelines issued by Basin Authorities and other overseeing bodies worldwide provide "standard" design criteria which results in fixed parameters (CALTRANS, 2020; CIRIA, 2013; USACE, 2020).

The second part of the datasheet relates to the cost for the construction, which includes entries related to preliminary activities for site preparation, materials and equipment, physical implementation of the works, and greening and finishing activities to complete the project. All these cost-related entries have been derived as a combination of variables and fixed parameters. However, each project includes also additional cost, encompassing the design and site safety management, land acquisition, VAT, etc, which are difficult to quantify physically, and therefore they were determined as a percentage of the total construction cost.

For each mitigation measures, the following cost items were determined:

- Levees and Embankments: excavation and mandatory cross-sectional excavations, earth volume for embankment, supply and transportation, soil processing and mechanical operations, road foundations, seeding and biodegradable blankets, land cleaning for laying preparation, cementitious conglomerates, aqueducts and sewers, sluice gates, metal works, and other associated expenses. Subsequently, quantities and unit prices have been computed for each individual element.

- Detention basin: excavation and demolitions, embankment volume, jet grouting, and marginal lining, regulation structures, hydraulic systems, electromechanical works, riverbed arrangements, roadways, ancillary works, and environmental arrangements
- River flow section adjustment: reprofiling excavations, materials for restoring the original riverbed level, and cliffs.

Quantities and unit prices were then calculated for each item.

A simplified physical model for each category of measure has been extracted from the complex set of relationships used in determining the bill of quantities for these types of mitigation works. These are summarized in the Table 2.

Table 2 Equations for the simplified geometric model of the physical dependant variables

Code	Dependent variables	Symbol	Equations
L, D	Embankment Base width	B	b+(H/pi)*2
R	Large – small parallel side	DF	d/pi
L, D	Cross Section area	SF	(B+b)*H/2; (B+b)*H/2/2
L, D, R	Slope length	i	(((B-b)/2)^2+H^2)^0.5; (DF^2+H^2)^0.5
L, D, R	Total lateral area	SL	i*L*2+2*L ; i*L*1.5; i*L*2
L, D	volume of embankment above ground	V	SF*L
L, D	Volume of excavation for foundation	VS	0.5*L*B; V/2
D	Perimeter embankment length	L	(V/H)^0.5*5
D	Inner area	Ai	V/H

By using combinations of the relationships summarized in Table 2, it is possible to compute the quantities involved in each of the construction operations and therefore determine the economic value of each cost item in Table 1.

In the case of the detention basins, some items such as flow regulation structures, hydraulic systems, electromechanical works, etc., are not directly correlated to the geometric dimensions of the hydraulic structure. Therefore, an analysis of the bearing of these costs on the total cost was conducted across the *Regional Authorities project sample* to compute them as a percentage of other related cost items.

Following the approach used in planning practice, when estimating the total cost of hydraulic mitigation works, eight items representing additional costs were computed as a percentage of the total construction cost. Table 3 shows the percentage value assigned to each item based on statistical analysis of the *Regional Authorities project sample.*

Table 3 Additional costs items

Additional costs	Quantity	Unit
Design, works management, and site safety management	8,00	%
Land acquisition	22,00	%
Inspection/testing	1,50	%
Surveys, assessments, and investigations	5,50	%
Connections to public infrastructures	0,15	%
Provision for price adjustment	1,50	%
Contingencies	15,00	%
Value Added Tax (VAT)	22,00	%

Nonetheless, the simplified model relies for each category on a relatively large number of geometric equations in order to derive the total cost and therefore depends on the availability of cost breakdown and a schematic representation of the mitigation work.

In order to generalize these results to a simple design tool which can easily investigate different solutions associated to different hazard scenarios through a cost-benefit analysis, a generalized function is introduced for each category, with the format:

$$C_{tot}(x,y) = C_{construction}\,(x,y,fixed\ parameters) + C_{additional}(C_{real}) \qquad (1)$$

where x and y represent length (L) and height (H) in the case of the levee, length (L) and storage volume (V) for the detentions basin and width (W) and length (L) for the river flow section adjustment, respectively. Using a matrix approach and a code developed in R Studio platform, a number of linear and polynomial regression models were used, to determine the most suitable parametric functions in the format as follow:

$$C_{tot}(x,y) = c_1 * x^k + c_2 * y^j + c_3 \qquad (2)$$

As described in Figure 1, equations 1 and 2 were validated against the *Regional Authorities project sample.*

2.2 MATERIALS

This section describes the materials used in this study. Firstly, an open-source database called ReNDiS (ISPRA, 2021) was integrated by the authors and used to identify the most frequent types of mitigation measures applied in Italy in the field of flood risk mitigation, their average cost and distribution. Secondly, a sample of fifty projects available online, published by Regional Authorities, which included general and technical reports, were used to investigate in depth all the components of a flood risk mitigation project's total cost to finally develop cost parametric functions, as outlined in the previous section.

2.2.1 Integrated Database

The process of identifying the most commonly implemented flood risk mitigation interventions was conducted using a database known as ReNDiS (National Repository of Soil Protection Interventions) (ISPRA, 2021). This database records a comprehensive collection of projects aimed at mitigating hydrogeological risks, which have been funded in Italy since 1999. Its aim is to provide a dynamic tool that offers, to administrators engaged in land defence planning, a regularly updated snapshot of projects and allocated resources. Projects are categorized into two main groups: those awaiting funding, which are currently not accessible, and those already funded, accessible through an Open-data web-based interface. This interface also serves as the primary public access point for citizens seeking data and information on hydrogeological risk management efforts undertaken by public authorities (Gallozzi et al, 2020), fulfilling the requirement of the European Flood Directive on citizen information and participation (European Union, 2007).

The database is structured into sections based on the specific environmental threats that interventions seek to address, spanning from flood control to coastal erosion, landslides, avalanches, fires and also includes efforts targeting multiple hazards. This study has leveraged data related to hydraulic mitigation works implemented within projects addressing flood and landslide risks. In the ReNDiS database (ISPRA, 2021), a comprehensive taxonomy outlines 31 different types of hydraulic interventions. However, in a significant number of entries, a clear attribution of this taxonomy to specific interventions is lacking. Additionally, even though the nature of the work might be classified, specific details such as physical dimensions or project timelines are not provided. While data on allocated funding is available for the overall project in each entry, a detailed breakdown of costs also remains elusive.

In 2020, ISPRA published a report as a comprehensive statistical analysis on efforts done in the field of hydrogeological risk mitigation, including projects funded up to 31st December 2019 and recorded in the ReNDiS database. The ISPRA report (Gallozzi et al,

2020) contains 1963 flood risk mitigation projects corresponding to 3671 specific mitigation measures. However, the authors accessed a version of the database updated to February 2021 which included 2620 projects and 4649 measures, approximately 800 more than the sample used for the analysis conducted by ISPRA (Gallozzi et al, 2020). This is a fundamental step in reducing the uncertainties in correlating costs to specific classes of mitigation works.

2.2.2 Project selections

This section presents concise summaries of essential details for each of the ten projects which underpin the cost model development. Figure 2 shows the geolocation of this sample of projects.

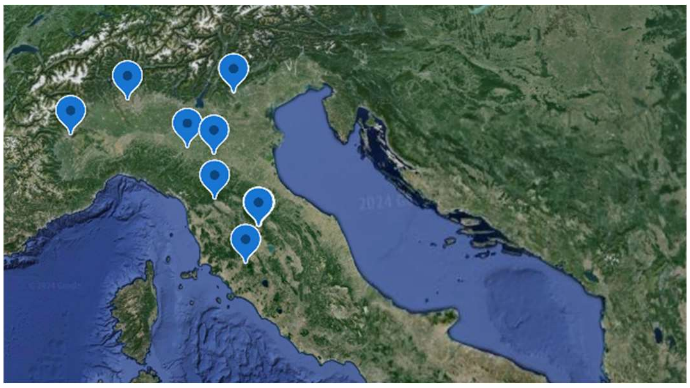

Figure 2 Geolocation of the sample of ten projects

Table 4 Summary of key parameters for the projects selected to derive the cost functions

Project ID	River	Region	Municipality	Type	Return Period [years]	Length [m]	Height [m]	Volume [m3]	Width [m]	Discharge [m3/s]	Project Date m-yy	Budget [k €]	Budget with inflation [k €]
1	Panaro	ER	Modena	L	200	1830	2,5	-	-	940	Mar-20	980	1136

2	Po	P	Moncalieri	L	200	2400	3	-	-	2600	Feb-09	2400	3120
3	Galioffo	T	Arezzo	L	-	140	2,7	-	-	-	Nov-21	330	371,25
4	Bozzente	L	Nerviano	D	100	-	4	1000000	-	28	Oct-14	10500	12474
5	Baganza	ER	Parma	D	200	-	10	10000000	-	460	Oct-16	50000	59450
6	Orolo	V	Isola Vicentina	D	30	-	6	1000000	-	300	Feb-15	11000	13112
7	Bure	T	Pistoia	D	200	-	5	750000	-	220	Mar-22	15000	16,23
8	Rio Riolo	T	Arezzo	R	200	35	-	-	1,2	32,25	Feb-23	38	38,11
9	Rio Ripa	T	Arezzo	R	200	750	-	-	2,5	-	Feb-23	400	401,2
10	Fosso Giunco	T	Arcidosso	R	200	188	-	-	3	6,5	Jun-17	570	670

Legend:
Region: T-Toscana, V-Veneto, ER-Emilia-Romagna, L-Lombardia, P-Piemonte
Type: L-Levee, D- Detention Basin, R-River flow section adjustment

Table 4 provides a summary of the key parameters of each project which have been used to derive the cost functions. The parameters include location, typology of mitigation measures, design return period, the value of the independent design variables, the date of project submission, original budget and budget normalized at December 2023 to take into account cost inflation.

The data confirms that the value of 200 years for the return period with medium probability of occurrence recommended by the legislation (ADBPO, 2016) is indeed the most commonly used to design levee and embankment, and river flow section adjustments, while, for detention basins, return periods of 30 and 100 years are also used where already existing hydraulic works can compensate for the difference in lamination volume between the return periods.

Notwithstanding the fact that the majority of the projects have been designed after the conclusion of the first cycle of the PGRA (2011-2015), an approach based on risk classification has not been included in the design analysis (European Union, 2007).

2.2.3 Matrix regression analysis programme

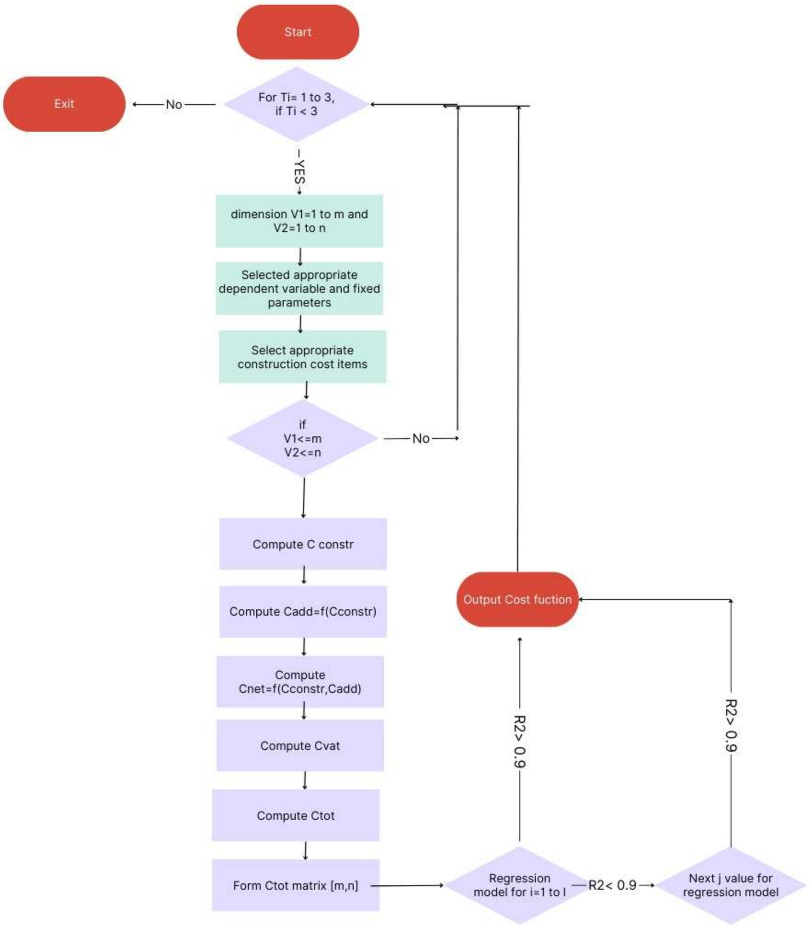

Figure 3 Flow chart methodology

Figure 3 illustrates the path followed to define the parametric functions for the three types of mitigation measures by way of regression analysis on matrix data. The R programming language is used in the integrated development environment RStudio Desktop. For each mitigation typology two vectors representing values for the two independent variables are created of dimensions m, n respectively. For each couple of values, using the equations for cost items developed on the basis of Table 1 and Table 2, the partial and the total cost are calculated, and corresponding matrices created. The RStudio allows to consider different types of regression models: linear, multilinear, polynomial, logistic, etc. The added value is that useful statistical parameters are automatically computed to determine the goodness of fit of the models, such as R^2 and p-values. It also provides a series of graphical outputs that help in visualising confidence boundaries and other useful indicator of the reliability of the model. For this specific application, for each mitigation works typology, different regression models are considered, and the programme run, until suitable values of R^2 and p-value are obtained.

3. RESULTS

3.1 STATISTICS OF THE ReNDiS DATABASE

The data analysis, aimed at identifying the most representative types of hydraulic interventions, was conducted using the Integrated ReNDiS database. Every mitigation measure employed in each project was meticulously documented, including instances of multiple interventions within the same project. The analysis was focused on identifying the intervention types most commonly used for flood risk reduction and calculating the distribution of cost and the average cost associated with each intervention type.

The analysis was performed on a sample dataset comprising 5,937 mitigation measures, out of which 901 were classified as 'undefined hydraulic interventions.' Consequently, the study focused on a total of 5,036 specific hydraulic interventions, forming the basis of this research. Table 5 compare the number of mitigation works in the original ReNDiS database and after its integration.

Table 5 Comparison of mitigations works between the Integrated ReNDiS and the ReNDiS database.

Hazard	Mitigation works by hazard class (Integrated ReNDiS database vs ReNDiS database)	Total (Integrated ReNDiS database vs ReNDiS database)
Hydraulic risk mitigation	4649 vs 2777	5937 vs 4064
Landslide risk mitigation	1288 vs 1288	

The following Figure 4 illustrates the five most frequent classes of hydraulic interventions, documented in the Integrated ReNDiS database.

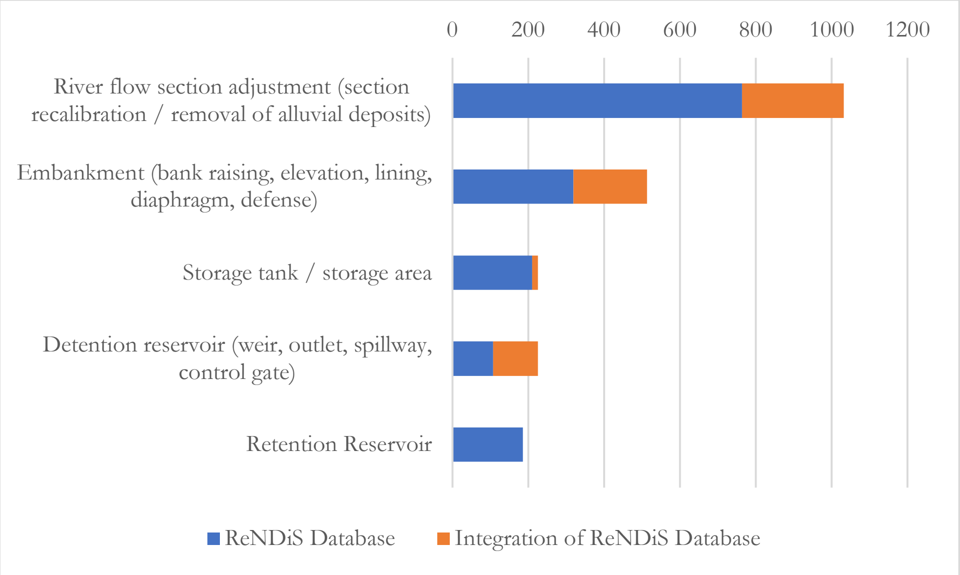

Figure 4 Frequency of flood mitigation measures from the Integrated ReNDiS database

Considering the specific focus of this study on structural hydraulic works for flood risk reduction and mitigation, it was decided to further investigate the following three classes: river flow section adjustment, embankments and levees, and control storage works such as retention and detention reservoirs and storage areas, as pertinent categories in this context. These typologies are present in 2181 on the integrated ReNDiS database records.

As a first step, a statistical analysis of the costs associated with each measure was performed to determine range and average cost for each category. Considering the structure of the ReNDiS data, only projects involving one type of hydraulic mitigation measures could be selected for this analysis, resulting in a sample of almost 200 cases.

Figure 5 shows histograms of costs for each category: the river flow section adjustment has a population of 96 cases with an average cost of € 124.000 but a median cost of only € 39.000 showing that the distribution is very skewed with almost 80% of the cases with a cost lower than € 100.000. Comparatively, the levee and embankment category, with a population of 46 cases, has a similar wide range between € 50.000 and € 5 million, however median and average are much closer at € 700.000 and € 970.000 respectively, showing a less skewed distribution. Finally, the basin category has a range between € 260.000 and € 33 million, a median of € 1 million and average of almost € 5 million.

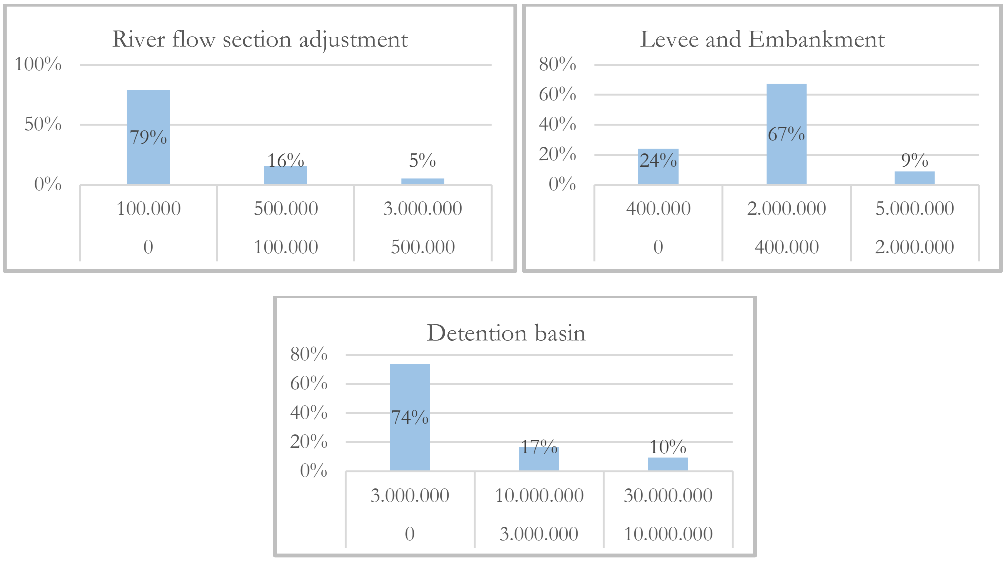

Figure 5 Distribution of cost for each category

While this data is useful to determine the cost order of magnitude for each category, clearly identifying the river flow section adjustment as the cheapest intervention and the detention basins as the most expensive, the lack of a cost breakdown for each construction item, as identified in Table 1, and the lack of geometric and hydraulic parameters, do not allow to use this sample as basis for the definition of the cost functions. For these reasons, as explained in Section 2.2.2, the construction of the functions for cost-implementation have been achieved using the project selected on the Regional Authorities website. The results are illustrated in the next section.

3.2 MULTIVARIABLE MODEL OUTPUT AND VALIDATION

Figure 6 shows the comparison between the project costs of the ten mitigation works and the corresponding cost obtained with the *simplified model*. The model has been compared with the original cost with and without inflation as shown in Figure 6a and 6b. The inflation computed at December 2023 induces a change in cost from as little as 0.3% for the two river flow section adjustment projects, whose cost refer to February 2023, to as much as 30% for one of the levee projects which was designed in February 2009.

In the case of the original project cost, it can be seen that the simplified model tends to overestimate cost from as little as 13% up to 59%, with three cases of underestimation ranging between 15% and 33%. When considering the inflation, the model most commonly underestimates by as little as 3% to a maximum of 47% while the overestimate range is between 3% and 52%. Therefore, the comparison with the inflated costs is slightly more suitable than the original project cost.

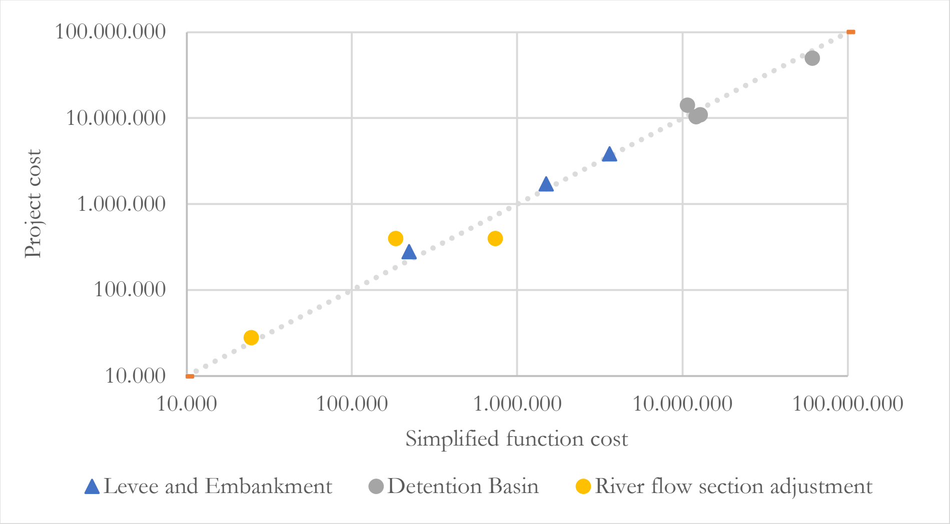

Figure 5 Comparison between cost evaluated with simplified functions and project cost

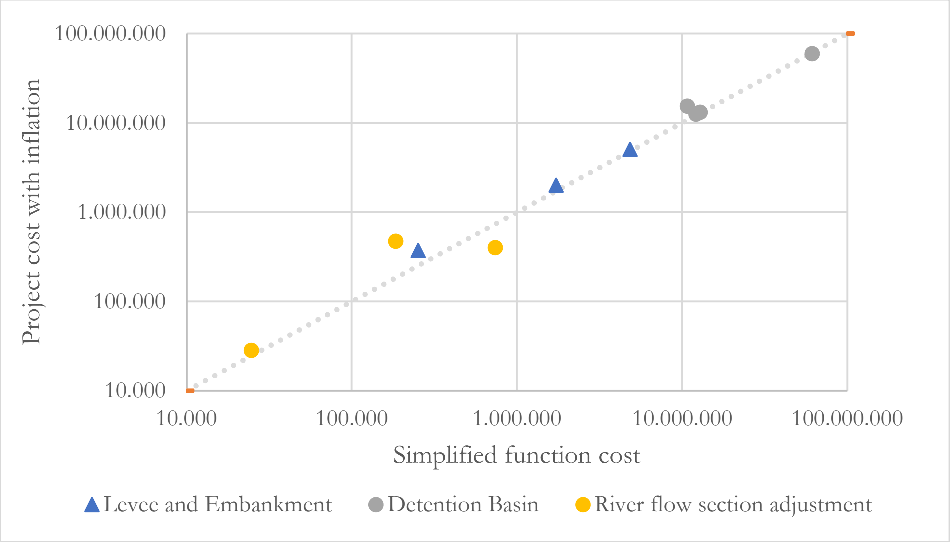

Figure 6 a) Comparison between Project cost and Cost evaluated with the Simplified Functions; b) Comparison between Project cost with inflation and Cost evaluated with the Simplified Functions

3.3 REGRESSION ANALYSIS

In this section the findings derived from the application of regression models are presented: the analysis was conducted on a total of ten projects, three related to the construction of levee, four about detention basin and three related to the adjustment of the river flow section. The regression expresses the correlation between the geometric design parameters and the cost of the project, in an attempt to improve on the already defined *Simplified Function*, and to assess the significance and strength of these correlations. Below is a description of each type of regression model implemented with the resulted cost function obtained, offering insights into the relationships between independent variables, i.e. geometric design variables, and cost.

3.3.1 Levee and Embankment

The model that best fits the matrix is the polynomial regression, where the relationship between the dependent variable and the independent variable is non-linear and it is modelled as an nth-degree polynomial function. For this type of mitigation defence, this regression analysis aims to model the relationship between the predictor variables (length, height, and their interaction) and the response variable, i.e. the associated cost.

The function obtained from the polynomial regression is the following:

$$Cost\ (L,H) = c_1L^2 + c_2L + c_3H + c_4\frac{L}{H} + c_5 \tag{3}$$

c_1= 62588.45

c_2=823331.97

c_3=0.00

c_4=0.00

c_5= 183218.60

The coefficient for the linear component of the polynomial transformation of length (L) is estimated to be 823,331.97 with a standard error of 257,003.86. The t-value of 3.204 indicates statistical significance (p-value = 0.002525), suggesting a significant linear relationship between length and cost. The parameters related to the quadratic component of the polynomial transformation of length (L) and to the linear component of the polynomial transformation of height (H) have t-value and p-value which suggest that these components are not statistically significant. On the other hand, the coefficient for the interaction between length and height is estimated to be 601.05 with a standard error of 15.85. The high t-value of 37.911 and the very low p-value (< 2e-16) indicate that this interaction term is highly significant.

Regarding the model's overall fit, the multiple R-squared value of 0.9958 suggests that approximately 99.58% of the variance in cost can be explained by the predictor variables. The adjusted R-squared value of 0.9954, which adjusts for the number of predictors, remains high, indicating a robust fit.

With an F-statistic of 2617 and associated p-value of less than 2.2e-16, the model is highly significant, indicating that at least one of the predictors has a nonzero effect on the dependent variable.

In general, the regression analysis elucidates the crucial role played by the intricate dynamics between infrastructure length and height in shaping cost predictions. Notably, the linear component of the polynomial transformation of length emerges as a substantial determinant of costs, while the quadratic component of length and the height variable demonstrate minimal impact within the model. The robust statistical support, reflected in elevated R-squared values and significant p-values, underscores the reliability of the model in furnishing accurate cost estimations.

3.3.2 Detention basin

In this case as well, the polynomial regression model emerged as the most effective choice due to its ability to capture the non-linear relationship between the predictor variables (volume and height of the infrastructure features) and the cost, providing a better fit to the data compared to alternative models. The function derived from the regression analysis is the following:

$$Cost\ (V,H) = c_1V^2 + c_2V + c_3H + c_4\frac{V}{H} + c_5 \tag{4}$$

c_1= -5.313 x10^6

c_2=1.469 x10^8

c_3=5.185 x10^6

c_4=-1.168x10^{-1}

c_5= 3,2 x 10^7

The coefficient for the linear component of the polynomial transformation of volume (V) is estimated to be 146,900,000 with a standard error of 5,548,000. The high t-value of 26.477 indicates statistical significance ($p < 2e\text{-}16$), suggesting a significant linear relationship between volume and cost. On the other hand, the coefficient for the quadratic component of the polynomial transformation of volume (V) is estimated to be -5,313,000 with a standard error of 2,863,000. The t-value of -1.856 suggests a lack of statistical significance at the conventional levels ($p = 0.0734$). The same results are obtained for the linear component of the polynomial transformation of height and for the interaction term. The multiple R-squared value of 0.9875 suggests that approximately 98.75% of the variance in cost can be explained by the predictor variables. The adjusted R-squared value of 0.9858, which adjusts for the number of predictors, remains high, indicating a robust fit. With an F-statistic of 592.6 and associated p-value of less than 2.2e-16, the model is highly significant, indicating that at least one of the predictors has a nonzero effect on the dependent variable.

Overall, the regression analysis for detention basins suggests that volume plays a significant role in determining the cost, as evidenced by the highly significant coefficient for the linear component of volume (V). However, the quadratic component of volume and the height variable do not contribute significantly to the model. The lack of statistical significance for the interaction term suggests that the combined effect of volume and height may not significantly influence cost estimation. Despite these nuances, the high R-squared values indicate a strong fit of the model to the data, suggesting its utility in estimating costs for Detention Basin construction projects.

3.3.3 River flow section adjustment

In the case of the river flow section adjustment, however, the linear regression model emerged as the better option, showcasing its efficacy in capturing the underlying linear trends within the data while providing a straightforward interpretation of the relationships between independent variables (length and width of the channel) and the related project cost.

$$Cost\ (L, W) = c_1 L + c_2 W + c_3 \frac{L}{W} + c_4 \tag{5}$$

c_1= 5.625 x10^2

c_2=6.093 x10^{-11}

c_3= 1.677 x10^2

c_4= -3.104x10^{-10}

The coefficient for length is estimated to be 562.50 with an extremely small standard error. The exceptionally high t-value of 1.256e+16 indicates statistical significance ($p < 2e-16$), suggesting a significant linear relationship between length and cost. Similarly, the t-value of the width component equal to 4.398 indicates quite good statistical significance ($p = 0.000113$), suggesting influence of width on costs. Also, the interaction between length and width, with an extremely small standard error and p-value, and an high t-value, shows a significant interaction effect on costs. The multiple R-squared value of 1 indicates that the model explains 100% of the variance in the dependent variable (cost). The adjusted R-squared value of 1 indicates a perfect fit.

The F-statistic of 6.756e+32 and associated p-value of less than 2.2e-16 point out that the model is highly significant.

The regression analysis for river flow section adjustment reveals significant correlation between length, width, their interaction, and costs. The model demonstrates a perfect fit to the data, suggesting its efficacy in accurately predicting project costs.

In light of the comprehensive analysis presented in the preceding parts, the following section proceeds to delve into the discussion and conclusion, wherein the key findings are synthesized, their implications explored, and insights for future research directions are offered.

4. DISCUSSION AND CONCLUSION

This study was carried out in light of the increasing request for design approaches based on the identification of the best ratio between cost for implementation and benefit, intended as reduction in the level of risk. Therefore, its aim is to identify cost functions that would provide a value for the implementation cost for three different types of mitigation measures, i.e. levee and embankment, detention basin and river flow section adjustment.

Figure 7 illustrates the comparison between costs adjusted with inflation and the costs derived from the applied regression models.

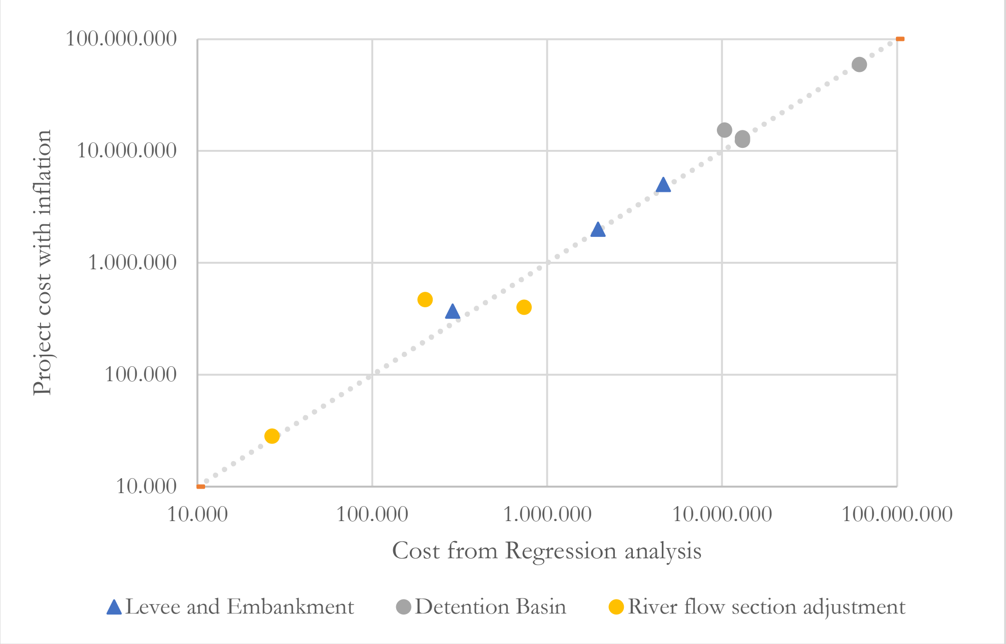

Figure 7 Comparison between Project cost with inflation and Cost evaluated with the regression analysis

In general, both the simplified cost functions with inflation and the functions derived from the regression models show a little underestimation of the cost: the average discrepancy between the simplified cost functions and project costs with inflation equal to -9%, is reduced when project costs are compared to the costs derived from the regression analysis equal to -4%, allowing to state that the regression models found functions that show a good fit to the data, indicating its ability to capture the patterns and variations present in the dataset.

The regression analyses conducted for three distinct functions—levee construction, detention basin implementation, and river flow section adjustment—have provided valuable insights into the relationships between predictor variables and the associated costs. For the functions related to levee construction, the linear component of the polynomial transformation of L exhibits significance, suggesting a linear relationship between L and cost. However, the quadratic component of the polynomial transformation of L and the polynomial transformation of H do not significantly contribute to the models, implying that their inclusion may not improve cost prediction accuracy. Nevertheless, despite the poor statistical significance of the quadratic components, polynomial regression produced superior and more satisfactory results compared to employing a linear model, for the two cases of detention basin and embankments.

In contrast, the regression analysis for river flow section adjustment reveals a different pattern. Here, the predictors include the length (L) and width (W) of the section, as well as their interaction. The statistical results show that both L and W have significant positive effects on cost estimation, with highly significant coefficients ($p < 2e\text{-}16$ for both). Moreover, the interaction term (L:W) is also highly significant, indicating that the combined effect of L and W significantly influences cost. The high adjusted R-squared value of 1 suggests that the model explains all the variance in cost, indicating an exact fit.

Considering that in some cases one of the parameters is statistically non relevant, it may be advisable to explore the hypothesis of constructing functions dependent on a single variable. Thus, conducting a regression analysis per linear meter of length for levees, or per cubic meter of volume for detention basins. Alternatively, given the substantial difference in order of magnitude between length and height for the levee and volume and height for the basins, two separate regression models should be considered, one that correlate unit costs to the height and shape of the defence work, and then one that correlates total costs to its length or volume.

Beyond the statistical significance of the predictor variables, it is crucial to consider practical implications. Stakeholders and technical personnel involved in mitigation defence planning can benefit significantly from these findings. By utilizing the regression models derived from the analysis, stakeholders can obtain draft estimations of costs for implementing various mitigation defence measures. For instance, in scenarios involving levee construction or detention basin implementation, understanding the relationship between length or volume, height, and cost can aid in budget allocation and project planning. For example, if a levee needs to be built along a river to mitigate flooding risks, stakeholders can use the regression model to estimate the cost based on the length of the levee and its height. This can then be directly correlated to the peak discharge chosen and therefore the level of protection afforded. Similarly, for river flow section adjustment, where length and width play crucial roles, stakeholders can use the regression model to obtain accurate estimates of cost based on different configurations of the river flow section.

Overall, the regression models for levee construction and detention basin implementation exhibit robust fits to the data, explaining approximately 99.58% of the variance in cost. However, for river flow section adjustment, the model achieves an exact fit to the data. These findings underscore the importance of tailored cost estimation approaches for different types of infrastructure functions and highlight the need to consider the specific characteristics and interactions of predictor variables.

Moreover, although the statistical parameters suggest a good fit of the regression model to the data, it is crucial to acknowledge certain limitations identified during the definition of the *Simplified functions*. These limitations may explain the observed discrepancy between declared project costs for the 10 case studies, and those derived from the regression analysis. In the first instance, prices for individual cost items are delineated within documents known as 'price lists,' which are published by each respective Region Authorities. These prices can exhibit considerable variation, thereby complicating the establishment of a universal function applicable across the entirety of Italy. Consequently, it may be prudent to contemplate the introduction of a parameter that accommodates these fluctuations. Additionally, there are some extra elements of costs in the real cases that are not captured by the model, or some cost items that are specific, not found in all cases examined.

As part of future efforts, a crucial step involves validating the model using additional projects sourced from the websites of river basin authorities. This validation process is essential for confirming the reliability and robustness of the model. By extending the analysis to encompass a broader range of projects, the aim is to ensure the generalizability and applicability of the findings across different contexts and scenarios.

In conclusion, the statistical analyses, coupled with practical implications, provide valuable insights into the factors influencing the costs associated with different infrastructure functions. These insights can inform decision-making processes and contribute to more accurate cost projections in the planning and implementation of infrastructure projects. Further research could explore additional factors that may influence cost dynamics in these contexts and refine cost estimation models accordingly.

Indeed, it is crucial to work towards establishing a correlation between the costs associated with implementing a project and the benefits it provides, interpreted as mitigating the risks associated with flooding. This involves delineating the *area of influence* of each project, which varies based on its type and scale, evaluating risk reduction using risk maps published by basin authorities, and linking this reduction to the project's financial investment.

What is meant by the term *area of influence* is thoroughly explained in the next Chapter.

CHAPTER 3 – INFRASTRUCTURE FOR FLOOD RISK REDUCTION: CORRELATION BETWEEN MAPPING TOOLS AND ALLOCATION OF RESOURCES IN ITALY

LIST OF FIGURES

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Infrastructure for flood risk reduction: correlation between mapping tools and allocation of resources in Italy

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Abstract: Floods cause disastrous events worldwide, affecting millions yearly, leading to loss of life and substantial economic damage. Italy is no exception. One fundamental, although often debated, strategy for flood risk reduction is the construction of hydraulic defence infrastructure. Since 1999, the Italian Institute for Environmental Protection and Research (ISPRA) has catalogued these defence measures in an open-access database called ReNDiS, documenting their location, characteristics, and costs. The 2007 EU Flood Directive (EU_FD), mandates Members States to update and map flood hazard and risk every six years. Using these two critical data sources, this study's objectives are: the correlation between defence infrastructure implementation and flood risk mapping for two Basin Districts located in the North of Italy; the assessment of effectiveness and efficiency of the implemented defence infrastructures. The study develops a multi-layered mapping tool that integrates existing hydraulic defences with flood risk maps of two successive cycles of reporting of the EU_FD, considering the period of measures funding between 2012 and 2017. Two indicators are introduced to quantify and verify the expected risk reduction: the *Risk Score* and the *Risk Score Variation.* These are compared with the defence infrastructures associated cost. A modest correlation is identified, between mapped risk class and infrastructure's location, and also between risk reduction benefits and project costs, with a minority of cases showing effectiveness and efficiency. The study is constrained currently by the quality of risk representation in official flood risk maps and the completeness of the ReNDiS database, but it proves the relevance of the methodology, able to determine risk reduction in subsequent cycles of flood risk management, and the corresponding allocation of resources.

Keywords: flood risk management; flood risk mapping; hydraulic infrastructure; flood resilience financing

1. INTRODUCTION

Flooding constitutes one of the most destructive natural hazards which affect every year millions of people worldwide, causing enormous economic losses averaging around $50 billion annually (Salman & Li, 2018), and it accounts for 40% of all global loss-related natural hazard events since 1980 (Munich Re, 2021).

According to a flood hazard map published by the European Spatial Planning Organization Network (ESPON, 2024), which displays hazard recurrence based on average number of significant flood events for the period 1987-2002 for the European Union small regions (according to the Nomenclature of Territorial Units for Statistics system at level NUTS3), the Italian territory is prone to flooding, particularly on the North-West with high and very high hazards recurrence and in the North-East and Centre with moderate probability of flood recurrence due to its geological, morphological and hydrographic characteristics (Lodi et al., 2023).

Interestingly, provinces such as the ones affected by the Emilia-Romagna destructive events of 2023 were classified as affected by very low recurrence. Indeed, the MunichRe NatCatService shows the high risk that floods pose to all European countries and the increasing trend in flood losses (Kron et al., 2019)

Over the past decades, floods have garnered increasing attention worldwide due to global warming, as their frequency, severity, and intensity continue to rise (EEA, 2010; H.-O. Pörtner et al., 2022). Extreme events are more frequent, and they could be related to climate change. However, there is increasing evidence that many of these events correlate geographically with instances of uncontrolled urban development and questionable physical transformations of the territory. Examples of these alterations are artificially hidden/culverted rivers, urban areas with low ground porosity due to impermeable pavement and poor drainage systems, illegal construction and vertical additions to residential buildings in floodplain regions, poor land management (Apollonio et al., 2020); (Legambiente, 2013); (Scionti et al., 2018).

According to (EEA, 2023), between 1980 and 2022, climate-related extremes amounted to an estimated EUR 650 billion (2022 prices) in the EU. Floods account for approximately 43%, with a substantial increase in economic losses in the last two decades, as evidenced by the 2002 flooding in Central Europe (EUR 34 billion), the 2021 in Germany and Belgium (EUR 44 billion) and the 2023 in North-East Italy Po Valley, for EUR 9.2 billion (Swiss Re, 2023). Tapia et al., 2017 assessed the flood vulnerability of 571 European cities across 27 States, finding that no specific patterns could be identified across Central and Southern Europe equally at risk from both fluvial and pluvial flooding.

In a recent assessment, it has been estimated that in Italy, 7275 municipalities (91% of the total) are at risk from landslides and flooding, and more than 6 million people live in areas at risk of flooding (Trigila A., Iadanza C., Bussettini M., 2018). Specifically, the Italian territory is classified as follow: 5.4% as a high-probability flooding area, 10% as a medium-probability flooding area and 14% as a low-probability flooding area (Lastoria B et al., 2021), according to the probability event classification in the Legislative Decree 49/2010. However, this classification only provides a partial picture because it does not explicitly mention the flood severity, i.e. depth and duration, which directly correlate to damage.

In terms of the exposed population, more than 2 million people (4.1% of the Italian population) live in regions categorised as high-probability of flooding, i.e. with a return period of 20 to 50 years; almost 7 million people (11.5%) reside in region classified as medium-probability with a return period of 100-200 years, and more than 12 million(20.6%) inhabit areas with low-probability, i.e. with a return period up to 500 years (Lastoria B et al., 2021).

River flooding caused by intensive rainfall events is common in Italy, representing one of the deadliest types of floods (Zanchini et al., 2020). Flash flood events and pluvial flooding are common and are usually responsible for socio-economic and environmental damage. From 2010 to 2020, events of flooding caused by intensive rainfall increased from less than 10 to more than 80 per year, while river flooding events increased from 2 to 15 per year over the national territory (Zanchini et al., 2020).

In the last 70 years, in Italy, more than 1300 people were killed by flooding events (IRPI, 2018). Major extreme events have affected the entire Po River Basin; northern Italian regions such as Piemonte, Emilia Romagna, Veneto, Lombardia and Liguria are highly influenced by floods (ESPON, 2024; Lodi et al., 2023). However, the rest of the Italian territory is not exempt from flood risk. A report issued in the 2021 by ISPRA (Italian Institute for Environmental Protection and Research) (Trigila et al., 2021), shows that regions such as Toscana, in Central Italy, and Calabria and Puglia, in South Italy, also have a substantial portion of their territory susceptible to flooding. In these cases, although floods are less recurrent, given the orography and hydrology of the territory, they are expected to be just as destructive and harmful to people.

Among the most disastrous events, the 1951 Polesine region floods stand out as they caused multiple embankment failures in the city of Rovigo, triggered by intense rainfall all over the whole basin of the Po River (Viero et al., 2019) and resulted in the death of 101 people; in the Province of Salerno, an event in 1954 caused 325 fatalities due to a storm characterised by 500 mm of rain in less than 16 hours triggering several landslides (Fiorillo et al., 2019); one of the events with the highest rainfall intensity in Italy occurred in Palermo province in 2018, causing flooding of some small rivers lasting three days and resulting in 13 deaths (Francipane et al., 2021).

The most recent chain of extreme events occurred in mid-May 2023 in the Romagna region: the first extreme event with a precipitation of 200 mm of rain in 48 hours, 150mm of which in 24 hours, was followed, ten days later, by a second extreme precipitation with 300 mm of rain in 48 hours. These resulted in the flooding of 23 rivers, 13 watercourses exceeding the level 3 alert hydrometric threshold and more than 250 landslides triggered in the region, leading to the closure of over 400 roads. The death toll amounted to 16, over 36,000 people were displaced, and the estimated damage amounts to approximately 8.8 billion euro (ISPRA, 2023; Regione Emilia-Romagna, 2023b, 2023a).

For all those reasons, flood risk mitigation represents a pressing priority for Italy. In 2015 the Italian Government published a document outlining the National Strategy for Climate Change Adaptation, which proposes several actions for hydrogeological risk reduction (Ministero dell'Ambiente e della Tutela del Territorio e del Mare, 2017) as part of the Flood Risk Management Plan in fulfilment of the European Flood Directive 2007/60/EC (EU_FD) (European Union, 2007; Müller, 2013). The Directive is required in the first cycle to identify areas of significant risk and develop a management plan for such risk (European Commission - SWD, 2021). The adaptation strategies developed in Italy include measures such as banning new construction in areas affected by geological risk, relocating existing constructions built-in high hydrogeological risk areas, preserving and restoring soil permeability in urban areas, forbidding the construction of basements and underground storeys in residential buildings, ensure safety for urban infrastructure from extreme weather events, banning the culverting of rivers and bringing back to open surface existing hidden rivers, planning underground basins for rainwater detention, setting up urban forests and other actions.

According to the Italian central government (Italian Government, 2017), regional and local administrations need €26 billion of additional funds in capital investment, representing the essential level of resources for addressing hydrogeological instability, including flooding, landslides, avalanches, and coastal erosion. Out of this sum, approximately €8 billion is already accessible through European Union funds, central government transfers and European Investment Bank debt. However, funding from Italy's central government is less specific, as it is subject to yearly allocations (Crisafulli et al., 2018).

The ReNDiS Report (Repertorio Nazionale degli interventi per la Difesa del Suolo, *National Database of the Soil Defense Interventions*) collates information on flood defences implemented on the Italian territory in the period between 1999 and 2019 (Gallozzi et al., 2020). In the last 20 years, more than 6.5 billion euro have been spent by the Italian government for hydrogeological risk mitigation, of which more than 3 billion are allocated for flood risk reduction. However, the investment in risk prevention - pre-disaster - (330 million per year on average) is modest when compared to the figures provided by the Italian Civil Protection about emergency and recovery costs of about 1.9 billion euro per year, yielding a ratio of 1:6 between pre- and post-disasters costs (Zanchini et al., 2020). Given this large discrepancy between resources invested in risk prevention and the cost of recovery following annual damaging events, it is of significant interest to identify the geographical correlation between the implementation of defences and the occurrence of events and how commensurate such defences are to the declared level of risk in the localities where they have been implemented.

Italy has a long history of flood management legislation, with the first law advocating a systemic approach dating back to 1989[1]. In 2006, the Hydrological Basin District Authorities were empowered to develop and implement plans to protect the natural environment, including hazard mitigation. (art.56 of D.Lgs 152/2006). The operational tool mandated by Italian law to identify and plan necessary actions aimed at mitigating the adverse impacts of floods on human health, territories, properties, the environment, cultural heritage, and economic and social activities (D.Lgs 49/2010) is the Piano Gestione Rischio Alluvione (PGRA). Such plans, which each Basin Authority develops, are designed by the European Directive 2007/60/EC, commonly known as the 'Floods Directive' (EU_FD) (D.Lgs 49/2010). Each plan should be updated every six years to ensure its relevance and effectiveness, therefore undergoing regular revision cycles. To date, two cycles have been implemented: the first between 2011 and 2015, the second between 2016 and 2021, and the third cycle started in 2022. The responsibility of preparing the maps rests with the regions, and Italy is one of the few European countries to have developed risk maps besides hazard extent maps (De Moel et al., 2009).

The research presented in this study relies on flood risk maps published for the first and the second cycle of the PGRA by by two basin Basin District Authorities which included the central and north-west part of Italian territory, and detailed information on 40 specific flood mitigation interventions funded over the same period. This study has two main objectives: the first objective is to integrate and analyse the ReNDiS database to identify mitigation measures funded in the intervening period between the publication of risk flood maps related to the two PGRA cycles. The second objective is to evaluate whether a

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[1] D.L. 183/89: Norme per il riassetto organizzativo e funzionale della difesa del suolo, later updated by D.L. 253/90

significant reduction in the level of risk can be determined where the selected mitigation measures have been applied. This will be achieved by overlaying the maps of the two PGRA cycles with the geographical coordinates of these measures. The method used to provide a synthetic interpretation and measurement of this potential correlation at the territorial level involves the definition of an index its variation over time. This quantitative assessment aims to determine whether the interventions have been located in the areas at highest risk and whether they have effectively reduced the level of risk within their respective areas of influence. Considering that mitigation measures can be constructed either close to the exposed assets that need protection, such as levees, or upstream of the sensitive assets, such as detention basins, understanding the effects of these measures in terms of their area of influence is paramount. By analysing the risk maps produced through the PGRA cycles, this study seeks to assess whether the current criteria used to create flood risk maps in Italy can accurately capture and document the benefits of flood risk reduction resulting from mitigation measures.

Ultimately, this study aims to ascertain whether economic and technical resources are appropriately invested and located to reduce hydrogeological risk over time. The findings of this study could provide valuable insights for policymakers and contribute to the optimal allocation of funding, considering risk in all its components when producing maps.

The rest of the manuscript is organised into distinct sections: Section 2 explores the materials used in this study, specifically an Italian database of geospatially located flood defence infrastructure and the flood risk maps produced according to the EU Flood Directive. This section details the methodology employed to establish the correlation between funding allocation and risk reduction. The correlation was determined by overlaying the data above and applying an index proposed by the authors. In Section 3, the study's results are presented and further divided into two sections, one devoted to the evaluation of the proposed indicators, and the other to the assessment of the effectiveness and efficiency of the interventions implemented. The concluding section conducts a comprehensive discussion, interpreting the results and delving into their implications.

2. MATERIALS AND METHOD

This section firstly presents the existing Italian legislation concerning flood risk, explicitly addressing the implementation of the EU Floods Directive (EU_FD) requirements and its enactment through Legislative Decree 49/2010. Furthermore, this section also outlines the two sets of data sources: a catalogue of flood defences implemented on the Italian territory in the period between 1999 and 2019, the ReNDiS database (ISPRA, 2021) and a collection of regional flood risk map produced in two different periods for the exact locations by the Basin Authorities, which support a diachronic reading of the evolution of flood risk with time. Finally, the methodology used to integrate these two sets of data and produce the two main outputs of the study is outlined.

2.1. FLOOD LEGISLATION IN ITALY

In 2007, substantial improvements in flood risk management were brought about thanks to the Flood Directive 2007/60/CE issued by the European Commission (European Union, 2007). The Directive aims to establish the criteria for flood risk assessment and management across the European Union territory to reduce potential damage and losses to human health, economic activities, the environment and cultural heritage (Trigila A., Iadanza C., Bussettini M., 2018).

The EU_FD defines the steps to be followed by the Competent Authority to produce Flood Risk Management Plans (Piani Gestione Rischio Alluvioni, PGRA). For each Unit of Management[2], the following activities should be performed:

- Preliminary flood risk assessment and identification of potentially affected areas.
- Flood hazard maps in the most appropriate scale: they should include three scenarios: low probability event (P1), medium probability events (P2) and high probability event (P3) according to the Legislative Decree 49/2010. For each scenario, flood extent, water level, velocity and discharge should be specified.
- Flood risk maps in the most appropriate scale: starting from flood hazard maps, for each scenario, Member States have to report potential negative consequences in terms of number of people potentially affected, type of economic activities potentially affected, industrial plants that could trigger environmental accidents, protected areas potentially affected, and cultural heritage exposed; so, based on the expected level of loss for homogenous level of value of the asset, Member States have to assign a class defined as follows:

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[2] Area of land and sea, identified under Directive 2007/60/EC of the European Parliament and Council as the main unit for management when an alternative to the River Basin Districts or Sub-Districts are chosen (European Union, 2007).

- D1 (very low or absent potential damage): wild vegetation areas and degraded land),
- D2 (medium potential damage): areas crossed by secondary infrastructure and minor productive activities have a limited impact on people and socio-economic fabric.
- D3 (high potential damage): Areas with safety and economic challenges intersected by crucial communication lines and services and hosting significant productive activities.
- D4 (very high potential damage): areas at risk of loss of life, highly urbanised, significant damage to vital economic, natural, historical, and cultural assets.

Once all steps are completed, risk classes R1 (lowest), R2, R3, and R4 (highest) can be defined using a matrix approach considering the convolution of the hazard probability level with the exposure level at each location, as shown in Table 1. The spatial extent of each risk level should then be visualised on risk maps.

- Flood Risk Management Plans (FRMP): they are essentially prepared based on the Flood hazard maps and flood risk maps. FRMPs articulate flood risk management objectives in areas susceptible to significant risks. They aim to mitigate adverse consequences on human health, land, property, the environment, cultural heritage, and economic and social activities. This is achieved primarily through implementing non-structural measures and actions designed to minimise hazards. These plans encompass a comprehensive approach to flood risk, emphasising prevention, protection, and preparedness. They include the development of flood forecasts and early warning systems, considering the unique characteristics of the river basin or sub-basin.

Table 1 Risk assessment matrix (Autorità di Bacino del Po, 2013)

RISK CLASS		HAZARD CLASS		
		P3	P2	P1
POTENTIAL DAMAGE CLASS	D4	R4	R4	R2
	D3	R4	R3	R2
	D2	R3	R2	R1
	D1	R1	R1	R1

Following adoption of the EU_FD in Italy, several additions and amendments were included and approved with the Legislative Decree 49/2010 (Italian Parliament, 2010).

Considering Italian-specific hazard conditions, the three scenarios mentioned above were defined as: a) very rare flood with extreme intensity: return period of up to 500 years (low probability), b) rare flood: return period between 100 and 200 years (medium probability) c) frequent flood: return period between 20 and 50 years (high probability).

2.2. DATA COLLECTION: ReNDiS DATABASE AND ITS IMPROVEMENT

The development of this work is based on data recorded by ReNDiS (ISPRA, 2021), a national database that collects hydrogeological mitigation projects funded from 1999 to date. The objective is to offer a tool that can provide a continuously updated overview of the projects and resources allocated to administrators involved in land defence planning. Projects are organised in two large classes: one of the projects awaiting funding, which is not accessible, and one of the already funded projects, which can be consulted through an *Open-data* web-based interface representing the main public access point for citizens to obtain data and information on work done in the field of hydrogeological risk by public authorities (Gallozzi et al., 2020).

The database is structured into subsections based on the particular environmental risks targeted by the interventions, ranging from flooding, coastal erosion, landslides, and avalanches to fires. It also includes interventions designed to address multiple hazards. The present study has utilised data on hydraulic mitigation works implemented in flooding and landslide risk mitigation projects. In ReNDiS (ISPRA, 2021), a detailed taxonomy is included for hydraulic interventions encompassing 31 different typologies of works, such as retention basin, embankments, river flow section adjustment, etc. However, in a relevant proportion of cases, such taxonomy needs to be clearly attributed to the interventions. Furthermore, although the specific work might be classified, no particular information is provided on the physical dimensions or start and end date of each project. While data on allocated funding is reported for all interventions included, a detailed breakdown of costs is not available.

A first analysis of the ReNDiS data was published in 2020 by ISPRA (Institute for Environmental Protection and Research) (Gallozzi et al, 2020) which identified 1963 flood risk mitigation projects, corresponding to 3671 specific mitigation works, 32% of the total recorded interventions. The associated investment amounts to € 3.2 billion, equal to almost 50% of total investment for hydrogeological risk mitigation. This data was updated to 2019. In the present study, an updated version of the ReNDiS database (February 2021) with data uploaded up to 2020 was analysed, containing 2620 projects and 4649 measures, about 800 more than the sample used in the ISPRA report. However, among those 2620 projects, more than 1600 records did not contain information on the specific mitigation works implemented. The authors of this study have integrated the database by further reviewing and analysing the existing metadata associated with each entry and a short technical description of the intervention. The purpose of this integration was to identify with greater confidence which specific mitigation works are most commonly applied for hydrogeological risk mitigation in Italy, with the objective of determining whether defence measures are still predominant with respect to adaptation measures.

The integration of the ReNDiS database was achieved by using two different data repositories of the ReNDiS *OpenData* section, i.e. *Elenco Interventi* and *Classificazione opere.* The first one contains the catalogue of projects officially included in the ReNDiS database, while the second one was used to coherently integrate the first file with information on the type of intervention implemented, using the intervention ID as the matching identifier parameter.

The *Integrated ReNDiS database* follows the organisation of the original ReNDiS database, and it contains the following data:

- Flood risk mitigation section: 2620 projects, including 4649 hydraulic mitigation measures. Of these, 1015 projects had specific descriptors for each hydraulic mitigation measure, whereas 1605 projects did not. Of these, 856 projects didn't contain sufficient metadata to identify unequivocally the type and extent of measures implemented. Therefore, the integration was successful in providing a total of 1764 records useful for the purpose of this study.
- Landslide risk mitigation section: 2150 projects for landslide risk mitigation in which 1288 hydraulic mitigation works were implemented, which did not need further integration.

Table 2 shows a summary of the data available before and after the integration: 5937 is the total number of flood mitigation measures contained in the *Integrated ReNDiS database*. However, 901 of them belong to the category *of Undefined hydraulic work due to a* lack of sufficient information for unequivocal classification. Hence, 5036 is the number of mitigation measures used as the basis for this study. These represent about 85% of all projects contained in the *Integrated ReNDiS database*, and therefore, the conclusions drawn from the ensuing data analysis can be considered robust and relevant.

Table 2 Comparison of mitigations works between the Integrated ReNDiS and the ReNDiS database.

Hazard	Mitigation works by hazard class (Integrated ReNDiS database vs ReNDiS database)	Total (Integrated ReNDiS database vs ReNDiS database)

Hydraulic risk mitigation	4649 vs 2777	5937 vs 4064
Landslide risk mitigation	1288 vs 1288	

2.3. BASIN DISTRICT AUTHORITIES RISK MAPS

The Italian territory is subdivided into seven basin districts, five on the peninsula and two on the major islands, each of them administered by an independent separate authority. Over the past ten years, a significant amount of effort has gone towards the development of flood risk maps to cover the national territory, towards compliance with the D.Lgs. 49/2010, for the adoption of the European Flood Directive. Since its inception, within the PGRA, each Basin District Authority has published flood risk maps with a cadence of five years so that the first cycle of mapping covered the period 2011-2015, while the second cycle related to the period 2016 -2021, and we are currently in the third cycle.

In this study, flood risk maps produced by Autorità di Bacino Distrettuale del Fiume Po (AdBPO), North-West of Italy, and Autorità di Bacino Distrettuale dell'Appennino Settentrionale (AdBAS) have been analysed, West-Central Italy. These maps provide four levels of risk (R1 to R4), which are obtained by correlation between the level of hazard at a particular location for a particular return period range (P1, P2, P3) and the level of potential damage that can affect the exposed assets within the floodplain as described in section 2.1.

Several uncertainties affect this risk mapping approach. An important element of uncertainty that concerns this study is the temporal variable. This takes two forms: first, the information on land use is not produced as a snapshot at a particular moment in time across the country therefore there are inconsistencies across the territory; second, although the maps have a reference release date, the information mapped is not time-stamped, therefore it is not certain whether a particular flood defence work has been taken into account and over which period, in other words, whether a change in mapping over time can be correlated to a particular hydraulic defence measure.

Moreover, differences also exist in the way risk maps are produced by the different Basin Authorities. While using the same classes of hazard and exposure, the AdBAS chooses to map the worst level of risk for each location while the AdBPO provides a map of compounded risk, which indicates for each location the level of risk associated with each level of hazard. An example of these two ways of producing the risk maps, is shown in Figure 1: in Figure 1a, a large portion of the territory appear as classified in R2 and R3 which overlay a class R4, invisible, while they are also overlayed by the class R1 hatching. In other words, the risk classes are layered, with the lowest risk, related to the highest hazard return period, being the uppermost layer. Figure 1b shows the modification of the mapping of the AdBPO case, by juxtaposing the risk classes, with the highest risk having the more confined areas and the lower classes expanding away from the source of flooding, as the return period increases. This approach avoids the overlaying of different risk classes, allows to identify immediately the areas at *significant* risk and homogenise the mapping of the AdBPO with those produced using the AdBAS approach, as shown in Figure 1c. This procedure is necessary to evaluate the *Risk Score*, as explained in section 2.3.

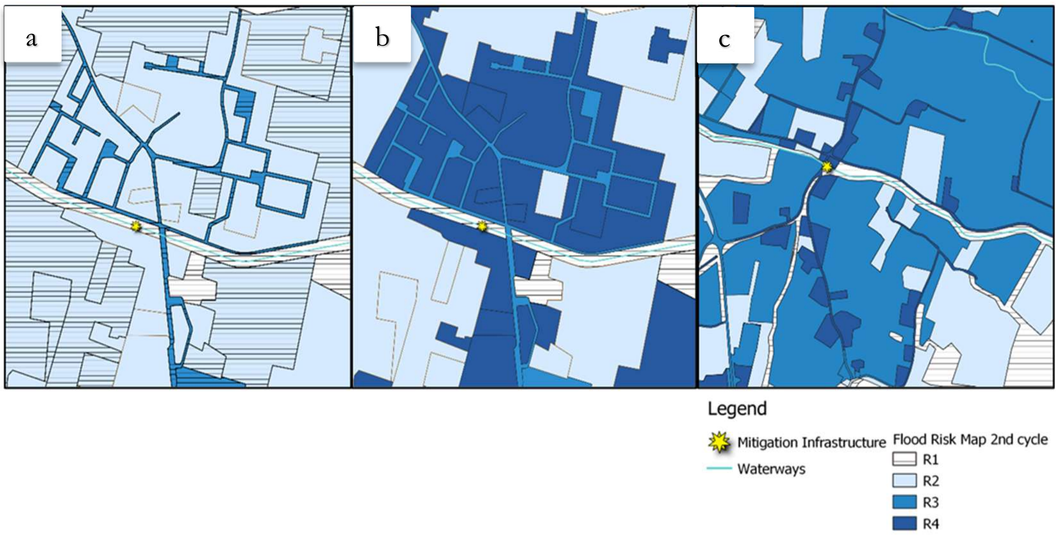

Figure 1 Risk Map produced for the second cycle of PGRA: a) overlayed areas with different risk class in map produced by AdBPO; b) modification of the map in juxtaposed areas by this study; c) map produced by AdBAS without overlaying of different risk classes.

2.3. METHODOLOGY

The workflow diagram in *Figure 2* illustrates the procedures followed. First, a statistical analysis was conducted using the data contained in the *Integrated ReNDiS Database*, to identify the distribution of interventions by class of flood mitigations, the ones that have been overseen by previous classification and trends of different types of interventions in time. The main trust of the study is, however, the correlation between flood mitigation measures and risk. This has been achieved by using the geolocation of all hydraulic works implemented in each project and overlaying them on the updated flood risk maps. The objective is whether the implementation of the specific measures has resulted in a reduction of the risk class in the surrounding area of influence, i.e. in a change of the risk level reported at the same location in the cycle of mapping following the realization of the flood defence work.

Projects were selected from the Integrated Database chosen from the two Basin Districts, according to the following considerations on time scale: i) the time frame required to realise a flood defence infrastructure from the year the funding decree is issued to the full construction and commissioning; ii) the time needed for the collection of data and the production of the maps themselves during each mapping cycle.

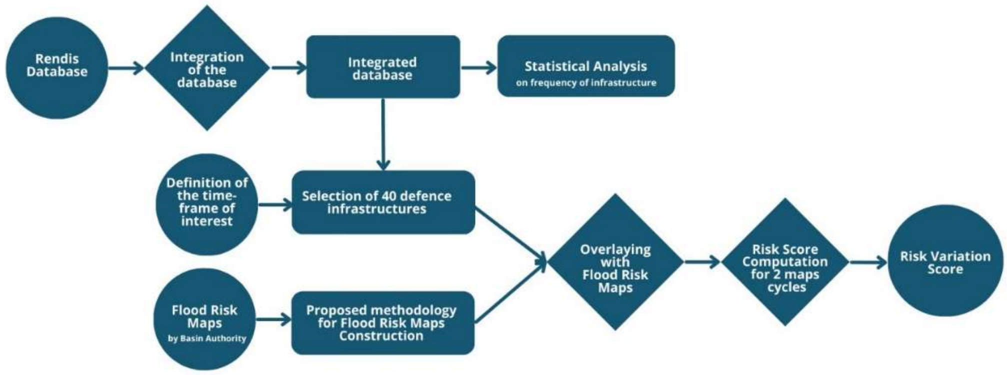

Figure 2 Methodology for the computation of the Risk Variation Score

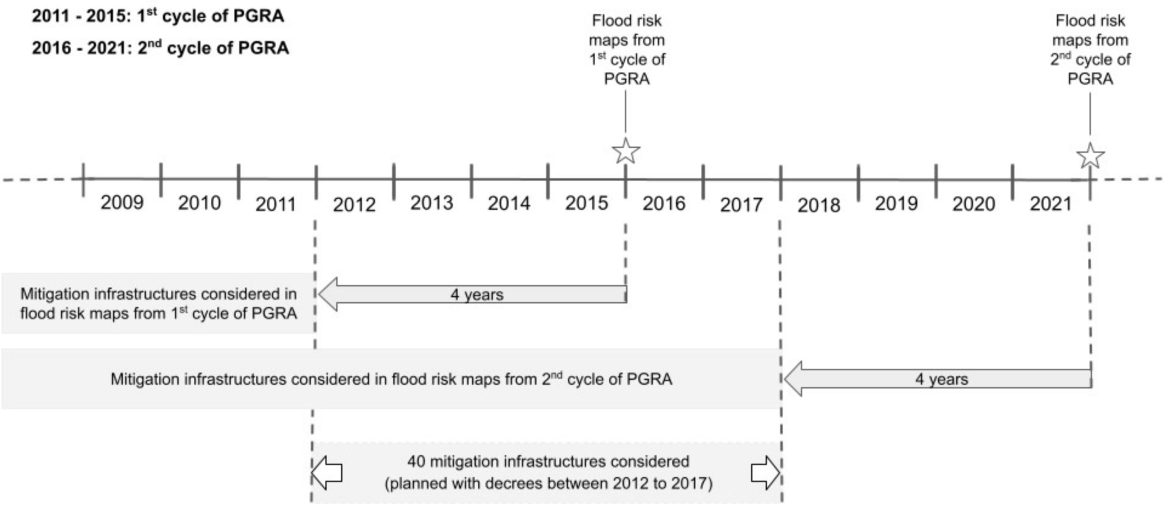

Figure 3 Schematic representation of the criteria used to define the period of interest for the selection of the flood risk reduction projects

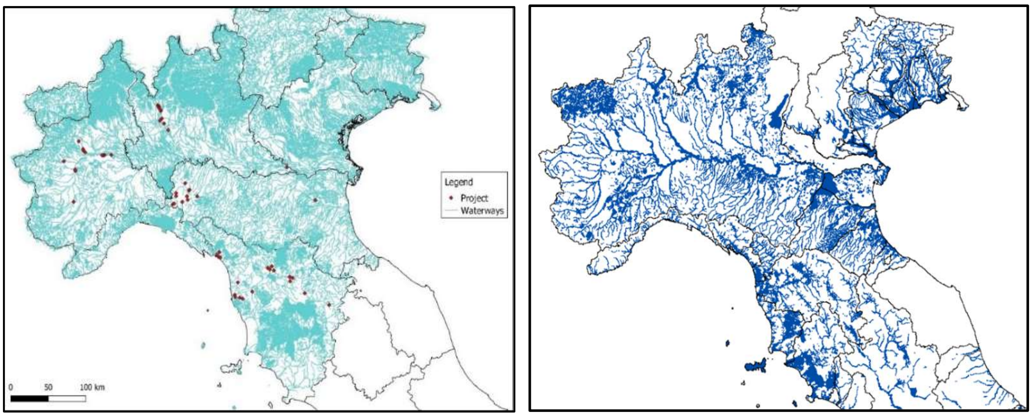

Figure 4 a) Geolocation of the 40 projects selected funded between 2012 and 2017. They are located in Toscana, Emilia Romagna, Lombardia and Piemonte regions; b) high probability flood hazard map (adapted from Trigila et al., 2021)

As shown in *Figure 3,* taking into account that the information available in the ReNDiS database relates to the date in which the funding had been allocated for a given flood defence work, not its date of commissioning, it is reasonable to assume that works funded up to 2011 would be included in the first cycle of mapping, while the effects of mitigation measures planned with decrees between 2012 to 2017 would be reported in the second cycle of mapping completed in 2021. Any work funded in the period 2018 to 2021 might not have been completed and commissioned during this period, an hence captured in the mapping of the second cycle of PGRA. Therefore, for the purpose of evaluating whether the change in risk level mapped between the two cycles is the result of flood defence implementation, works funded in the period 2012 to 2017 in 4 Italian Regions, i.e. Emilia-Romagna, Lombardia, Piemonte and Toscana, were chosen. As a result of this procedure, in the 4 Italian regions located in the two Basin Districts, 40 hydraulic projects respond to the criteria, out of the 1112 recorded in the 20-year period. These are geolocated in the map in *Figure 4a*, where they are overlaid to the waterways map. The Lastoria et al (2021) report highlights that in the same period of interest (2012 to 2018) 97 events occurred in the Po Basin district and 73 in the Appennino Settentrionale Basin District, equal to 31% and 23% of all events on the national territory, respectively. While an open-source catalogue of past flooding events with mapped affected area is not available (FloodCat, CIMA, 2020), *Figure 4b* shows the high probability flood hazard map produced by Trigila et al., 2021. The comparison highlights that most of the 40 projects selected are indeed located in areas that have been affected by flooding in the period of interest.

Considering the spatial variability of risk with time and the fact that hydraulic defences are not necessarily built at the location of maximum hazard or risk, the spatial dimension across which the analysis of the effects of implementing hydraulic works shall be assessed, should not focus narrowly on their geolocation and their immediate vicinity, as a mitigation infrastructure will influence not only the location in which it is built but a wider area both upstream and downstream. Moreover, this area of influence changes depending on the typology of work implemented, on the morphology of the site and on the hydraulic dynamics associated with it.

Therefore, a wider area that considers the influence of the work in the surrounding territory has been identified. In order to standardize the evaluation of the *Risk Score*, a conventional area of influence has been computed considering the same buffer zone irrespectively of the previously stated parameters. It is acknowledged that such area should be defined on a case-by-case basis when a detailed analysis is performed. The area of influence has been sized considering the different river regime of the water courses affected by the projects considered: some implemented on creeks or minor rivers, and some on major courses such as the Po River. Accordingly, the area of influence has been set as 2 km in length downstream and upstream from the hydraulic infrastructure, and 600 metres on each side of the embankment at the location of the infrastructure. *Figure 5* shows a schematic representation of the construction of the conventional area of influence done for the 40 mitigation measures considered.

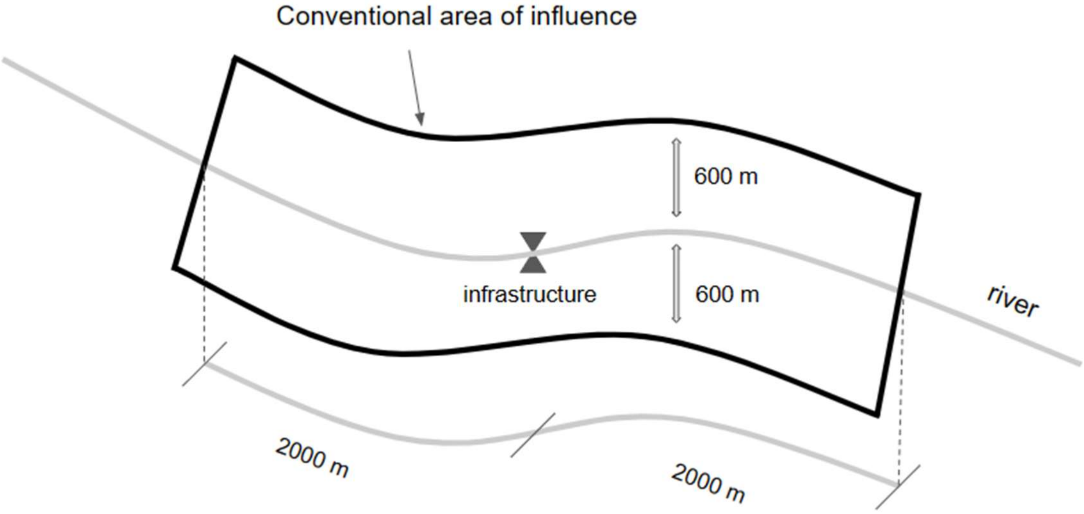

Figure 5 Schematic representation of the methodology used to define a conventional area of influence

To understand if the current mapping of flood risk is suitable to capture the benefit of risk reduction of the mitigation measures, firstly, a *Risk Score (RS)* is proposed, defined with reference to the sum of areas at risk:

$$RS_i = \frac{\sum_{j=1}^{4} AR_j * r_j}{\sum_{j=1}^{4} AR_j} \quad i = 1,2 \qquad (1)$$

Where:

- i=1,2 refers to the Risk Score evaluated from respectively first and second cycle of PGRA risk maps
- r_j are Risk Weight Factor
- AR_1 is area at risk 1 (= low risk or absent)
- AR_2 is area at risk 2 (= medium risk)
- AR_3 is area at risk 3 (= high risk)
- AR_4 is area at risk 4 (=very high risk)

For the *Risk Weight Factors (RWFs)* r_1, r_2, r_3, r_4, empirical values equal to 0.1, 0.3, 0.5, and 1 have been assigned, respectively, coherently correlated with the probability of occurrence of an event.

The classification of the risk is coherent with the legislation and production of the risk maps by the Basin District Authorities. It is worth noting that the value assigned to *RWFs* can be modified according to criteria established by different legislation or identified by any Basin District Authorities. Then, to determine and quantify the benefit intended as a risk reduction, the difference between the RS_i is defined as the *Risk Score Variation* (RSV):

$$RSV = RS_2 - RS_1 < 0 \tag{2}$$

where RS_2 and RS_1 are the *RS* computed respectively for the second and first cycle of PGRA mapping.

For RSV to indicate a benefit of the realization of the project, as reduction of the Risk Score computed in the second cycle with respect to the Risk Score computed in the first cycle, it should result in a negative value.

3. RESULTS

This section firstly shows a national level analysis of the hydraulic infrastructure based on the information collected in the integrated ReNDiS database. The analysis encompasses the identification of typologies of hydraulic works most commonly implemented and their distribution, including the corresponding funding over time. This data has then been correlated with the mapping of flood risk in 4 Italian regions within the two District Basins of interest, where more than 40% of all interventions funded in the last 20 years are located, according to the ReNDiS database. The correlation is performed by computing the *Risk Score* and *Risk Score Variation* for each of the 40 cases of mitigation measures identified in the previous section. These results are further analysed to determine if the interventions had been designed specifically for areas of *significant* risk, as identified in the first reporting cycle, and to assess their efficiency and effectiveness via a cost/benefit analysis based on investment and computed risk reduction.

3.1 ANALYSIS OF THE INTEGRATED ReNDiS DATABASE

Figure 6 compares the number of flood mitigation works by year before and after the integration of the ReNDiS database. It can be seen that the original records were relatively accurate in the first decade, while a large gap is present in the second decade after the introduction of the legislation in 2007 at European level. In 2010, following the enactment at national level, the number of reported works for that year was substantially higher representing 34% of the total number of works reported in the 20 years period (see also

Figure 9). Of these, only 30% were present in the original database. This substantial increase of funding, however, has not been sustained in the following years neither renewed at the beginning of the second cycle in 2016.

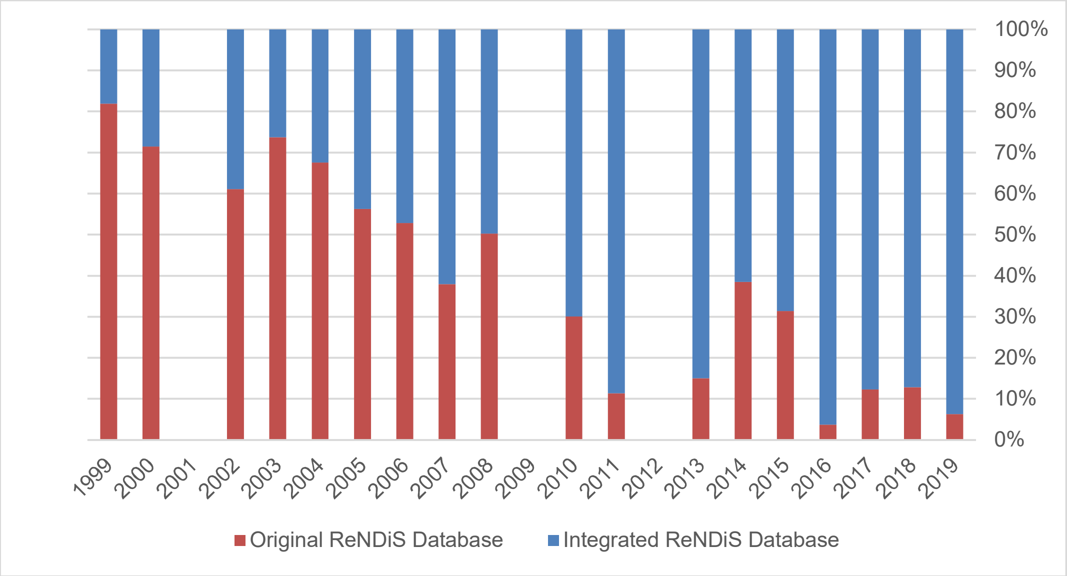

Figure 6 Proportion of funded projects by year in the two databases

The first ten typologies reported in *Figure 7* account for little more than 50% of the possible 45 typologies included in the ReNDiS. This highlights that while larger structural projects such as detention reservoirs have been consistently reported in the ReNDiS original database (shown by 100% reporting in *Figure 7*), the more nature-based solutions needed more substantial integration. The most common of all typologies is *River flow section adjustment* which accounts for 1/6 of all interventions, of which at least 1/3 was added with the integration activity. Moreover, in the original database the sixth most common class represents *Other complementary works* which does not allow an interpretation of the type and importance of the intervention. Furthermore, when clear details were not provided, in the Integrated Database these have been classified as *Undefined hydraulic works* which becomes the second most common class. Because of this uncertainty and the fact that funding is reported for a project as a whole irrespective of the number and type of specified works within it, it is difficult to identify trends in allocation of funding for nature-based interventions as opposed to structural defence works, at this stage of the study.

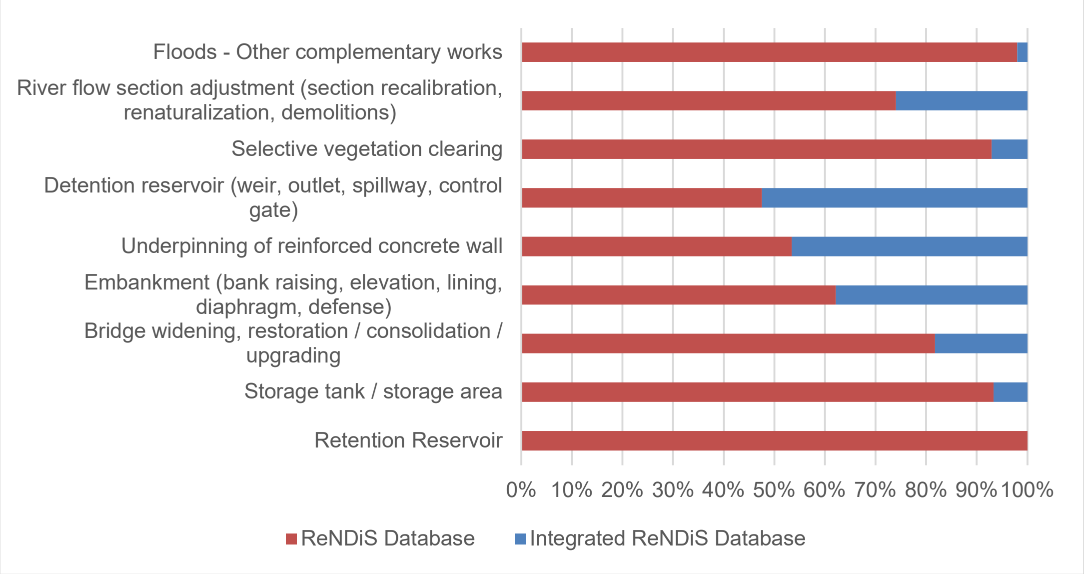

Figure 7 Figure 13 Proportion of class of flood mitigation works in the two databases

Figure 8 shows the classification of the intervention included in the Integrated Database and their occurrence, reported by year of funding and subdivided in four periods, which are correlated with the risk map reporting periods. According to the assumptions discussed in the methodology section, the four periods have a different range identified by critical events:

- 1999-2007: from inception of the ReNDiS database to the European Flood Directive
- 2008-2011: between the Flood Directive and the assumed end of the funding period included in the first
cycle of risk mapping
- 2012-2017: the period during which the interventions recorded in the risk maps of the second cycle were
funded.
- 2018-2019: intervening period of funding between the second cycle of mapping and up to the latest year of funding of the most recent update of the ReNDiS database

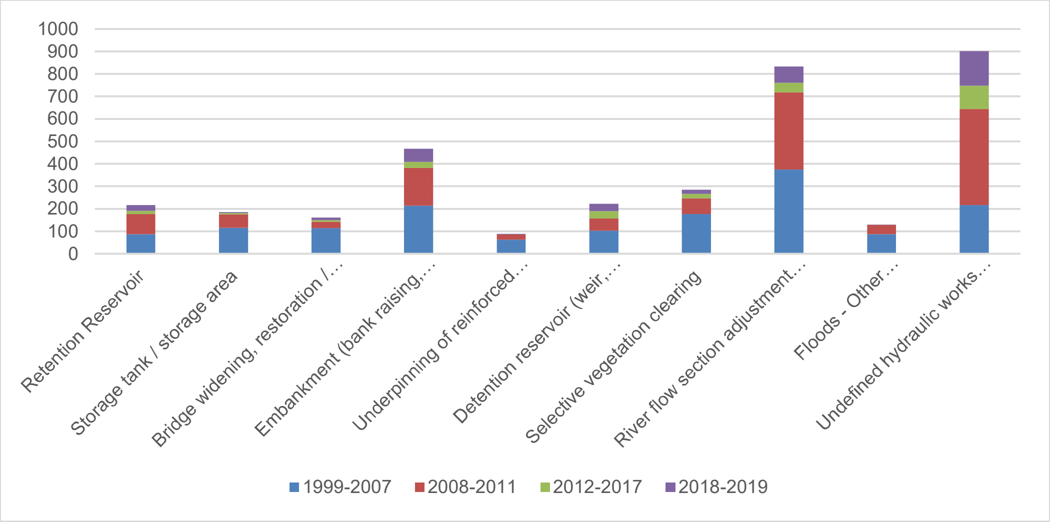

Figure 8 Types of mitigation measures funded in the period 1999-2019 according to the Integrated Database

As shown in *Figure 8*, the number of mitigation works recorded within the third period, which is of interest for computing the risk indices, accounts for 7% of reported works for the ten most common typologies, in line with the observations that more than 80% of the interventions reported in the database received funds before 2012. Nonetheless, it can be noticed that the frequency distribution of the typologies of interventions for the period of interest represents well the distribution over the whole period of the database. The most common interventions remain *River flow section adjustment*, while an increase in the frequency of the *Detention reservoir* is observed compared to the whole database. This is significant because this type of infrastructure usually entails substantial funding, and they are well known to be implemented explicitly with the objective of flood risk reduction.

Indeed, *Figure 9*, which summarises the proportion of total projects and funding by year, shows a substantial correlation between projects and funding for the years up to 2010, with a substantial increase in 2010, as already noted. What is relevant for the specific analysis conducted in this study, is that in the period 2012-2017 to a 8% of total projects were funded, corresponding to 22% of total funding, with a concentration in 2015. Indeed, for this year, of the 35 projects funded, 54% include *Detention reservoir* work.

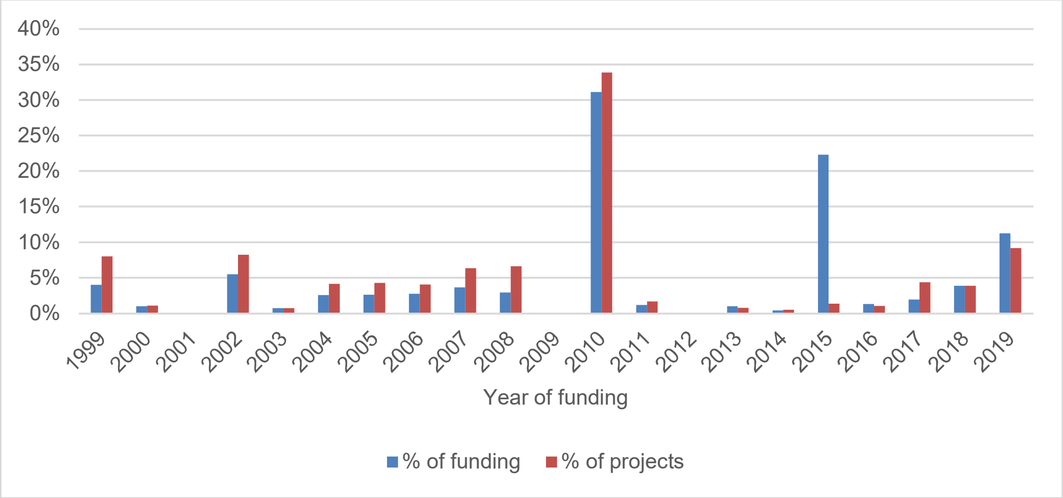

Figure 9 Distribution of projects and funding by year

The Integrated Database was also used to analyse the geographical distribution of funding allocation, and results were compared to the number of flood defence infrastructure in each of the Italian Regions, as shown in *Figure 10*, which highlights that there a clear correlation between investment in flood defence infrastructure and the number of mitigation infrastructures. Of the two Basin Districts of interest introduced in the methodology, AdBAS and AdBPO, the study concentrates on 4 Italian Regions, Emilia-Romagna, Lombardia, Piemonte and Toscana, where 44% of the total projects included in the database are located, corresponding to 39% of the total funding. Therefore, the application of the procedure highlighted above, if successful, can be considered significant at the national level. Of the 2620 projects recorded in the ReNDiS database, 209 were funded in the period 2012-2017, and 40 of these are located in the 4 Italian Regions of interest. Therefore, the analysis of the correlation of financed projects to risk zonation has been developed for this reduced set of projects.

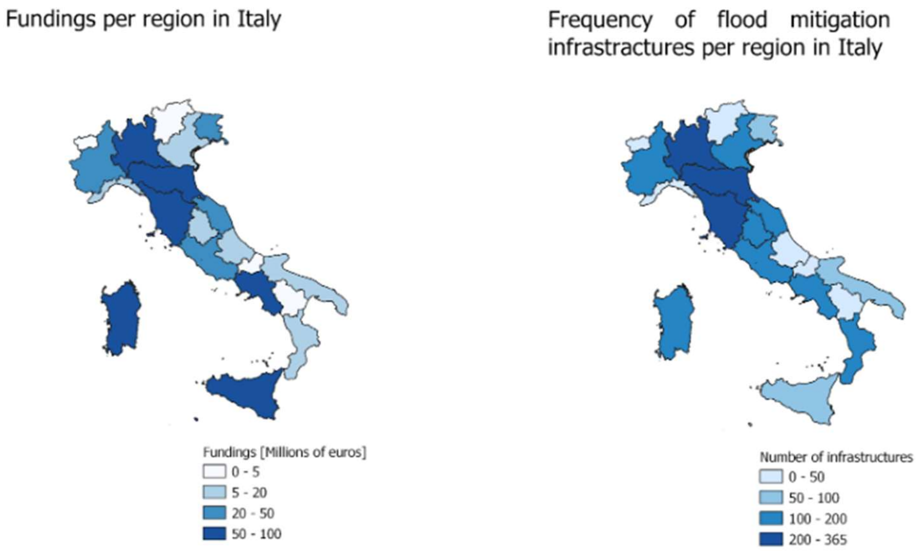

Figure 10 Funding (on the left) and frequency (on the right) of flood mitigation infrastructures per region in Italy according to the Integrated ReNDiS Database

3.2 EVALUATION OF RISK SCORE AND RISK SCORE VARIATION

As already highlighted in *Figure 4*, the 40 projects considered are clustered in a specific territory of each region. They are located in areas encompassing the four risk classes identified by the PGRA. For 3 of the four regions, i.e. Piemonte, Lombardia and Toscana, the projects are all located in urbanised areas, from high exposure cases such as Milano, Torino and Firenze, due to their high-density population to urban medium-density in provincial cities such as Livorno and Massa, to rural settings in Emilia Romagna near smaller town centres. Therefore, the PGRA mapped risk is affected not only by differing levels of hazard associated with the different hydrogeological characteristics of the waterways included in the area of influence considered but also by significantly differing levels of exposure, which is at the basis of the definition of risk classes for the PGRA ((European Union, 2007; Italian Parliament, 2010). Given this distribution, results may be considered significant beyond the relatively small area of influence determined for each project location and at a larger scale beyond the four Regions and the two Basin Districts considered. *Figure 11* shows the correlation between RS_i computed for the first and second cycle of mapping. The methodology used to calculate the RS_i proves to be appropriate as it provides the full range of values without saturating to 1.00, which would be unrealistic as all areas of influence considered include relevant portions of the lower-risk classes. The analysis of the 40 cases highlights that the mapping of the two cycles was substantially different: within the same area of influence chosen as discussed in the methodology section, in many cases, the second cycle mapping assigned a risk class to areas which had not been classified during the first cycle, as shown in *Figure 12*. This notwithstanding, in many cases, the values of RS_i computed for the first and second cycle of mapping are very similar as it can be seen in *Figure 11*, where the ratio of the two scores is close to 1 in more than 70% of the cases. Nonetheless, a reduction in subscript base, cap R, cap S, end base, and sub i. is visible in 20% of cases, while a modest increase can be noted in less than 10% of cases.

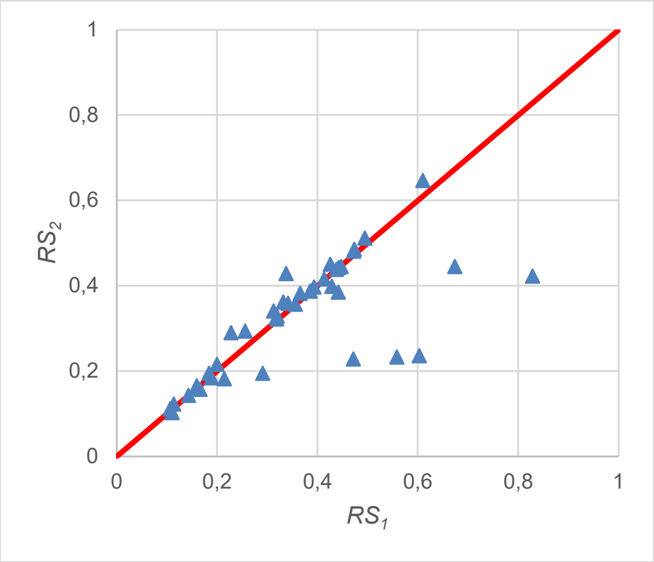

Figure 11 Correlation between RS computed for the two cycles of PGRA

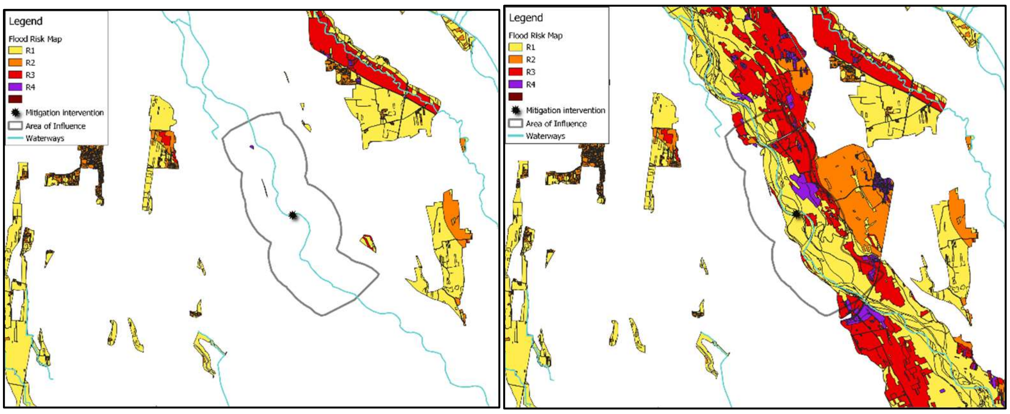

Figure 12 Differences in risk mapping between the first and second cycle of PGRA. The second cycle mapping assigned a risk class to areas which had not been classified during the first cycle within the area of influence

Given these considerations, although in theory it might be more rigorous to quantify the RS_i with respect to the same total area in two subsequent cycles; in practice, such computation would not be significant given the substantial difference in area with no defined risk between them. Indeed, *Figure 13* shows that for all risk classes, there is a substantial increment in the total area mapped between the two cycles, reaching more than 40% for the AR_1 and AR_4. Therefore, although both approaches were initially considered, it was finally decided to use only the areas classified in any of the risk classes in the two cycles of reporting.

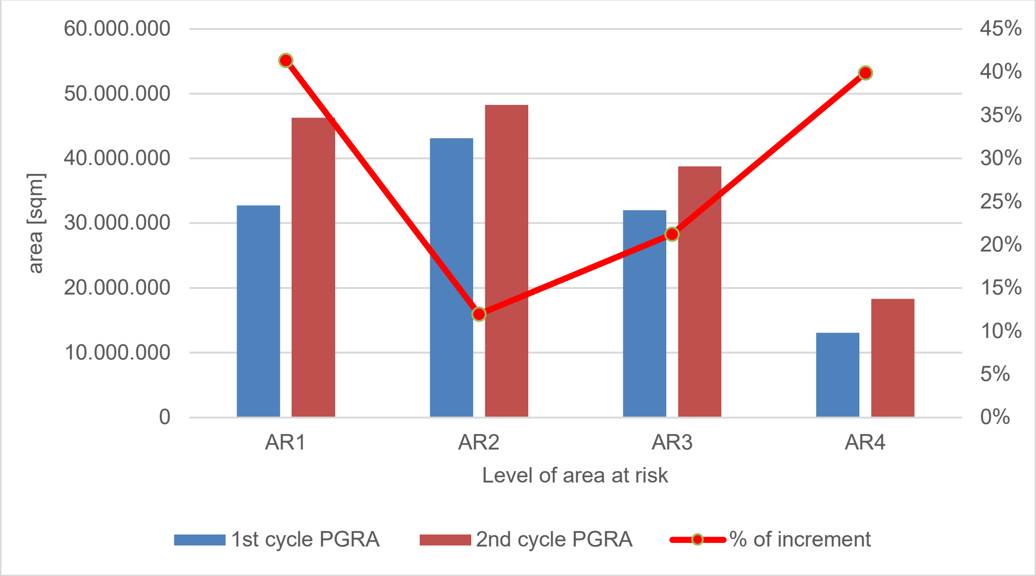

Figure 13 Overall variation of risk class areas between the two cycles for 40 projects

The *Risk Variation Score* is therefore computed considering the difference in RS_i, as shown in *Figure 14*, which could result from a more comprehensive mapping, as explained above and shown in *Figures 12 and 13*. However, it should be noted that the larger reduction in risk corresponds to the larger increase in the area at risk mapped in the second cycle concerning the first cycle (*Figure 15*). This is an interesting result as it shows that areas at low risk (AR_1 and AR_2) have higher proportion of the total area in respect to the areas at higher risk in the second cycle maps. Moreover, in few cases there is a reduction of the area at risk between the second and the first cycle, to which does not correspond a negative RSV. Nonetheless, these values of RSV although positive are relatively small. In these cases, it should be evaluated if the effect, in terms of reduction of the risk related to the implementation of mitigation works in the specific area of influence, has been considered and recorded in the map.

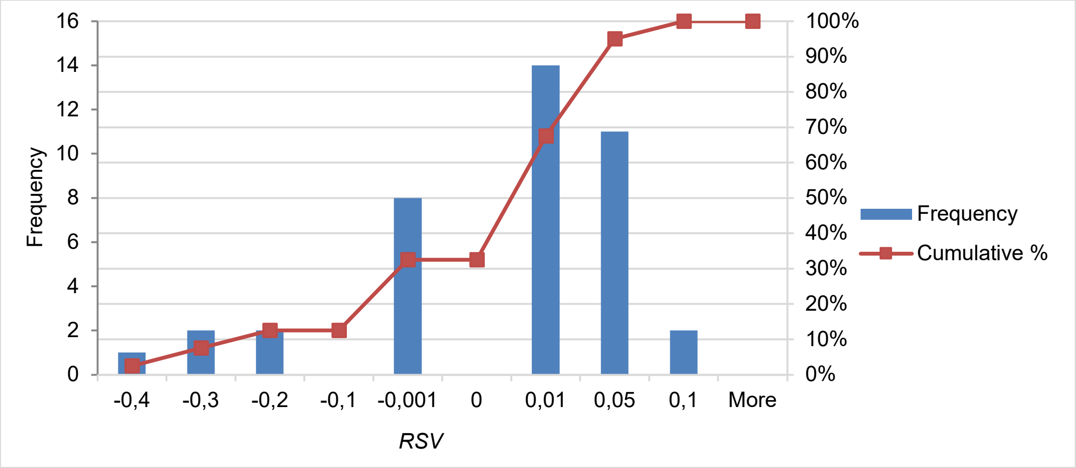

Figure 14 Risk Score Variation distribution and cumulative rate

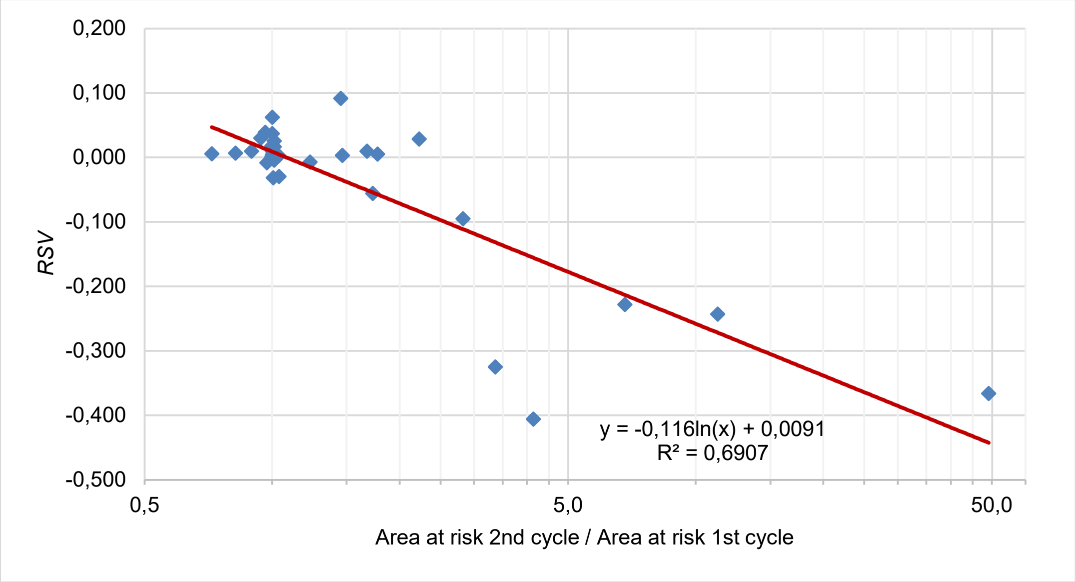

Figure 15 Correlation between the RSV and the ratio of area at risk between the two reporting cycles

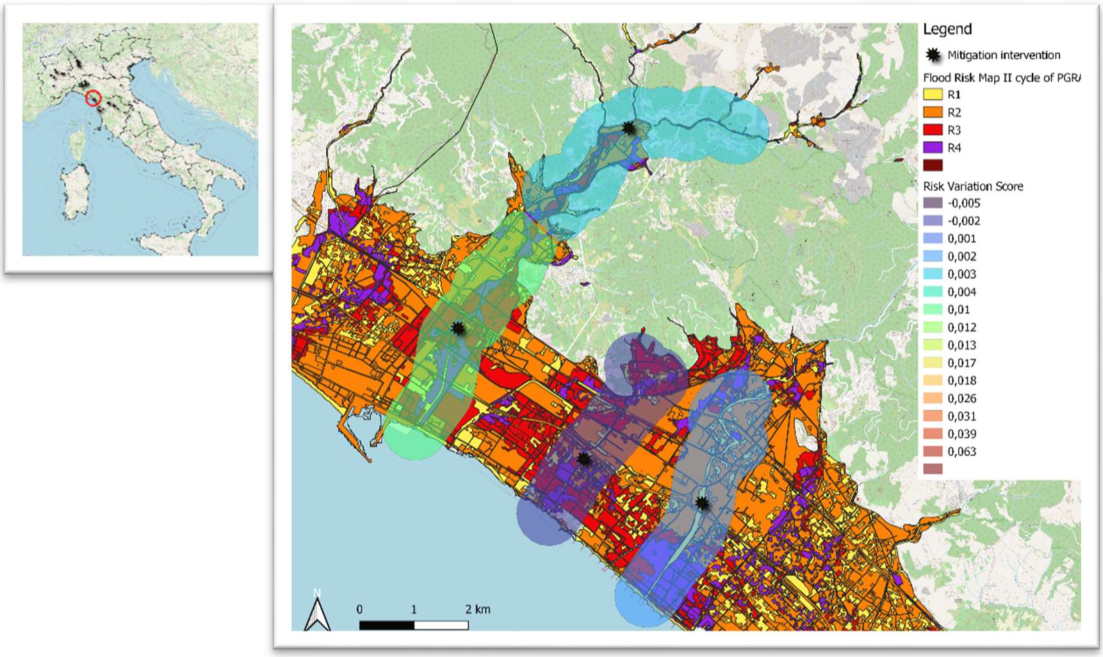

Figure 16 RSV mapping for 4 areas of influence related to projects in Marina di Carrara urban area, Toscana. Underlaid the flood risk map produced for the second cycle of PGRA

Almost 50% of the cases appear to have no change in the area mapped as at risk and values of the RSV close to zero, showing that there is no change in the attribution of risk classes to the area and, therefore, no apparent capture of the beneficial effects of the risk mitigation works, as shown in *Figure 16* , which are very slightly negative or positive.

The computation of the RS_i was also compared with the amount of funding for each project. *Figure 17* shows the relation between the RS_i and fundings. No strong correlation between the two variables exists, although the slope of the regression lines is smaller for the RS_2 indicating a reduction in the overall risk. Indeed, it should be noted that irrespective of the funding amount the four cases with the higher RS_1 show a substantial reduction in RS_2.

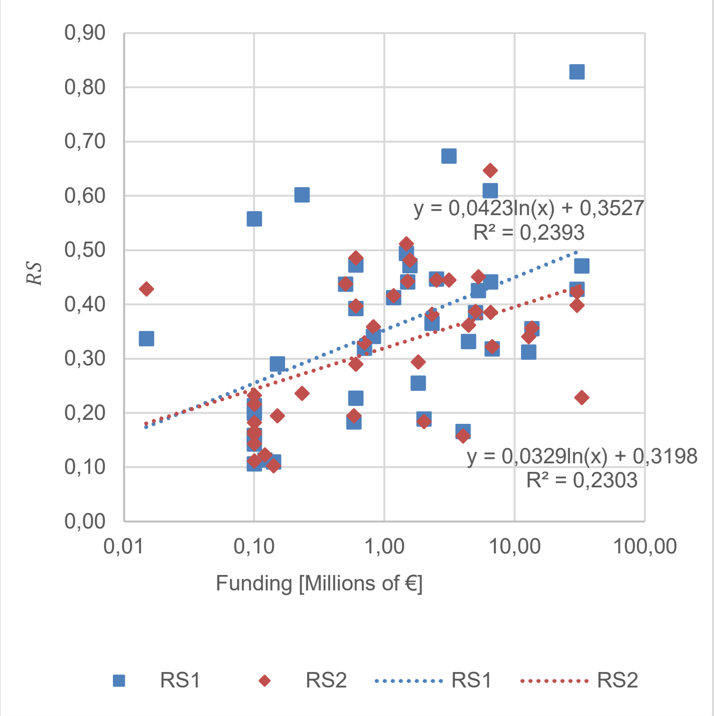

Figure 17 Correlation between RS for the two cycles and fundings associated to the 40 projects

3.3 EFFECTIVENESS AND EFFICIENCY OF THE INTERVENTIONS

As discussed in the introduction, The EU_FD is required to identify areas at *significant* risk in the first cycle of assessment and then use the maps to plan, locate and implement mitigation interventions in the period between the two cycles of reporting. Therefore, if this procedure has been followed, within the two Basin Districts of interest, the value of RS_1 recorded for the 40 interventions considered should be relatively high, to reflect the EU_FD strategy. *Figure 18* shows that as many as 25% of the case studies have a value of risk lesser or equal to 0.2, which highlights that there was no contribution of the highest risk classes to the risk zonation within the area of influence considered, while only about 10% show a value of RS_1 is greater than 0.6, outlining a *significant* risk.

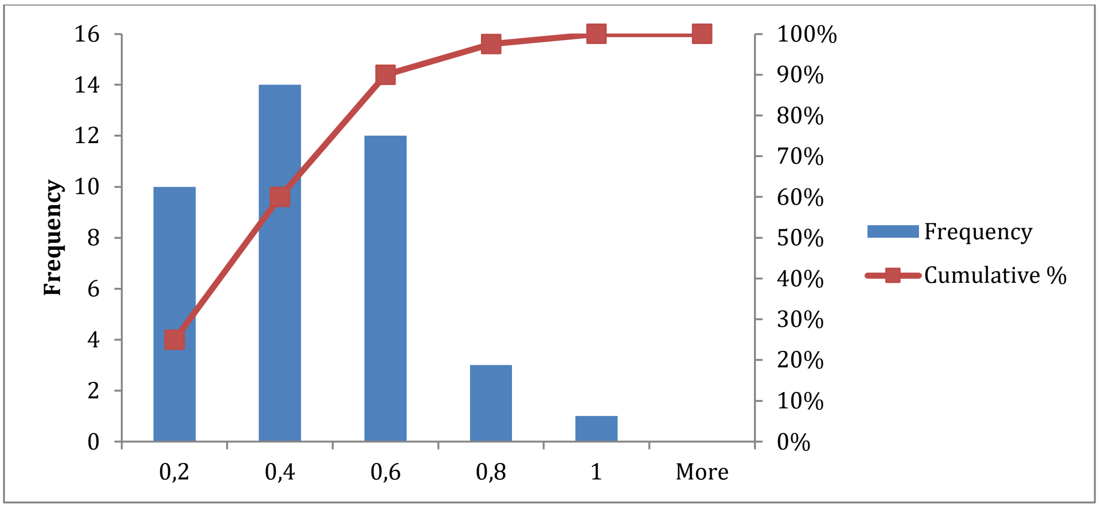

Figure 18 Distribution of RS_1 values in the studied sample

In addition to understanding whether funding and infrastructure were implemented where the need was greater, and thus where the level of flooding risk was higher, efforts were also made to address another aspect regarding the reduction, or lack thereof, of the risk level following the construction of infrastructure within its relative area of influence. It was therefore chosen to investigate whether the investments have been effective and efficient. The term *effective* refers to an investment that has led to a reduction in the risk level; the term *efficient* refers to an investment that has a benefit/cost ratio greater than 1. Indeed, quantifying the benefits of adaptation measures is crucial for planning nationwide coordinated actions for flood risk reduction, given the potential intensification of the hydrological cycle and its extremes and the increasing urbanisation pressure (Alfieri et al., 2016).

Figure 19 shows the RSV as a function of funding. It is quite evident that no correlation can be identified. The black line, which coincides with the x-axis, divides positive and negative value of RSV is useful to identify which projects have been effective. Moreover, the red line is identified by the ratio between the maximum investment and the maximum reduction observed in the sample of interventions analysed, and it can be used to identify efficient projects. If this is assumed as the rate of efficiency for the projects considered, then points on or below the red line represent interventions with an optimal efficiency while points between the two lines represent interventions which are effective but not necessarily efficient. Of the six projects highlighted in green that show a good level of efficiency, two are located in urbanized areas in Lombardia and they refer to the construction of two large detention reservoirs with the largest investment cost of the analysed sample; two projects are located in Piemonte, one relative to the construction of river embankments and the other one a smaller intervention on river flow section adjustment; and two projects are located in Emilia Romagna related to the flow section adjustment of a creek corresponding to a very low value of investment.

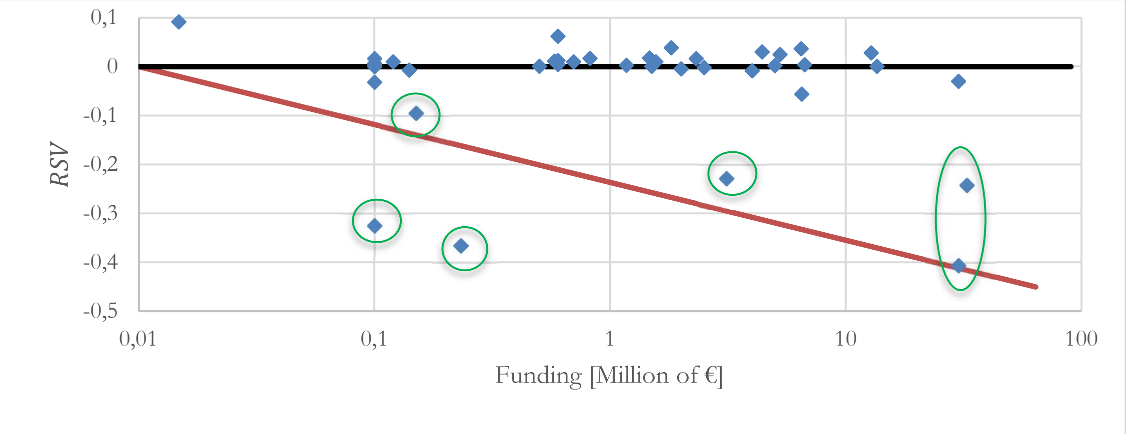

Figure 19 Correlation between RSV and funding associated to the 40 projects

4. DISCUSSION AND CONCLUSION

The EU_FD had two major objectives: to harmonise the representation and communication of flood hazards and flood risk among the Member States, and to improve citizen participation in the flood risk management cycle (European Union, 2007) from prevention to preparation, response and recovery (Wehn et al., 2015). The timely and accurate production of hazard and risk maps and the integration of these maps with the position and area of influence of hydraulics works, is therefore a priority to achieve both objectives, to provide correct information and to record the evolution in flood risk with investment in flood defence and mitigation. A recent European Commission Report (European Commission - DGE, 2021) on risk mapping practices across the Member States highlights that the process of defining baseline maps for hazards and risks is a well-established practice across the Member States. However, establishing appropriate indicators to monitor the effectiveness of the measures taken is rather limited. The European Commission SWD 2021 document (European Commission - SWD, 2021) requires the Member States to report the state of implementation of mitigation measures identified by each River Basin District Authority during the first cycle by the end of the second cycle.

In this context the attempt of the present study to perform a multi-layered mapping analysis of hydraulics existing infrastructures and flood risk zonation to understand if there is a correlation between geographical distribution of funding for flood risk mitigation, and the official level of risk recorded for a specific area, by comparing the risk reported in the two successive cycles, is therefore timely and innovative. Indeed, no other study has been identified in the literature proposing a methodology to provide a quantitative risk index (Adamson, 2018).

However, the application of the methodology has found several hurdles, which are not limited to the Italian implementation of the EU_FD, according to the EC SWD 2021 document (European Commission - SWD, 2021). The first is the accurate reporting and classification of the mitigation measures implemented. The authors obviated to this by producing the Integrated ReNDis database at Italian level, updated to 2019. The integration was particularly critical for projects funded in the period 2012 to 2017, which are the ones that would have been financed and implemented between the two reporting cycles. However, some uncertainty on the date of implementation remains and, therefore, might affect the results obtained. Moreover, a further uncertainty relates to the fact that the maps' publication date is not necessarily the correct reference for the data collection date, underpinning the map production. However, this date is not available. To mitigate this, only projects which had been funded 4 years before the end of reporting of the second cycle were considered for the analysis, which substantially reduced the size of the initial sample.

The second issue is the harmonization of mapping. In October 2023 the European Commission Directorate-General for Environment released an online “Flood Risk Area Viewer” (European Commission - DGE, 2023) which allows an overview of all areas considered at *significant* risk of flooding, as identified and mapped by Member States. The tool does not define a specific level of risk, and the areas at risk are mapped with different symbols by Member States, providing a different perception of risk and making comparisons difficult. Importantly, with reference to the present study, some countries include existing flood protection measures in their calculation and representation of risk, while others do not. Differences in the production of the risk maps for different Italian Regions were identified and modified in this study. However, the major limitation is in the fact that across many European countries risk mapping has been a progressive process, whereby in the first cycle, members states were tasked with identifying only the area at *significant* risk. In contrast, the second cycle of mapping has produced new cartography where risk zonation has been extended often to include areas at lower risk. For this reason, the extent of areas at risk in the two cycles within the areas of influence chosen in this study, are not commensurable and this limits the outcome of the *Risk Score Variation.* Nonetheless, as maps have been substantially integrated during the second cycle, future variation in mapping shall be mainly related to the reduction of risk delivered by the implementation of mitigation measures. Therefore, the methodology proposed will be able to provide more meaningful results in future cycles. The proposed *Risk Score Variation* has successfully measured a reduction in risk between the two cycles, in a few of the cases part of the studied sample, as shown in the Results section. It can be expected that, as more projects will be implemented in future cycles, and the monitoring of flood hazard and flood risk will become more regular and consistent, it will become possible to fully quantify and communicate the significance of interventions on risk reduction and, therefore, justify the investments.

A critical parameter for the calculation of the *Risk Score Variation*, and the benefits afforded by the implementation of the interventions, is the determination of the area of influence of each project, in relation to the existing mapped hazard and mapped risk. No information is provided to ascertain if the hydraulic infrastructures and their influence are included in determining risk. To determine their influence rigorously, information on the hydraulic and hydrological details of the project are needed and these are not currently captured by the ReNDiS database. For this reason, a conventional area of influence was chosen in this study, adapted to the specific hydrology of the location of the project considered. In computing the RS_i two approaches were tested, finally opting for the one in which the area sum excludes areas which were not mapped at risk, as this provided a more realistic assessment of the RS_i, as shown in the previous section, where negative value of RSV are well correlated to increases in area at risk between the two cycles.

The implications of these findings are significant: it appears that infrastructures were not planned and built in the most high-risk areas; the majority of the case study are located where the RS_1 is lower than 0.5. Similarly, no strong correlation between funding and RSV is achieved. Hence, it should be concluded that the relevance of the infrastructure is not directly recognised in the risk maps. Nonetheless, it has been possible to identify projects that can be classified as effective and even efficient. The largest projects are detention reservoirs, a typology which has been identified by Dottori et al., 2023 as the most economically attractive option in reducing flood losses and population exposure in Europe, when considering scenarios without climate mitigation. In the past century, engineered hydraulic infrastructure, such as dams, levees and deep embankments, have preferentially been used to control river discharge and prevent flooding. However, many of these infrastructures worldwide is now aged, deteriorating and increasingly costly to maintain (Opperman & Galloway, 2022). Moreover, it is increasingly recognised that the presence of flood defence infrastructure may diminish the perception of risk and favour development, which becomes vulnerable to the defence's failure or leaves the community unprepared for events with a higher return period and more devastating consequences (Alfieri et al., 2016; Vogelsang et al., 2023) . While construction on flood plains has been a consistent drive of urbanisation in the past 50 years, current trend in flood management now increasingly recommends non-structural interventions, such as zoning to avoid development in flood-prone areas, as well as structural interventions (Opperman & Galloway, 2022). The restoration of floodplains by implementing nature-based solutions integrated in urban areas is gaining increasing attention. Although the literature on cost-effectiveness of these solutions is modest, a few studies identify storm water retention areas and river flow section adjustment, through re-naturalisation, as cost-effective (Li et al., 2019; Turkelboom et al., 2021). This confirms the four cases of river flow section adjustments that the present analysis has indicated as effective and efficient.

Overall, the present study indicates that planning and decision-making for flood prevention do not sufficiently rely on risk-based considerations in allocating funds, with decisions being driven more by assessing hazard than risk. Nevertheless, it is essential to consider that the dataset is relatively limited to draw overarching conclusions. The method will benefit from including new infrastructure-related data in the database and the next update of national-level risk maps for the third cycle of reporting of the EU_FD. The ReNDiS database, in conjunction with the risk maps, represents highly valuable information for assessing the current state of flood defence implementation at the national level and establishing risk-based criteria for the design of infrastructure projects.

Data availability

Data will be made available on request.

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CHAPTER 4 – CONCLUSIONS AND FUTURE DIRECTIONS

This doctoral research was carried out in light of the increasing request for design approaches based on the identification of the best ratio between cost for implementation and benefit, intended as reduction in the level of risk. The focus has been on hydraulic infrastructure for flood risk mitigation, a fundamental although debated strategy for flood risk mitigation, with the objective of addressing two key questions: firstly, whether it is feasible to identify cost functions directly correlated with geometric design parameters, and secondly, whether the risk reduction resulting from their implementation is observable and effectively reflected in risk maps.

In the perspective of surpassing traditional approaches, with the aim of adopting a novel approach for the design phase centred on identifying the optimal balance between implementation cost and risk reduction, a cost model is proposed based on project data. Efforts are made to limit the number of independent variables to a maximum of two. The objective is to determine whether the variability in the cost of a project (comprising three distinct types) can be accurately captured by only two variables. Consequently, the cost function is conceptualized as a bidimensional function, illustrating the relationship between the project's cost and these two parameters.

Following the design and implementation of mitigation measures, this work analyses the correlation between defence infrastructure implementation and flood risk mapping and reduction, using an open-access database and flood risk maps published by few Basin District Authorities in Italy. Through the introduction of two indicators (the *Risk Score* and the *Risk Score Variation),* it was possible to correlate reduction in risk classes and implementation of infrastructure.

Regarding the first topic addressed, the results obtained from the regression model generally indicate a slight underestimation of costs by 4% compared to project costs. However, in cases where polynomial regression was employed, it became apparent that, despite showing an improvement over linear regression, some higher-order components of the variables used were statistically not very significant. It is evident, therefore, that among future steps, there is a need to verify if additional regression models provide a better fit to the project data.

Moreover, despite the parameters demonstrating a good fit of the data, there remains a discernible difference between the modelled costs and those of the project. This disparity is undoubtedly due to some difficulties and limitations encountered during the definition of Simplified Functions, as explained previously. Hence, among future steps, it is also necessary to determine if it is feasible to introduce a parameter that accounts for some substantial differences in the project's geometry, for example, or for some cost items that carry significant weight but are entirely absent in some projects.

In conclusion, among future steps, as previously mentioned, there is the task of establishing a correlation between the implementation costs of a project and the benefits derived from it. This entails defining an *area of influence* for each project, calculating risk reduction within it using available risk maps, and linking the reduction to the project cost.

The integration of flood risk maps with the positioning and influence areas of hydraulic infrastructure emerges as a pivotal aspect in this research, recognized as essential for ensuring accurate information and monitoring the evolution of flood risk in response to investments in flood defence and mitigation strategies.

In this context, the current study aimed to conduct a multi-layered mapping analysis of existing hydraulic infrastructure alongside flood risk zoning. This approach aimed to elucidate any potential correlation between the geographical distribution of funding for flood risk mitigation and the officially recorded risk levels for specific areas. By comparing the risk assessments reported in successive cycles, this analysis promises to offer timely and innovative insights. Notably, the literature review has not revealed any prior studies proposing a methodology to establish a quantitative risk index, as introduced in this study (Adamson, 2018).

Despite encountering several challenges during its application, as explained in the corresponding section, the proposed methodology will be able to provide more meaningful results in future cycles. Notably, the Risk Score Variation introduced has effectively captured reductions in risk across select cases within the study sample, as detailed in the Results section. Looking ahead, with the implementation of additional projects in subsequent cycles and the establishment of regular and consistent flood hazard monitoring, it will be feasible to comprehensively quantify and communicate the impact of interventions on risk reduction. Consequently, this will provide a solid basis for justifying investments in flood risk management strategies.

To conclude, in general, the methodology will benefit from including new infrastructure-related data, both in the ReNDiS database for the evaluation of the risk reduction, and in the *Regional Authorities projects sample* to validate the model with a larger dataset.

However, the present study indicates that planning and decision-making for flood prevention do not sufficiently rely on risk-based considerations in allocating funds, with decisions being driven more by assessing hazard than risk.

The next update of national-level risk maps for the third cycle of reporting of the EU_FD in conjunction with the risk maps, and a larger *Regional Authorities projects sample,* can represents highly valuable information for assessing the current state of flood defence implementation at the national level, evaluating the cost and establishing risk-based criteria for the design of infrastructure projects correlating cost with risk reduction.

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