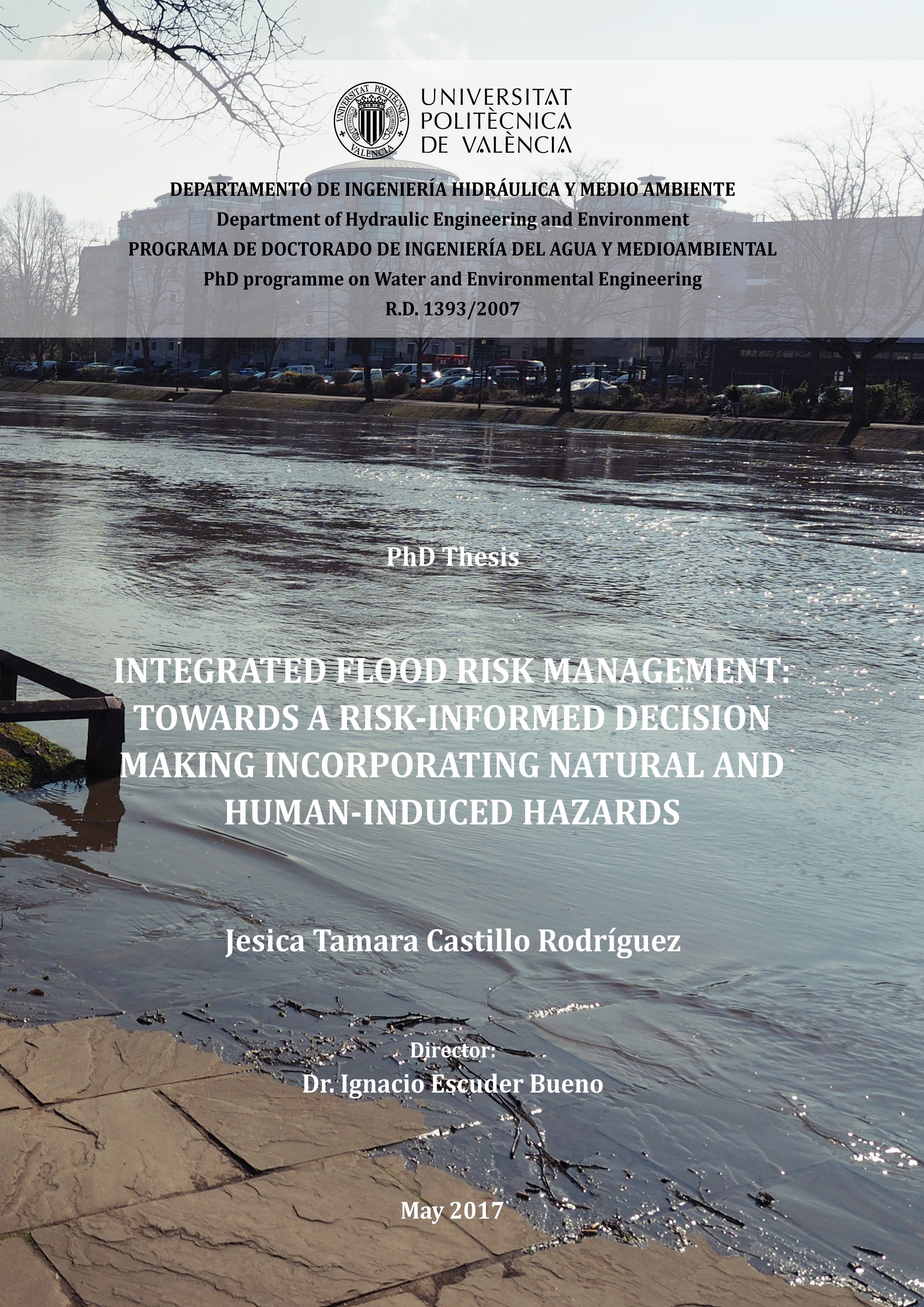

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DEPARTAMENTO DE INGENIERÍA HIDRÁULICA Y MEDIO AMBIENTE
Department of Hydraulic Engineering and Environment
PROGRAMA DE DOCTORADO DE INGENIERÍA DEL AGUA Y MEDIOAMBIENTAL
PhD programme on Water and Environmental Engineering
R.D. 1393/2007

PhD Thesis

INTEGRATED FLOOD RISK MANAGEMENT: TOWARDS A RISK-INFORMED DECISION MAKING INCORPORATING NATURAL AND HUMAN-INDUCED HAZARDS

Jesica Tamara Castillo Rodríguez

Director:
Dr. Ignacio Escuder Bueno

May 2017

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In addition, part of the research work here presented is also part of the activities conducted within the framework of the Memorandum of Understanding signed in August 2015 by the Department of Defence of the United States, acting through the U.S. Army Corps of Engineers (USACE), and the Spanish Ministry of Agriculture, Food and Environment (MAGRAMA), promoting collaboration in efforts involving Dam Safety and Risk Management of hydraulic infrastructures.

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ABSTRACT

Flood risk reduction is a global challenge. Society demands higher safety and security levels, including those actions related to flood defence infrastructure protection against natural hazards and manmade threats.

Dams and levees, among other flood defence infrastructures, are critical hydraulic infrastructures, aiming at reducing the likelihood that people and property will get flooded, but whose failure would result in consequences for the community downstream, including not only economic damages but also loss of life. There is always a probability associated with infrastructure failure, although in general it might be very low.

The purpose of the PhD research, with title "Integrated flood risk management: towards a risk-informed decision making incorporating natural and human-induced hazards", here presented is to propose a framework to enhance integrative flood risk management from a multi-hazard perspective (pluvial flooding, river flooding, dam and levee failure, including also man-made threats), addressing current needs for decision making on flood risk reduction and analysing the complexity of multiple hazards and systems which include multiple components.

The thesis is structured in three main parts, including: (i) Part I, a methodology aiming at providing a common framework for identifying and characterizing flood risk due to pluvial flooding, river flooding and dam failure, and to incorporate information on loads, system response and consequences into risk models to analyse societal and economic flood risk, (ii) Part II, an approach for quantifying and analysing risk for complex dam-levee systems, to incorporate information from levee failure into risk models based on the aforementioned methodology, and to analyse societal and economic flood risk, including the potential failure of these infrastructures, and (iii) Part III, a screening tool to characterize the impact of human induced threats on risk due to dam failure or mission disruption.

Results from this research have proven that the use of risk models provides a logic and mathematically rigorous framework for compiling information for flood risk characterization and analysis from different hazards and flood defence performance.

The proposed framework in this thesis and applications aimed at encouraging key actors on flood risk management (infrastructure managers, authorities, emergency action planners, etc.) on the use of quantitative risk analysis (QRA), and at demonstrating to what extent QRA can contribute to better understanding risk drivers and inform decisions on how to act to efficiently reduce flood risk.

RESUMEN

La reducción del riesgo de inundación es un reto global. La sociedad actual demanda cada vez mayores niveles de seguridad, incluyendo la consecución de acciones vinculadas a la protección de las infraestructuras de defensa frente a inundaciones ante amenazas naturales y antrópicas.

Presas y diques, entre otras obras de defensa, son infraestructuras estratégicas cuyo objetivo es reducir la probabilidad de inundación. Sin embargo, su fallo puede resultar en consecuencias para la comunidad situada aguas abajo, incluyendo no sólo daños económicos sino también pérdida potencial de vidas. Siempre existe una cierta probabilidad asociada al fallo de estas infraestructuras, aunque en general muy baja.

El objetivo de la investigación llevada a cabo en la presente tesis doctoral, con título “Integrated flood risk management: towards a risk-informed decision making incorporating natural and human-induced hazards”, es proporcionar un marco que fomente la gestión integral del riesgo de inundación desde una perspectiva multi-amenaza, considerando las necesidades actuales en la toma de decisiones para la gestión del riesgo de inundación y analizando la complejidad de sistemas con múltiples componentes.

La tesis se estructura en tres partes, incluyendo: (a) Parte I, una metodología para proporcionar un marco común para la identificación y caracterización del riesgo de inundación por inundación pluvial, fluvial y fallo de presas, incorporando información sobre solicitaciones, respuesta del sistema y consecuencias en modelos de riesgo que permiten analizar y evaluar el riesgo social y económico por inundación, (b) Parte II, un método para la cuantificación y análisis del riesgo en sistemas complejos presa-dique, con el objetivo de incorporar información referente al fallo de diques en la metodología propuesta en la Parte I, y analizar el riesgo social y económico por inundación incluyendo el fallo de varias infraestructuras de defensa, y (c) Parte III, una herramienta de cribado que permite caracterizar el impacto de amenazas de origen antrópico en el riesgo asociado al fallo de presas.

Los resultados de esta investigación demuestran que el uso de modelos de riesgo proporciona un marco lógico y matemáticamente riguroso para la consideración de toda la información necesaria para la adecuada caracterización y análisis del riesgo de inundación por amenazas naturales y por fallo o mal funcionamiento de obras de defensa, así como la incorporación al análisis de amenazas antrópicas.

El marco metodológico propuesto y las aplicaciones descritas en esta tesis tienen como objetivo impulsar la aplicación del análisis de riesgo por parte de los actores clave en la gestión del riesgo de inundación (gestores de infraestructuras, autoridades locales, gestores de emergencias, etc.) y demostrar en qué medida estos análisis pueden contribuir a alcanzar un mejor conocimiento de los factores que influyen en el riesgo existente e informar en la toma de decisiones hacia una reducción más eficiente.

RESUM

La reducció del risc d'inundació és un repte global. La societat actual demana majors nivells de seguretat, incloent-hi la realització d'accions vinculades a la protecció de les infraestructures de defensa enfront del risc d'inundacions afectades per amenaces naturals i antròpiques.

Preses i dics fluvials, entre altres obres de defensa, són infraestructures crítiques i tenen l'objectiu de reduir la probabilitat d'inundació però el seu trencament pot resultar en conseqüències en, danys econòmics i també pèrdua potencial de vides. Sempre hi ha una certa probabilitat vinculada al trencament d’aquestes infraestructures, encara que en general molt baixa.

L'objectiu de la investigació duta a terme en aquesta tesi doctoral, amb títol “Integrated flood risk management: towards a risk-informed decision making incorporating natural and human-induced hazards”, és proporcionar un marc per a fomentar la gestió integral del risc d'inundació des d'una perspectiva multi-amenaça, tenint en compte les necessitats actuals per prendre decisions per a la gestió del risc d'inundació i analitzant sistemes complexes amb múltiples components i afectats per diferents amenaces.

La tesi s'estructura en tres parts principals: (a) Part I, una metodologia proposada per a proporcionar un marc comú per a la identificació i caracterització del risc d'inundació per inundació pluvial, fluvial i trencament de preses, incorporant informació de sol·licitacions, resposta del sistema i conseqüències en models de risc que permeten analitzar el risc social i econòmic per inundació, (b) Part II, un mètode per a la quantificació i anàlisi del risc en sistemes complexes, amb l'objectiu d'incorporar informació referent al trencament de dics fluvials en la metodologia descrita en la Part I, i analitzar el risc social i econòmic pel trencament de diverses infraestructures de defensa, i (c) Part III, una ferramenta de pre-anàlisi per a caracteritzar l'impacte d'amenaces de origen antròpic en el risc associat al trencament de preses.

Els resultats de la investigació demostren l’utilitat de l’aplicació de models de risc, proporcionant un marc lògic i matemàticament rigorós per a la consideració de tota la informació necessària per a l'adequada caracterització i anàlisi del risc d'inundació per amenaces naturals i per trencament d'obres de defensa.

El marc metodològic i les aplicacions derivades d’aquesta tesi tenen com a objectiu impulsar l'aplicació d'anàlisi de risc quantitatius per part dels actors vinculats a la gestió del risc d'inundació (gestors d'infraestructures, autoritats locals, gestors d'emergències, etc.) i demostrar que poden contribuir a disposar d'un millor coneixement dels factors clau que componen el risc, i per a informar les decisions necessàries per a una reducció del risc més eficient.

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- **Annex 6.** A risk-informed journey towards improved dam safety governance in Spain.

ACRONYMS

ACSLS	Adjusted Cost per Statistical Life Saved
AEAP	Annual Expected Affected Population
AED	Annual Expected Damages
AENI	Annual Expected Number of Injured people
ANCOLD	Australian National Committee on Large Dams
DHS	United States Department of Homeland Security
EAP	Emergency Action Plan
FRM	Flood Risk Management
IIAMA	Research Institute of Water and Environmental Engineering
IRGC	International Risk Governance Council
MAGRAMA	Spanish Ministry of Agriculture, Food and Environment
NOL	Normal Operating Level
PAMRI	Local action plan for flood risk management
QRA	Quantitative Risk Analysis
SPANCOLD	Spanish National Committee on Large Dams
UPV	Universitat Politècnica de València
USACE	United States Army Corps of Engineers

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1. INTRODUCTION

1.1. Topic and focus

The title of this PhD thesis, "INTEGRATED FLOOD RISK MANAGEMENT: TOWARDS A RISK-INFORMED DECISION MAKING INCORPORATING NATURAL AND HUMAN-INDUCED HAZARDS", includes the three **core** concepts which represent the focus of the conducted research:

- Flood risk management (What).

  Flood risk management (FRM) can be defined as 'the continuous and holistic societal analysis, assessment and mitigation of flood risk' (Gouldby and Samuels, 2009). Nevertheless, flood risk management involves a wide range of considerations that cannot be easily represented in a concise statement. Flood risk management should be based on the identification, characterization and analysis of all risk components, including hazard, exposure and vulnerability.
  Flood risk can be analysed for systems of different size and complexity, such as a city, a province, a hydrological subsystem, or a country; and for different sources of hazard.
  In this thesis, different sources of hazard are considered including natural hazards and manmade threats.

- Decision making (Why).

  All agents involved in flood risk management (e.g. flood defence designers, operators, authorities, emergency services, other stakeholders, etc.) should promote and achieve a broad vision of flood risk management, taking into account the context, the objectives and restrictions inherent to the risk management process (SPANCOLD, 2012). This aspect is in line with the first part of the well-known expression, "Think Global, Act Local".
  Due to the lack of resources and given restrictions, prioritization of risk reduction measures is required to achieve an efficient flood risk management. Outcomes of risk analysis may help to support decisions on how to allocate investments and take actions for flood risk reduction. This aspect relates to the second part of the expression ("Act Local").

- Integration (How).

  A global and integrated vision is required to analyse flood risk from a comprehensive perspective, to provide better and more complete information to decision makers. Therefore, the analysis of multiple hazards is needed when analysing risk in a given area and tools are required to help decision makers on how to analyse existing risk and proceed based on a risk-informed approach.

Combining the aforementioned triplet, the conducted PhD research has focused on providing new methods and tools to support key actors of FRM towards a more integrated and risk-informed decision-making.

1.2. Research motivation

Dams and levees, among other flood defence infrastructures, are critical hydraulic infrastructures whose failure would result in consequences for the society and the community downstream, including not only economic damages but also loss of life. There is always a probability associated with infrastructure failure, although in general it might be very low.

There is nowadays a trend towards seeing dam and levee safety as an active and continuous management process. Flood defence operation and flood emergency management requires risk-informed decisions on how to prioritize actions for risk reduction. Risk assessment helps key actors to understand system response and consequences related to a given hazard or threat, along with related uncertainties, and provides a logical process of identifying, evaluating risk, and assessing the effectiveness of risk reduction measures. For this reason, in recent years, risk assessment techniques have been developed worldwide and applied in the dam and levee industry to inform safety governance (ANCOLD, 2003; ICOLD, 2005; SPANCOLD, 2012; USACE, 2014).

In this context, the Research Institute of Water and Environmental Engineering (IIAMA) at the Universitat Politècnica de València (UPV) has leaded the application of risk analysis techniques to inform dam safety governance in Spain and to collaborate in the development of local action plans for flood risk management.

As part of the Water Resources Engineering research group at IIAMA-UPV since 2010 and also now as Head of the RDI Office at iPresas (spin-off company of UPV, founded in 2011), I have been involved in dam safety and flood risk related projects. The work conducted has allowed to identify needs for research and for providing tools to support key FRM actors on how to reduce flood risk in a more efficient and effective manner.

Current state-of-the-art lacks of formal consideration and integration of risk estimates under a multi-hazard environment and one of the objectives of this research is to provide a framework to consider this aspect.

In addition, despite the 10 years that have passed since the publication of the EU Floods Directive (European Parliament, 2007), later transposed into national legislation in Spain in 2010, the development and application of local action plans for flood risk management are neither fully developed nor implemented. For this reason, this PhD research is focused on solving main difficulties found on quantitative flood risk analysis and how to contribute for increasing implementation of action plans and risk reduction measures.

Outcomes obtained under the presented thesis will address, in a more comprehensive way, the development of risk analyses under a more integrated perspective to boost implementation of required flood risk emergency action planning.

In conclusion, this thesis is focused on how integrated risk analysis can be used to inform local authorities and flood defence infrastructure owners on the existing situation and how to allocate investments for flood risk reduction.

1.2.1. Flood risk from natural hazards and manmade threats

Floods are among the most damaging natural disasters in Europe and worldwide. Flood risk assessments for future scenarios in several countries show that risks might rise due to climate or socioeconomic changes. Examples of analyses and projections of future exposure and risk at national scale can be found, e.g. in The Netherlands (Jongman et al., 2014), United Kingdom (Sayers et al., 2015) and Austria (Fuchs et al., 2015). In addition, analyses at European scale can also be found (Barredo, 2009) which show that the increase observed on flood risk is mainly due to socioeconomic shifts. However, future risks are influenced by both climate and socioeconomic projections and these may significantly vary for each region or country.

In addition, urban areas concentrate population and economic activities thus presenting high flood vulnerability. In the Mediterranean, severe winter storms and flood have increased in frequency and intensity (Kreimer et al., 2003). In many Mediterranean cities, the combination of basin physical characteristics and intense and irregularly distributed rain generates frequent floods.

As a result of the impact of past flood events and the need for reducing existent flood risk, the European Commission published the Directive 2007/60/EC of 6 November 2007 (European Parliament, 2007), aiming at reducing and managing the risks that floods pose to human health, the environment, cultural heritage and economic activity.

After the EU Floods Directive, flood risk reduction has become a top priority in many countries (e.g. Member States have been working on preliminary assessments, flood risk maps and flood risk management plans). In such a changing and demanding environment, flood risk analyses arise as comprehensive and robust approaches to determine the nature and extent of risk by analysing potential flood hazards and evaluating existing conditions of vulnerability.

However, despite recent legislation and work conducted on flood risk management, there is still a need for local flood risk analyses to complete those developed at regional scale, to inform action planning and to better orientate risk reduction actions at urban scale.

In addition to natural flood hazards, man-made threats have arisen in recent years as an important question for effective flood defence infrastructure management. As a result of past attacks to strategic infrastructures (e.g. 9/11 events), the need for also addressing security risks was incorporated into European regulatory context after publication of Directive 2008/114/EC of 8 December 2008 on the identification and designation of European critical infrastructures and the assessment of the need to improve their protection.

Therefore, a new perspective towards higher standards for safety and security has risen in the last years and decision-makers (especially those involved on flood defence management and flood risk protection at local scale) are asked to take actions to reduce the potential consequences of natural or man-made hazards.

1.2.2. Risk-informed dam safety, dam security and flood emergency management

As a consequence of the described context, risk analysis techniques have arisen as a useful tool to analyse and assess existing flood risk from natural hazards and flood defence system performance.

Among the wide range of existing flood defence infrastructures, small and large dams provide significant benefits to society, such as hydroelectric production, flood protection, water supply, irrigation and recreation. Despite this great value, they represent a public safety concern, due to the likelihood of a failure that can result in a source of flooding in downstream areas. For that reason, dam risk assessment has turned into an excellent technique to evaluate different failure scenarios.

Concerning the background related to the conducted research activities in this PhD thesis, the following projects related to dam and flood risk analysis are highlighted:

- The DAMSE project 'A European Methodology for Security Assessment of Dams' (2007-2008), which proposed a qualitative risk assessment that includes threat, vulnerability and consequences from manmade threats into dam risk analysis.
- The project 'Application of risk analysis to maintenance, rehabilitation and management of dams and reservoirs' (2007-2008), which allowed the development of a software tool for risk modelling of dams and reservoir systems (iPresas software, developed at the UPV and now by iPresas Risk Analysis).
- The SUFRI project 'Sustainable Strategies of Urban Flood Risk Management with non-structural measures to cope with the residual risk' (2009-2011), which proposed a methodology for analysing flood risk in urban areas, including pluvial and river flood events.
- The basic principles of risk analysis applied to dam safety management included in the Technical Guide on Dam Safety, 'Technical Guide on Risk Analysis applied to management of Dam Safety', published by the Spanish National Committee on Large Dams in 2012 (SPANCOLD, 2012).
- Advances on the international context, mainly in the United States, highlighting the work of the U.S. Department of Homeland Security (US Department of Homeland Security, 2011a, 2011b) and the U.S. Army Corps of Engineers (USACE, 2014).
- In the Netherlands, the long-term project FLORIS (Flood Risk and Safety in The Netherlands), a study commissioned by the Dutch Ministry of Transport, Public Works and Water Management in cooperation with water boards and provinces, aimed at estimating and mapping the probabilities and consequences of flooding for all 53 dike rings in The Netherlands (Hazenoot, E.C. et al., 2008). In addition, the VNK2 project has also included probabilistic risk analyses for all major levee systems in The Netherlands (Jongejan et al., 2011).

In most cases, despite some exemptions found in the literature such as guidance and examples of micro-scale flood risk assessment carried out e.g. in England and Wales (Penning-Rowsell et al., 2013), there is a lack of applications of risk analysis techniques at local scale or the required level of detail to support decision making on local flood risk reduction and planning.

1.2.3. The need for integrated flood risk management

As it has been mentioned above, after the EU Floods Directive (European Parliament, 2007), many countries have developed legislation concerning flood risk analysis in the last years. However, for example, quantification of societal and economic flood risk is not required by current legislation in Spain and is relatively novel in local flood risk management as a result of a lack of guidance, standardized methods or tools for local flood risk analysis. Examples can be found in other countries such as in England and Wales (Hall et al., 2003), but are still scarcely applied in Spain.

Therefore, the following research needs were identified:

- Analyse how to integrate different sources of flood hazard into risk modelling.
- Analyse how to include levee systems into risk models to assess complex flood defence systems.
- Analyse how to incorporate malevolent threats into risk models to include security aspects

1.3. Objectives

The main objective of this doctoral research is to develop a comprehensive and robust methodology for flood risk analysis, including the analysis of malevolent threats and failure of flood defence infrastructures such as dams and levees.

The overarching purpose is to analyse flood risk one step forward, towards an all-hazards risk-informed decision making on flood risk management to guide decision makers on future actions for risk reduction and to demonstrate how risk analysis may support decisions, for example, on how to allocate investments for emergency action planning.

Risk models, influence diagrams and event trees (Castillo-Rodríguez et al., 2014) are proposed for risk identification, characterization and calculation towards a risk-informed decision making in dam safety and security management and flood risk management.

The general objective can be subdivided in a set of more specific milestones which are the following:

O1. Review of the state of the art regarding methods and tools for flood risk analysis, specifically those applied to flooding from flood defence failures.

O2. Develop a methodology to integrate different hazards on flood risk analysis.

O3. Develop a methodology to integrate failure of multiple infrastructures for flood risk analysis.

O4. Application and verification of the proposed methodologies to a case study in Spain and a complex dam-levee system in United States.

O5. Develop a screening procedure to integrate the analysis of manmade threats into flood risk analysis to balance the state-of-the-practice on flood defence failure analysis.

In conclusion, this thesis aims to analyse how the use of risk models and the application of risk analysis techniques offers great added value to flood risk assessment methodologies and may contribute to reduce flood risk, providing outcomes that can be used by authorities, infrastructure owners and stakeholders to improve flood emergency management strategies and to prioritize flood risk reduction measures.

2. PUBLICATIONS

This PhD thesis has been developed and is presented as a compendium of research papers. It includes two journal articles published in *Natural Hazards and Earth Systems Sciences*, and a third journal article published in *Structure and Infrastructure Engineering*, both are peer-reviewed journals indexed in the Journal Citations Report (JCR). In addition, other journal article has been submitted to the peer-reviewed journal *Safety Science*. Two conference papers are also included.

The list of publications related to the PhD thesis is here provided:

<u>Papers published in indexed journals (JCR):</u>

- Castillo-Rodríguez, J.T., Escuder-Bueno, I., Altarejos-García, L., and Serrano-Lombillo, A.: "The value of integrating information from multiple hazards for flood risk analysis and management", Nat. Hazards Earth Syst. Sci., 14, 379-400, doi:10.5194/nhess-14-379-2014, 2014.

  Impact factor 2015: 2.277; Q1.

  Included in Annex 1.

- Castillo-Rodríguez, J.T., Escuder-Bueno, I., Perales-Momparler, S., and Porta-Sancho, J. R.: "Enhancing local action planning through quantitative flood risk analysis: a case study in Spain", Nat. Hazards Earth Syst. Sci., 16, 1699-1718, doi:10.5194/nhess-16-1699-2016, 2016.

  Impact factor 2015: 2.277; Q1.

  Special issue: Resilience and vulnerability assessments in natural hazards and risk analysis.

  Included in Annex 2.

- Castillo-Rodríguez, J.T., Needham, J.T.; Morales-Torres, A.; and Escuder-Bueno, I.: "A combined risk analysis approach for complex dam-levee systems", Structure and Infrastructure Engineering, Published online: 18 Apr 2017, http://dx.doi.org/10.1080/15732479.2017.1314514.

  Impact factor 2015: 1.202; Q2.

  Included in Annex 3.

- Castillo-Rodríguez, J.T., Escuder-Bueno, I., and Morales-Torres, A.: "Screening procedure for analysing the impact of manmade threats in dam risk management", Under review, submitted to Safety Science in December 2016 (manuscript ID SAFETY_2016_401).

  Impact factor 2015: 2.157; Q1.

  Special issue: societal safety, critical infrastructure reliability and related intersectoral governance.

  Included in Annex 4.

Papers published in Congress Proceedings:

- Castillo-Rodríguez, J.T., Escuder-Bueno, I., Altarejos-García, L., and Perales-Momparler, S.: "Towards an integrated flood risk management in urban areas: pluvial and river flooding including structural collapse", In Proceedings of 9th ICOLD European Club Symposium. Sharing Experience for Safe and Sustainable Water Storage. Venice (Italy). 10-12 April 2013.

  Included in Annex 5.

- Castillo-Rodríguez, J.T., Escuder-Bueno, I., and Morales-Torres, A.: "A risk-informed journey towards improved dam safety governance in Spain", In Proceedings of 2nd International Dam World Conference. Lisbon (Portugal). 21-24 April 2015 (LABORATÓRIO NACIONAL DE ENGENHARIA CIVIL, ISBN 978-972-49-2274-4).

  Included in Annex 6.

Aforementioned publications are related to the objectives described in Chapter 1 as follows:

- Regarding objectives O1, O2 and O4, an approach for flood risk analysis including pluvial flooding, river flooding and dam failure has been developed and it is described in **Annex 1**. Its application to a real case study (the municipal term of Oliva in Spain) is presented in **Annex 2**.
- Regarding objectives O3 and O4, an approach for flood risk analysis including failure of multiple infrastructures has been developed and it is described and applied to a real case study (a dam-levee system in United States) in **Annex 3**.
- Concerning objective O5, a screening procedure to integrate the analysis of manmade threats into flood risk analysis from dam failure has been developed and it is described in **Annex 4**.

Table 1. Objectives and PhD thesis outcomes.

Objective	Annex
O1 Review of the state of the art regarding methods and tools for flood risk analysis, specifically those applied to flooding from flood defence failures	1, 6
O2 Develop a methodology to integrate different hazards on flood risk analysis	1, 2, 5
O3 Develop a methodology to integrate failure of multiple infrastructures for flood risk analysis	3
O4 Application and verification of the proposed methodologies to case studies	2, 3
O5 Screening procedure to integrate the analysis of manmade threats into dam risk analysis	4

3. RESULTS AND DISCUSSION

Results of this Thesis are presented in the publications included in the Annexes of this document, and summarized in this chapter. In Sect. 3.1, PhD contributions are presented as key components of a common framework for integrated flood risk management. Sections 3.2 to 3.4 provide a short description of each methodological component and related case studies.

3.1. Introduction

The main outcomes of this Thesis are three contributions towards an integrated flood risk management. In this section, contributions and connections among them are described.

3.1.1. PhD contributions

Contributions are structured in three main parts, including the following:

Part I: Methodology to integrate pluvial flooding, river flooding and dam failure into flood risk assessment

Local governments in Europe are facing multiple challenges regarding risk mitigation from natural hazards. Actions are changing from just reacting to regional, national or European requirements to more active strategies towards improved risk management.

However, while the roles and responsibilities of municipal governments regarding flood risk management have grown, e.g. after publication of regional plans for flood risk management in some regions in Spain and the requirements for local action planning (Porta-Sancho et al., 2016), there is still a lack of tools to support local flood risk analysis (e.g. required analyses are complex and time-consuming for local actors who may lack of experience on conducting detailed flood risk analyses).

Aiming at providing a common framework for identifying and characterizing flood risk due to pluvial flooding, river flooding and dam failure, and incorporate information on loads, system response and consequences into risk models to analyse societal and economic flood risk, a methodology is proposed and described in **Annex 1**.

The journal article titled "*The value of integrating information from multiple hazards for flood risk analysis and management*" (Castillo-Rodríguez et al., 2014) presents and describes a methodology for estimating flood risk in urban areas integrating pluvial flooding, river flooding and failure of both small and large dams.

The first part of the paper includes a review of basic concepts on flood risk analysis, evaluation and management. Flood risk analyses may be developed at local, regional and national level, however a general methodology to perform a quantitative flood risk analysis including different flood hazards was still required.

The second part describes the proposed methodology, which presents an integrated approach – combining pluvial, river flooding and flooding from dam failure, as applied to a **first case study**: an urban area located downstream of a dam under construction.

The article also shows how outcomes from flood risk analysis provide better and more complete information (compared with qualitative or semi-quantitative flood risk approaches and analysed focused on just one hazard) to inform authorities, local entities and the stakeholders involved in decision making with regard to flood risk management. Outcomes from flood risk analyses can be used to compare risks for different scenarios, before and after implemented and planned measures for flood risk reduction, then supporting decisions and improving communication to the public.

In **Annex 2**, the journal article titled "*Enhancing local action planning through quantitative flood risk analysis: a case study in Spain*" (Castillo-Rodríguez et al., 2016) presents the application of the methodology to a **second case study** to show the benefits of risk-informed flood emergency management.

This article also presents how this method may help to incorporate and promote quantitative risk analysis to support local action planning for flood risk management.

The proposed approach aims to provide a framework for boosting quantitative risk analysis into local flood risk management, combining hazard mapping with vulnerability data to quantify risk in terms of expected annual affected population, potential injuries, number of fatalities, and economic damages.

Flood risk is estimated combining GIS data of loads, system response and consequences and using event tree modelling for risk calculation.

The second case study is the city of Oliva. Results from risk modelling have been used to inform local action planning and to assess the benefits of structural and non-structural risk reduction measures.

Results from this case study analysis highlight the need for robust and standardized methods for urban flood risk analysis replicability at regional and national scale.

Case studies 1 and 2 represent examples on FRM at local scale and how results from risk analysis based on the proposed methodology have proven to support decisions for flood risk reduction and emergency management.

Part II: Methodology to incorporate fluvial dikes (levees) into flood risk assessment for complex dam-levee systems

Dams and levees are built to reduce the likelihood of flooding. However, if they fail, the result can be catastrophic flooding beyond what would happen if they did not exist. Therefore, understanding the risk reduced by the dam or levee, as well as any risk imposed by these infrastructures is of high importance when determining the appropriate risk reduction investment strategy.

Research examples related to flood risk analysis from dike failure can be found in the literature (de Bruijn et al., 2014; Hall et al., 2005; Jongejan and Maaskant, 2015; Vorogushyn et al., 2010). However, combined dam and levee risk analyses are still required.

With the aim of improving the current state-of-the-art on flood risk analysis in complex dam-levee systems, the journal article titled "*A combined risk analysis approach for complex dam-levee systems*", in **Annex 3**, describes an approach for quantifying and analysing risk for complex dam-levee systems, to incorporate information from levee failure into risk models, and to analyse societal and economic flood risk, including the potential failure of these infrastructures.

The application of the proposed approach to a real **case study** shows how the contribution to system risk of each levee sub-system can be assessed. It also describes how decisions on risk mitigation measures, at the individual asset scale, can and should be informed in terms of how they impact the overall flood risk.

Part III: Screening procedure to incorporate malevolent threats into dam risk analysis and flood risk assessment

Dam risk analyses have traditionally incorporated aspects related to natural hazards and structural studies including failure modes such as sliding, overtopping, internal erosion or seismicity. As a result, the design, construction and maintenance of new and existing dams have been focused on dam safety aspects. But, in recent years, a new perspective has emerged towards the integration of dam safety and security with the aim of evaluating dam response in terms of human-induced threats.

With the purpose of providing a screening tool to characterize the impact of human induced threats on risk due to dam failure or mission disruption, in **Annex 4**, the journal article titled "*Screening procedure for analysing the impact of manmade threats in dam risk management*, and after reviewing the literature on asset and portfolio risk analysis, and discussing more specifically the strengths and limitations of existing methodologies for dam security risk analysis, a screening procedure for analysing the impact of manmade threats in dam risk management is proposed.

This procedure has two main advantages: it allows the combination of results from natural and manmade threats, providing a new perspective on the relationship between safety and security, and it may offer valuable information prior to the estimation of the probability of an attack, then allowing an holistic risk analysis aiming at reducing societal and economic risk in case of dam failure.

A **case example** is described in this paper to show how the procedure can be used by dam owners and operators.

This new approach aims to incorporate security aspects into dam risk analysis, including dam vulnerability in case of a potential attack (with the resulting structural or operative failure).

3.1.2. *An integrated framework for flood risk management*

Among existing tools for flood risk analysis, the use of risk models, influence diagrams, event trees and FN-curves is proposed in this thesis. Risk models arise as robust, complete and quantitative flood risk analysis tools that enable the integration of all information for estimating risk. Outcomes from risk modelling can be used to represent FN and FD-curves, tools that help to communicate outcomes from risk analysis.

Event trees are particularly applicable for risk calculation and analysis (IEC, 2009) as they allow the user to obtain and combine probabilities and consequences, but not for risk evaluation. FN-curves provide a comprehensive and robust tool to represent societal and economic risk quantitatively, thus these curves are helpful tools to support risk evaluation.

Risk models are a simplified representation of the system and allow to incorporate information on different risk components (hazard, vulnerability and exposure).

The proposed methodology is divided into 11 phases, as described in **Annex 1**, including:

Phase I:	Scope of the case study.
Phase II:	Review of available data.
Phase III:	Study of the system situation: definition of the Base Case.
Phase IV:	Flood events to be analysed.
Phase V:	Risk model architecture.
Phase VI:	Input data for the risk model.
Phase VII:	Risk calculation.
Phase VIII:	Risk representation.
Phase IX:	Risk evaluation.
Phase X:	Study of risk reduction measures.
Phase XI:	Risk management and governance.

Among proposed phases, the following are highlighted for their importance within the risk analysis process:

- **Phase V - Risk model architecture**. The correct definition of the risk model architecture is a key stage for conducting robust and replicable flood risk analysis.
  Therefore, **Part I** of the proposed framework describes how to estimate flood risk from three considered flood hazards, compiling information that is used as input data for a risk model, whose architecture definition is also included. The proposed risk model architecture is used to perform risk calculations providing risk outcomes that can be plotted on FN and FD-curves. Representations are then used to visualize different situations (e.g. existent risk or situations with new risk reduction measures), and propose risk reduction measures based on an integrated and comprehensive risk analysis.

Part II of the proposed framework, included in **Annex 3**, describes how to estimate flood risk for complex dam-levee systems, providing a generic risk model architecture, applied to a real case study in the United States.

- **Phase VI – Input data for the risk model**. Once the generic risk model architecture was defined (Annex I), the methodology was applied for the case study of Oliva in Spain, with emphasis on Phase VI.
  Annex 2 describes how the proposed methodology was applied, aligned with existing information and tools to support local action planning for flood risk management, and demonstrating the usefulness of the presented framework.

- **Phase XI – Risk management and governance**. A comprehensive and integrative flood risk management is required, analysing all sources of hazard. With such purpose, **Part III** of the thesis aiming at providing a screening tool to achieve a balance safety and security dam risk management, and consequently, flood risk management. The procedure is described in **Annex 4** to incorporate security aspects into the analysis, applied to a real case example of four dams in Spain.

Figure 1 shows connections among methodological parts of this thesis and the proposed methodology for flood risk analysis.

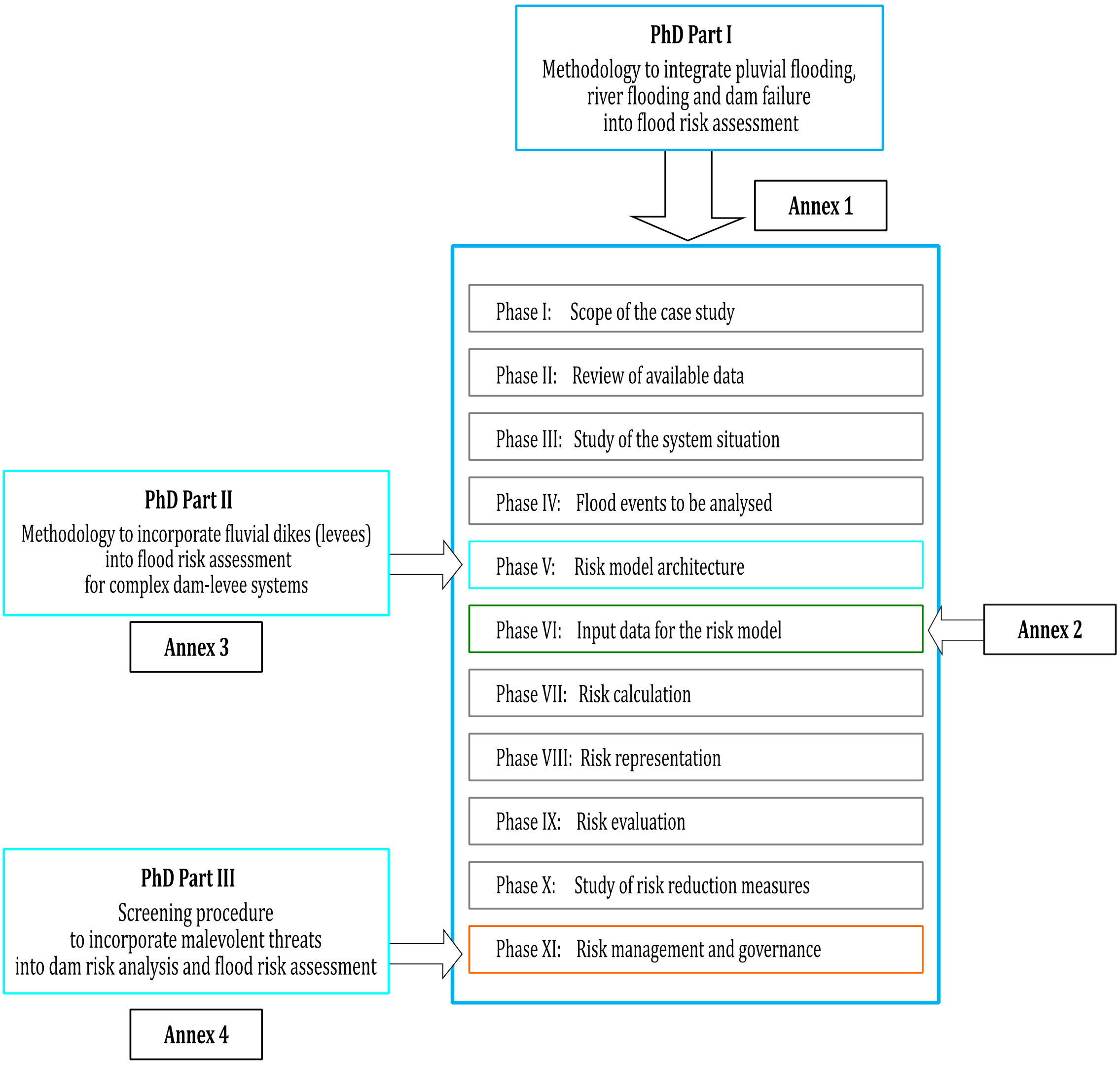

Figure 1. Phases of the methodology and additional contributions to key stages.

3.2. Part I: Methodology to integrate pluvial flooding, river flooding and dam failure into flood risk assessment

The detailed description of phases I to XI is included in **Annex 1**. In this section, key aspects of Phase V and VI, 'risk model architecture' and 'input data estimation', are included to describe the generic influence diagrams proposed for a mult-hazard flood risk analysis, including pluvial flooding, river flooding and dam failure. The generic risk models are the reference for the analysis of case studies summarized in Sect. 3.2.

Regarding Phase V, depending on the characteristics of each area under study, two situations may be distinguished: Situation A and Situation B.

- Situation A represents urban areas where initiating events, i.e. rainfall events within the urban and the river catchment areas, can be considered as independent phenomena thus potential flooding from these sources of hazard are assumed independent. In this case, different influence diagrams (and the corresponding event trees) may be used to analyse each flood hazard separately. Results can be later combined to obtain total flood risk. In this methodology, two generic schemes for defining the required influence diagrams are provided in Figure 2 and Figure 3 (Schemes A1 and A2, respectively), which correspond to the analysis of pluvial and river flooding (including the existence of dams), respectively.
- Situation B represents urban areas where rainfall events within the urban and the river catchment areas are related (including, for example, the river catchment area upstream of the dam), i.e. potential flood events are the result of the same initiating event. Therefore, a unique influence diagram to represent the risk model can be used for the analysis. Figure 4 shows the (simplified) generic scheme for the risk model architecture (and the corresponding influence diagram) for this situation (Scheme B). The same architecture shown in Schemes A1 and A2 can be used for Situation B, by adding a common initiating event and two connectors: one linking the node for the initiating event to the first node of Scheme A1, and, the second, linking the last node of Scheme A1 to the first node of Scheme A2.

These schemes are proposed as reference risk model architectures but they should be adapted for each case study, as demonstrated in Sect. 3.2.

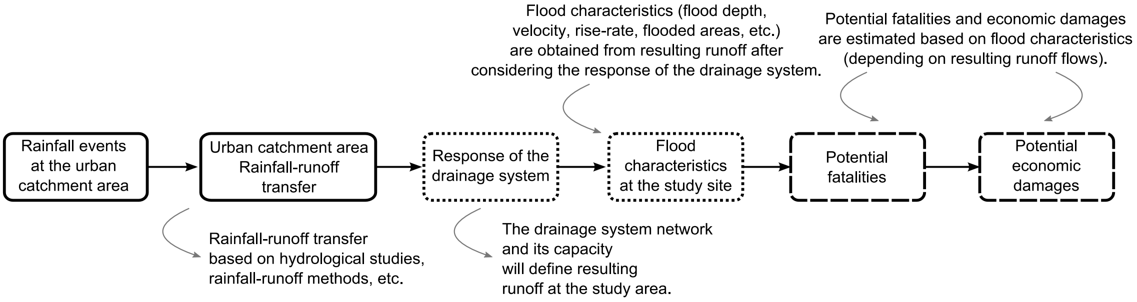

Figure 2. Generic influence diagram: Independent initiating event (Scheme A1).

Note: Nodes outlined with solid, dotted and dashed lines refer to loads, system response and consequences, respectively.

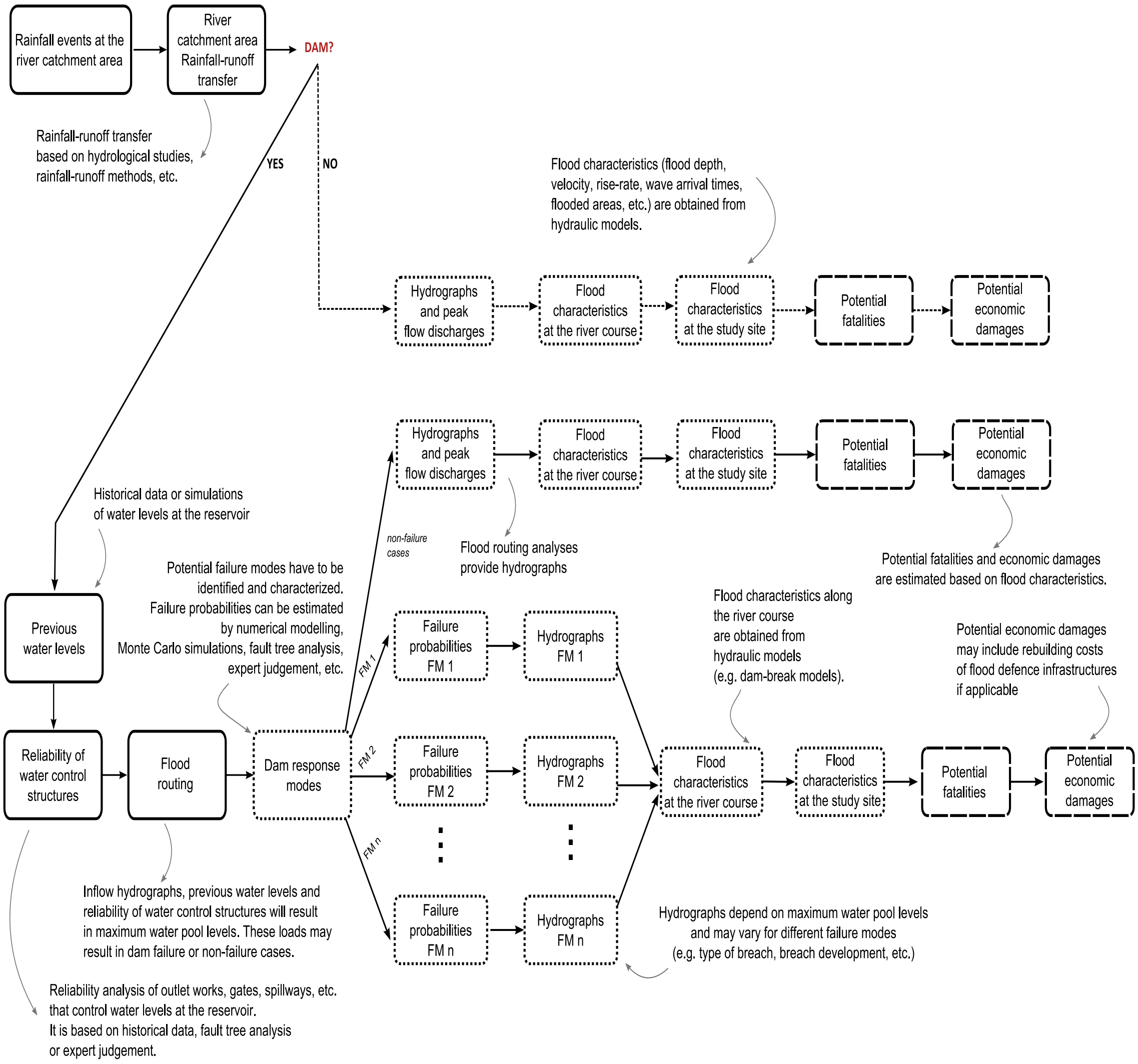

Figure 3. Generic influence diagram: Independent initiating event (Scheme A2).

Note: Nodes outlined with solid, dotted and dashed lines refer to loads, system response and consequences, respectively.

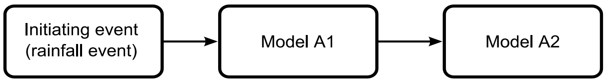

Figure 4. Generic influence diagram: Common initiating event (Scheme B).

The definition of the risk model architecture provides the framework for compiling information to estimate flood risk. With that purpose, defined influence diagrams are the compact representation of the event tree that includes all possibilities that can lead to flooding.

Influence diagrams are compact conceptual representations of the logic of a system. An influence diagram is any representation including the relations between possible events, states of the environment, states of the system or subsystems, and consequences.

This diagram offers a visual representation of a risk model. Each variable of the system is represented as a node and each relation as a connector (arrows depicted in Figures 2 to 4), Connectors are used to link nodes but do not represent direct relationships among variables.

A simple event tree can be modelled with a linear influence diagram. However when in an event tree there are qualitatively different paths going out from a node, it is necessary to diverge the influence diagram (e.g. to include different failure modes).

The risk model is a conceptual representation of the system, taking into account hazard(s), exposure to the hazard(s) and vulnerability of the system to that hazard(s). If several sources of hazard are considered, a unique influence diagram integrating information for all hazards can be used. However, if hazards are considered independent, then different influence diagrams can be used to represent the system for each source of hazard separately.

For Situation A, independent influence diagrams for analysing each flood hazard are considered. In this case, outcomes can be later incorporated to an overall scheme which obtains total flood risk due to the three sources of flood hazard, adapting input data to avoid double counting in areas potentially affected by several flood hazards.

Figure 5 shows a general scheme of the process for combining results from three independent risk models. The outcomes from Risk Models 1, 2 and 3 (represented by the FN curves) are used as input for an overall 3-node influence diagram. ‘Probability-consequence’ pairs of all flood events from Risk Models 1, 2 and 3 are incorporated into the overall diagram in each node, respectively.

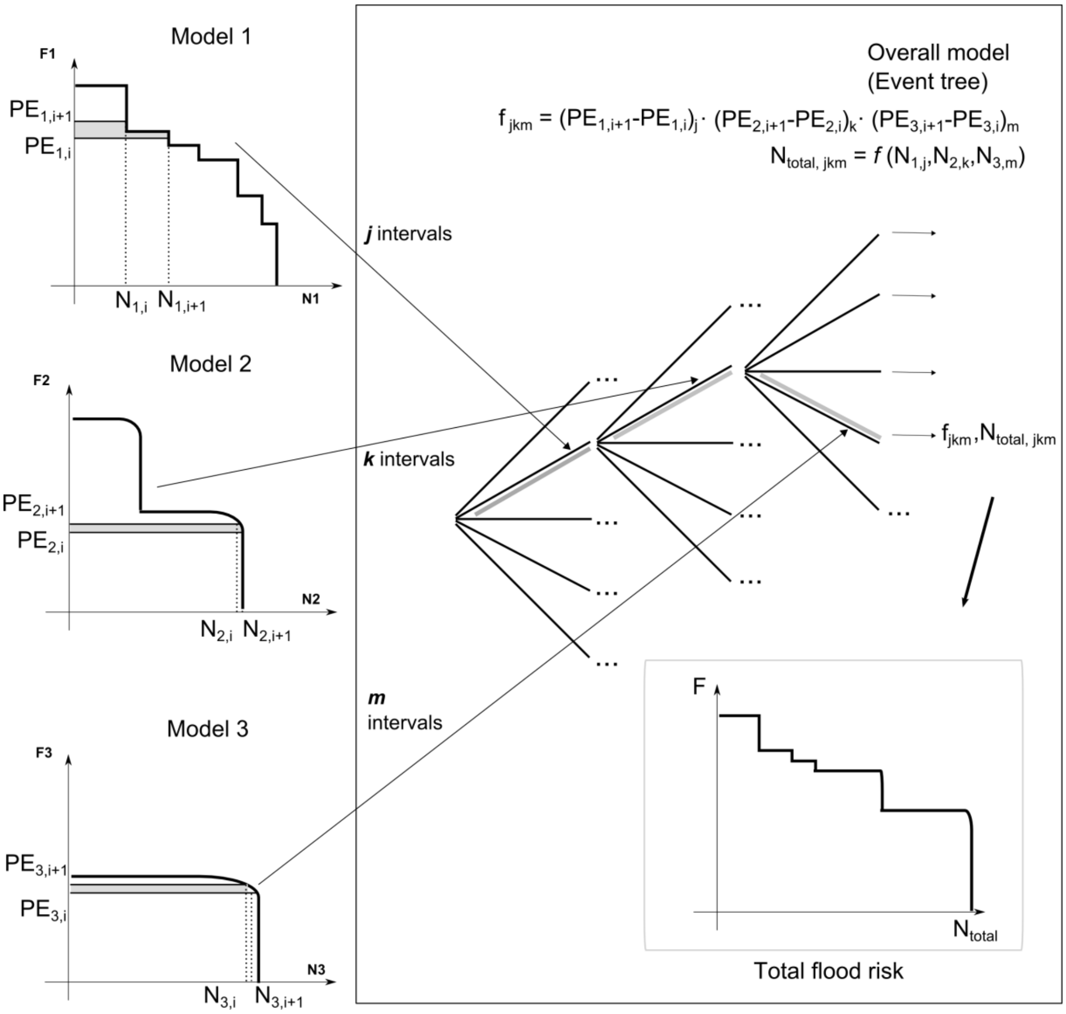

Figure 5. Combination of outcomes of different risk models.

The exceedance probability functions that result from each independent risk model (Models 1, 2 and 3 in Figure 5) are discretized into a number of intervals. Each interval has two endpoints defined by the values of the damage variable (N_i, N_{i+1}) and their corresponding exceedance probabilities (PE_i, PE_{i+1}). Intervals are generally evenly spaced in the exceedance probability axis. For each interval, the N value for the range i will be computed as the average of the pair N_i, N_{i+1} and the probability as prob = PE_{i+1} - PE_i.

The joint event tree (shown in Figure 5) resulting from this diagram includes all possible combinations of events in Risk Models 1, 2 and 3. If events in Risk Models 1, 2 and 3 are considered independent, the probability of the combined event (f_{jkm}) is obtained by multiplying the three probabilities of the corresponding events from Models 1, 2 and 3, respectively. Finally, the overall model obtains the FN (or FD) curve that represents flood risk by integrating the three sources of flood hazard.

For Situation B (Fig. 4), the analysis may be carried out by defining a unique risk model architecture which starts with a common initiating event and combines the three sources of flood hazard. Hence, only one event tree is necessary to obtain flood risk and it provides all FN (or FD) pairs that represent all potential flood events from pluvial flooding, river flooding and flooding from dam failure and non-failure cases.

Apart from the correct definition of the risk model architecture, input data estimation for the risk model is of high relevance within risk analysis. Nowadays, GIS data may help to optimize the process of input data gathering for the risk model. Results from hydraulic models, information on land use, databases on population characteristics, etc. are managed using GIS and can be applied to incorporate information into the risk model. However, there is a lack of standardization on methods to be used (e.g. a common framework and tools for quantitative flood risk analysis using GIS in Spain is still required).

In **Annex 2**, a GIS framework is presented and described to align current state-of-the-practice on GIS at local scale in Spain with the methodology proposed for flood risk analysis, aiming at boosting quantitative flood risk analysis and their potential applications, including the development of local flood risk assessments such as those required by regional and national legislation in Spain after the EU Floods Directive.

With such purpose and focusing on Phase VI, the framework for input data gathering and processing shown in Figure 6 (and described in **Annex 2**) is proposed, connecting required data and available tools with the proposed 11-stage flood risk analysis methodology.

Based on the proposed framework, risk outcomes can be obtained to evaluate risk and compare different scenarios to support decision making on flood risk management.

Case studies 1 and 2 illustrate its application and usefulness for providing information for defining actions for flood risk reduction.

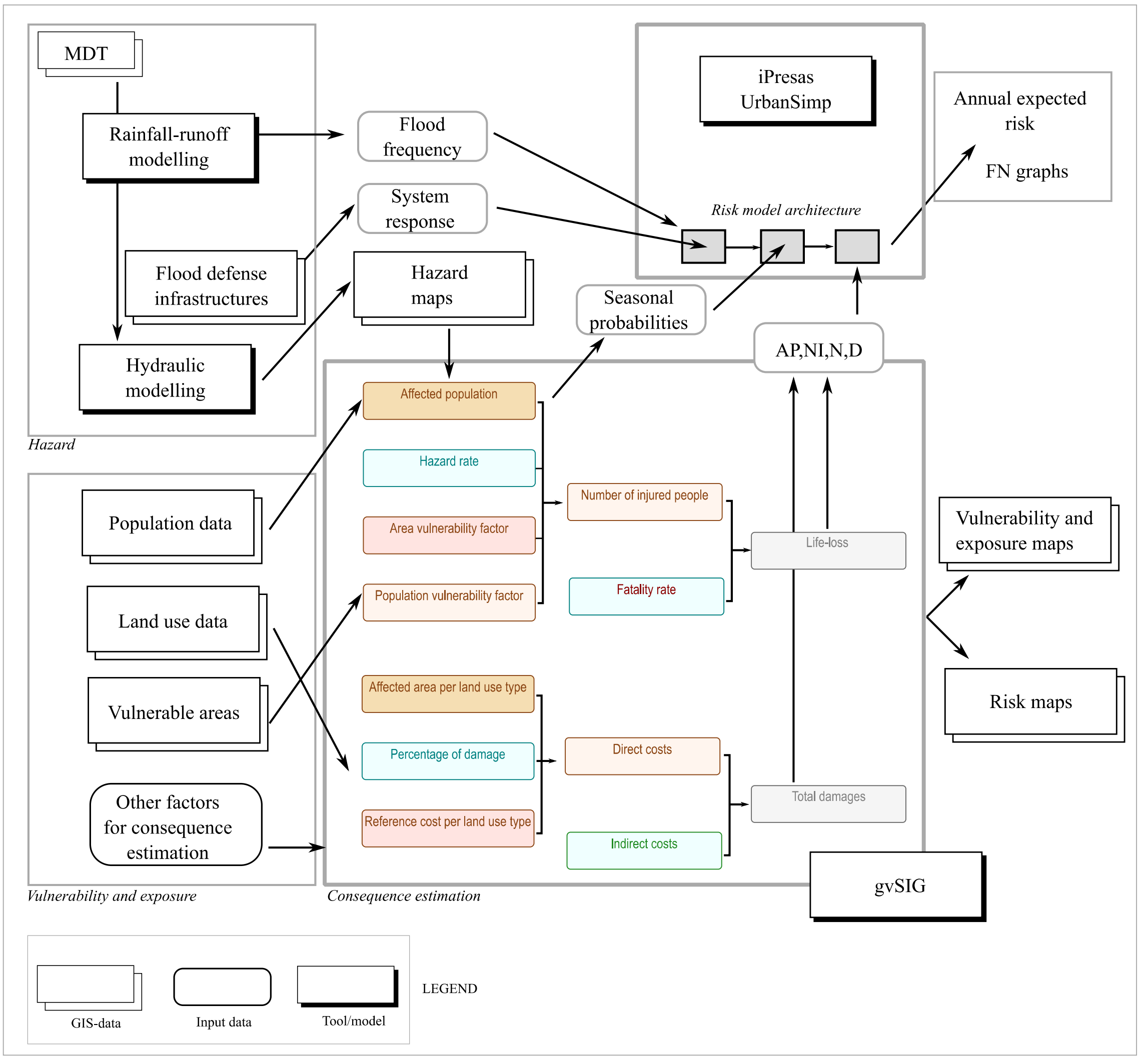

Figure 6. Flowchart of data and models for flood risk analysis.

3.2.1. *Case study 1: Flood risk analysis for a city in Spain*

The urban area of case study 1 is located in Spain. Location and details are kept confidential by request of the dam owner (public authority).

Short description of the case study

The urban area is located 8 km downstream of a dam under construction and crossed by a river course. With approximately 2150 inhabitants, the area is mainly devoted to residential, industrial and rural uses.

The aim of this case study was to analyse societal and economic flood risk for three different situations:

- the current situation before dam construction (natural flow regime of the river and existence of the current drainage system), denoted as Base Case;
- the situation after the construction of the dam, including implementation of the Dam Emergency Action Plan (DEAP-Case), and,

- the situation with new non-structural measures, denoted as NonSt-Case, which includes a program on public education and warning that complements the Dam Emergency Action Plan (DEAP).

Flood risk analysis

The analysis followed the phases presented in Sect. 3.2.1 and is described in detail in **Annex 1**.

Two influence diagrams were developed ad hoc for this case study: for the situations before and after dam construction. These risk models are based on the generic architecture proposed in Sect. 3.2.1.

Information on loads, system response and consequences was obtained in case of pluvial and river flooding, and was incorporated into the first risk model, represented by the influence diagram shown in Figure 7. The second risk model, depicted in Figure 8, includes four dam failure modes (Sanz-Jimenez D. et al., 2012): two failure modes related to structural-geotechnical aspects (slippage of dam blocks) and two failure modes related to failure of outlet works (e.g., stilling basin erosion or undermining of the toe of the dam).

Risk calculations were performed using the iPresas software, developed at the Universitat Politècnica de València. Input data for the three situations was estimated based on flood hazard characterization, system response analysis and consequence estimation methods described in **Annex 1**.

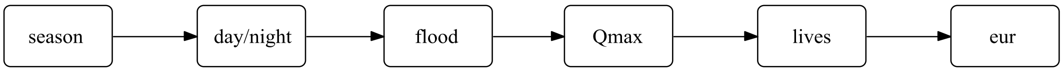

Figure 7. Influence diagram representing Risk model A for case study 1.

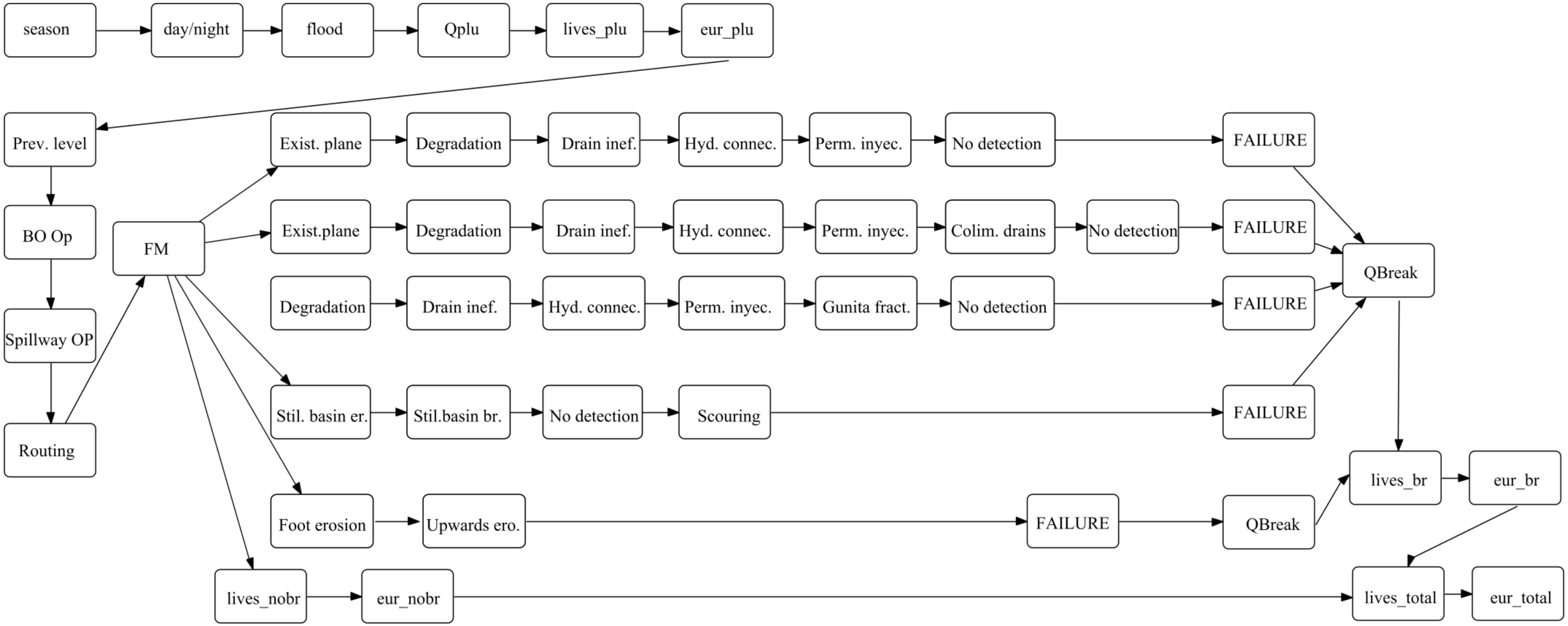

Figure 8. Influence diagram representing Risk model B for case study 1.

Results and discussion

Table 2 shows the results in terms of societal and economic risk for the three analysed scenarios, along with values of the ACSLS indicator obtained based on estimated measure costs of dam construction and operation, and implementation of non-structural measures for flood risk reduction. Figure 9 shows the FN curves for the three analysed situations for case study 1, which represent societal risk for each scenario.

Table 2. Societal and economic risk results for case study 1.

ID	Case	Societal flood risk (lives yr^{-1})	Economic flood risk (€ yr^{-1})	ACSLS indicator (€ lives^{-1})
Base Case	Drainage system and natural flow regime of the river	0.097	3 846 323	Not applicable
DEAP-Case	Drainage system and dam construction, including EAP	0.194	835 093	-19 591 730 (<0)
NonSt-Case	Drainage system and dam, including EAP and non-structural measures of public education and warning (Public Education and Warning Program)	0.069	672 897	-1 158 041 (<0)

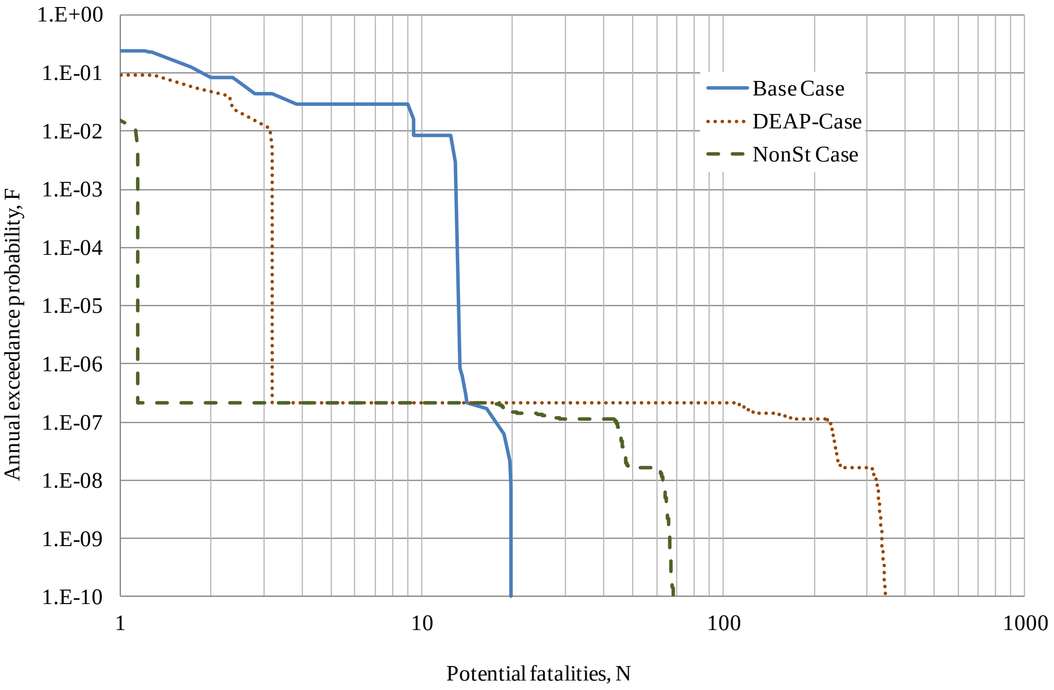

Figure 9. Results for three scenarios for case study 1: current situation (Base Case), after dam construction (DEAP-case) and after implementing non-structural measures (NonSt Case). Note: FN graph for the Base Case in Annex 1 shows results only from river flooding.

From risk outcomes shown in Table 2 and Figure 9, it is observed that potential fatalities in case of dam failure would be significant but related to low probability events.

The implementation of non-structural measures of public education, warning and improved coordination schemes in case of flood emergency may reduce existing risk (and risk after dam construction) by improving the implementation and impact of the Dam Emergency Action Plan.

The guiding principle for flood risk management and governance to protect this urban area should be ensuring effective communication mechanisms among dam operators, emergency services and local authorities to ensure a quick response in case of emergency (i.e. increasing available warning times).

Annual education programs on flood risk, improved warning systems and training exercises require relatively low economic and technical resources (the annualized cost for the program is estimated, approx.., in 17 m€ yr^{-1}) when compared to their potential for risk reduction. Results show that societal risk would decrease from 0.2 lives yr^{-1}, for the situation with only a Dam Emergency Action Plan, to 0.07 lives yr^{-1}, for the situation with improved public education and warning. In addition, results show that economic risk would decrease from 0.84 M€ yr^{-1} to 0.7 M€ yr^{-1}, respectively (i.e. the estimated reduction on economic risk is higher than the annualized cost of the proposed risk reduction measures).

For this case study, results shown that proposed non-structural measures of public education and warning are highly justified in terms of efficiency.

3.2.2. Case study 2: Flood risk analysis in Oliva (Spain)

Short description of the case study

Oliva is located in the eastern coast of Spain, 70 km south from Valencia. Oliva has been historically affected by flooding. In 1987, a flood event with 817 mm in 24 hours was recorded (highest record at the Iberian Peninsula). Oliva is affected by pluvial, river and coastal flooding and it is characterized by a complex and wide-ranging geography (e.g. hills up to 460 m.a.s.l., plains, coastal areas and wetlands). In addition, there is high seasonal variation in population (with 27,127 and 55,174 inhabitants of resident and seasonal population, respectively, distributed across 60.1 km^2).

Flood risk management is a key aspect for Oliva's current and future development. The goal of flood risk reduction poses a challenge for local authorities, as local economy depends highly on industries and tourism. In addition, Oliva's population is expected to grow, age, and become more diverse, with specific characteristics due to highly seasonal variability.

In addition, in 1999, the regional government approved the Special Plan against flood risk. This plan, reviewed in 2010, requiring all municipalities classified in high or medium flood risk levels to develop and implement a local action plan for flood risk management. In addition, all municipalities potentially affected by flooding due to dam failure or mission disruption should develop this plan in line with Dam Emergency Action Plans (as established by the 1995 Spanish Directive on Civil Protection Planning). Up to 2016, there are 20 (out of 136) approved local action plans at the Valencian Autonomous Region, and 27 approved Dam Emergency Action Plans.

For this case study, an ad-hoc quantitative flood risk analysis was conducted to provide local authorities with the information needed for developing a local action plan for flood risk management and to evaluate the impact of ongoing structural measures on flood risk reduction.

Risk outcomes of this analysis were used to develop the local action plan for this municipality.

Flood risk analysis

Four scenarios were considered for flood risk analysis for case study 2 as follows:

- Current situation (Scenario 0): this scenario represents the current situation of the system and it is used for benchmarking (to compare with results of Scenarios 1 to 3). This scenario is considered as the Base Case.
- Implementation of structural measures (Scenario 1): this scenario represents the situation after implementing structural measures for flood risk reduction, including dam construction. Differences in peak flow discharges in Rambla Gallinera are shown in Table 3 (e.g. from 282 to 182 m^3/s for a 25-yr flood event).
- Implementation of a local action plan (Scenario 2): this scenario represents the situation after implementing a local action plan for flood risk management (PAMRI), which includes improved warning and communication schemes, public education campaigns and training of all actors involved in emergency management.
- Implementation of both local action plan and structural measures (Scenario 3): this scenario represents the situation after implementing both structural and non-structural measures.

For this case study, the risk model architecture shown in Figure 10 is used. Flood characteristics after dam construction (Scenario 1) are considered based on flood routing analysis.

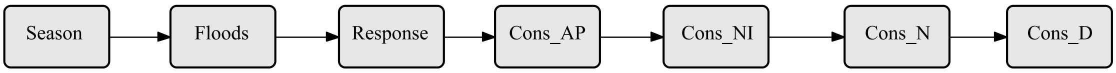

Figure 10. Risk model architecture for the case study 2.

The detailed description of input data estimation for the risk model is described in **Annex 2**.

Results and discussion

The iPresas UrbanSimp software tool is used to estimate risk by developing the event tree that includes all combinations of flood events, system response and related consequences.

Table 3. Societal and economic risk results for case study 2.

	Current situation (Scenario 0)	Structural measures (Scenario 1)	Local action plan (Scenario 2)	Structural measures and local action plan (Scenario 3)
Societal risk (AEAP) [inhabitants/yr]	2370	1168	2370	1168
Societal risk (AENI) [injured inh./yr]	28	21	24	18
Societal risk (AEN) [fatalities/yr]	0.56	0.28	0.48	0.24
Economic risk (AED) [Million EUR/yr]	6.11	2.10	5.57	1.89

Note: AE=annual expected; AP=Affected population; NI=number of injured people; N=fatalities; D=damage costs.

Table 3 shows results in terms of expected annual population affected (AEAP), number of injuries (AENI), fatalities (AEF) and damage (AED). Risk outcomes for the current situation show societal risk levels up to 2,370 of annual expected affected population and 0.6 fatalities per year. Considerable risk reduction can be achieved by implementing planned structural measures (Scenario 1) thus societal risk would be reduced to 1,168 inhabitants per year (AEAP) and 0.3 fatalities per year (AEF). Affected population remains equal after implementing local action planning (Scenario 2) but societal risk in terms of potential fatalities would be reduced to 0.5 fatalities per year.

In addition, results reflect the combined effect of both structural and non-structural measures (Scenario 3). Societal risk after dam construction and implementation of the local action plan might change from 0.6 to 0.2 fatalities per year. Economic risk in terms of annual expected damages would vary from 6.1 to 1.9 M€ per year.

Figure 11 shows F-AP, F-N and F-D curves for all scenarios. The first graph depicts the cumulative annual exceedance probability (F) of each level of potential affected population (AP). Results show that there is a probability of 10^{-2} of exceeding 8,300 affected people due to flooding for the scenario with structural measures. This value is higher when considering the current situation, with approx. 11,300 affected people for the same probability. The second graph depicts the cumulative annual exceedance probability (F) of each level of potential fatalities (N). Results show that there is a probability of 10^{-2} of exceeding 3 fatalities for the current situation (Scenario 0). This value decreases after implementing structural measures (Scenario 1) to approx. 2 and up to 1.6 for combined structural and non-structural measures (Scenario 3). The third graph shows potential economic damages (D) with a probability of 10^{-2} of exceeding 28 M€ for the current situation (Scenario 0). This value might decrease up to approx. 17 M€ after implementing combined structural and non-structural measures (Scenario 3).

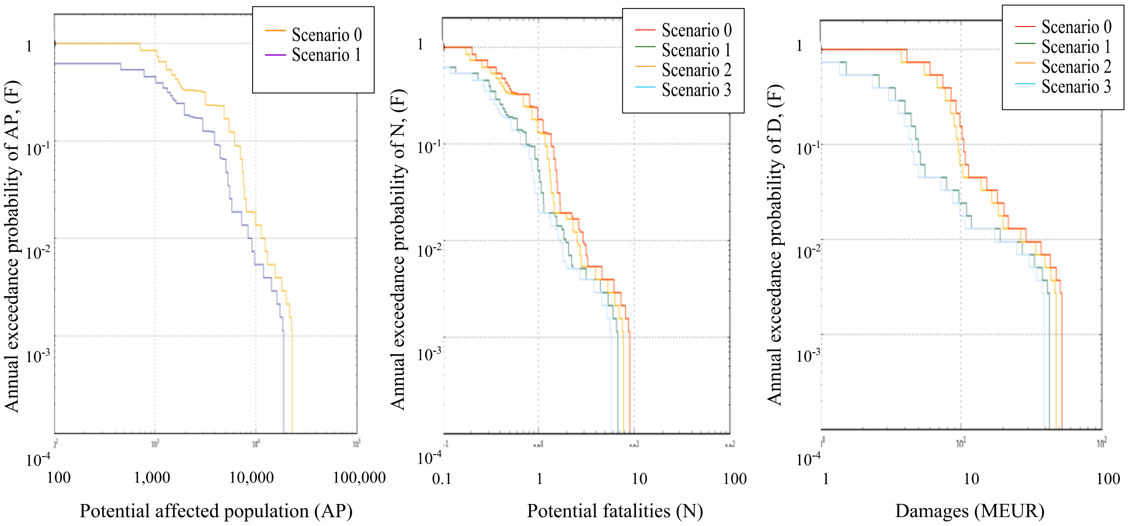

Figure 11. FN and FD curves obtained for case study 2.

Risk maps for case study 2 were developed to represent flood hazard and risk for the whole municipal term. Recommendations published in the literature for flood risk map representation (Fuchs et al., 2009; Meyer et al., 2012) were considered for elaborating these maps. An example is provided in Figure 12.

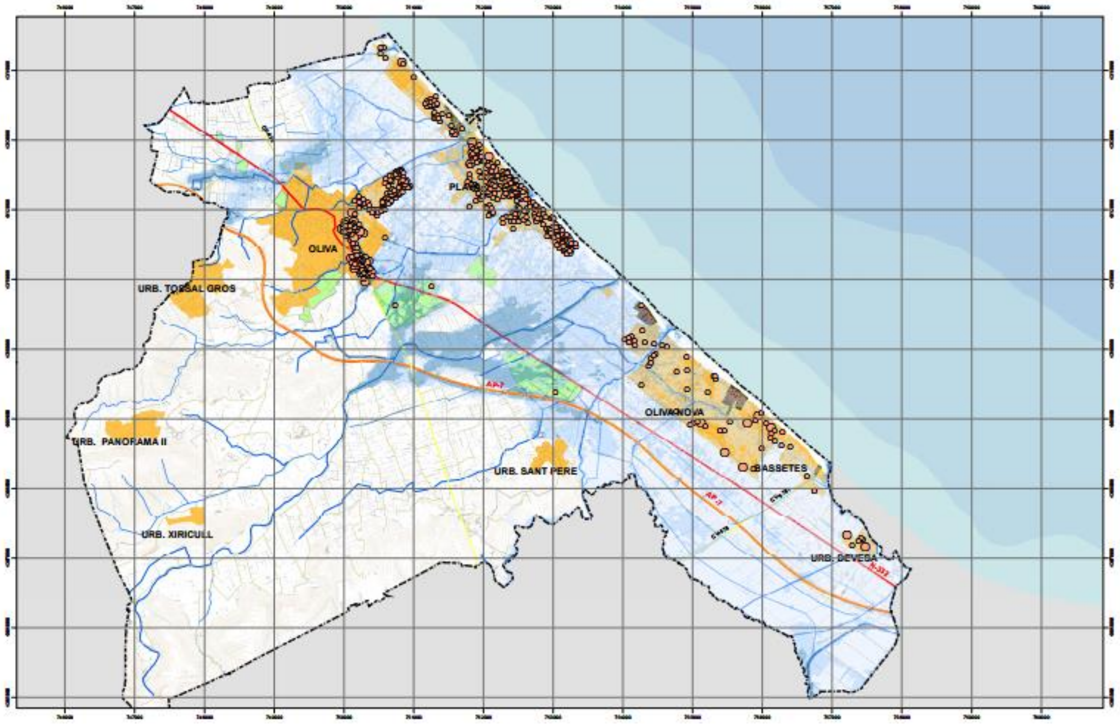

Figure 12. Example of risk map for case study 2. It can be downloaded from this link.

The ACSLS indicator is obtained to evaluate cost-efficiency of analysed measures. Table 4 shows implementation, maintenance and annualized costs for considered measures (local action plan and structural measures including dam construction). Results show that any of these measures would be justified in terms of efficiency on risk reduction since results show negative values (reduction of economic risk is higher than annualized costs). After implementing the local action plan (lowest

ACSLS value), the resulting ACSLS indicator still remains negative when risks before and after implementing structural measures are compared, thus supporting the decision of also implementing planned structural measures.

Table 4. ACSLS results for analysed measures in case study 2.

Measure	**Structural measures (Scenario 1)**	**Local Action Plan (Scenario 2)**	**Local Action Plan + Structural measures (Scenario 3)**
Discount rate (%)	5	5	5
Life span (years)	50	5	50
Implementation cost (EUR)	43,000,000	10,000	43,000,000
Maintenance cost (EUR/yr)	10,000	2,500	10,000
Annualized cost (EUR/yr)	2,253,238	4,700	2,253,238
Annualized cost	2.25	0.00	2.25
ACSLS (MEUR/life) [compared with current situation]	-6.27	-6.69	NA
ACSLS (MEUR/life) [compared with situation after implementing Local Action Plan]	NA	NA	-5.94

Note: ACSLS=Adjusted Cost per Statistical Life Saved, NA=Not Applicable.

As observed from risk analysis outcomes, implementation costs are lower than benefits in terms of economic risk reduction (ACSLS values are negative).

The application of the proposed framework for quantifying local flood risk for the city of Oliva represents a novel analysis in Spain. Recommendations were made to local authorities for defining strategies for local action planning, derived from outcomes of conducted flood risk analysis, and are described in **Annex 2**. Key strategic actions are here summarized:

- Definition of specific public education campaigns for resident and seasonal population, with emphasis in high vulnerable groups to reduce vulnerability.
- Definition of a procedure to formally reporting flood events, damages and effect of communication and evacuation procedures to validate assumptions concerning flood impact.
- Verification of established communication schemes between regional and local authorities, and with emergency and civil protection services to ensure effectiveness of non-structural measures
- Data gathering on additional urban characteristics to upgrade risk analyses in the future.

3.3. Part II: Methodology to incorporate fluvial dikes (levees) into flood risk assessment for complex dam-levee systems

3.3.1. *Description*

The proposed flood risk analysis approach, based on the aforementioned steps presented in Sect.3.1, was applied to analyse complex dam-levee systems.

The proposed generic influence diagram for complex dam-levee systems is presented in this section (Figure 13) and described in **Annex 3**.

The proposed risk model architecture provides an innovative model for analysing risk from complex dam-levee systems in an integrative and quantitative risk model, not yet considered in practice.

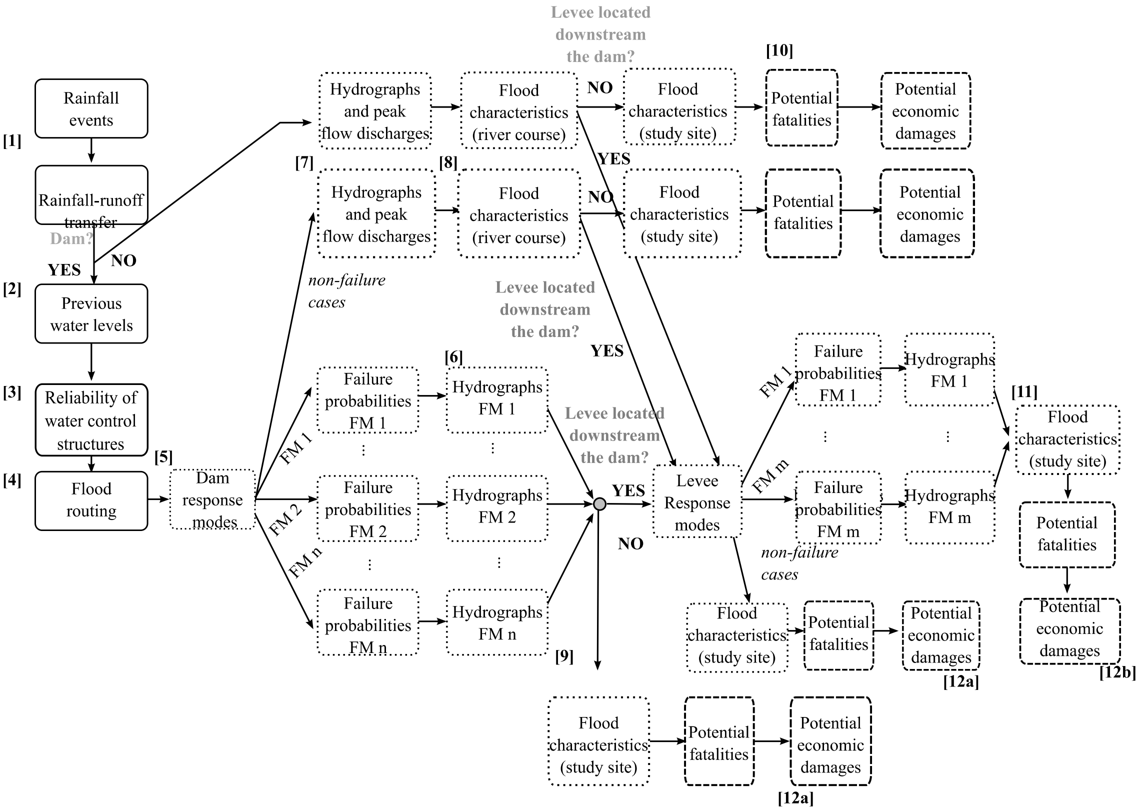

Figure 13. Generic combined dam-levee risk model scheme.
Note: Nodes outlined with solid, dotted and dashed lines refer to loads, system response and consequences, respectively

As indicated in Figure 13, the following information is required:

1) Rainfall-runoff transfer information based on hydrological studies, rainfall-runoff methods, etc. to characterize inflow floods at reservoirs or peak discharge in river courses.
2) Historical data or simulations of water pool levels at reservoir.
3) Reliability analysis of outlet works, gates, spillways, etc. that control water levels at river courses or reservoirs. Estimations may be based on historical data, fault tree analysis or expert judgement.
4) Flood routing results from inflow hydrographs, previous water levels and reliability of water control structures. Loading scenarios are characterized by maximum water pool levels.
5) Estimation of failure probabilities based on failure mode identification, numerical modelling, Monte Carlo simulations, fault tree analysis, expert judgement, etc.
6) Outflow discharges and hydrographs, depending on maximum water pool levels and failure modes (e.g. type of breach, breach development, etc.).
7) Results from flood routing analyses based on outflow hydrographs.
8) Flood characteristics in downstream areas (flood depth, velocity, rise-rate, wave arrival times, flooded areas, etc.), obtained from hydraulic models.
9) Flood characteristics along the river course obtained from dam-breach models.
10) Estimated potential fatalities and economic damages at the study area.
11) Flood characteristics at the study site from hydraulic modelling of levee failure scenarios.
12) Estimated potential fatalities and economic damages at the study area, including reconstructions costs.

The proposed scheme for combined dam-levee risk modelling can be used to estimate risk at system scale, incorporating loads, system response and consequences from scenarios that take into account both types of flood defence infrastructures.

Results from the combined analysis can be used to inform decisions on how to allocate risk reduction measures from a system-scale perspective rather than asset-specific.

The presented generic risk model architecture has been applied to a real case study in the United States.

3.3.2. Case study 3: Dam-levee system in United States.

The system of case study 3 is located in the United States. Location and details are kept confidential by request of the dam owner and authorities of downstream communities.

Short description of the case study

This case study was analysed following the proposed method and risk model architecture in Sect.3.2.

The system is composed by a 3-mile long earthen flood control dam and a set of levee segments located along two downstream river courses. The dam protects a population at risk of approximately 1.25 million people since areas both up- and downstream are highly urbanized. Two river courses (named A and B) are regulated by the dam with control structures on each river. The dam is normally dry with low water levels at the reservoir.

The analysis described in this paper has been performed to provide answers to the need for assessing existing risk in a complex system composed by multiple structures. Previous studies have focused on single structures (dam risk analyses or levee performance assessments) but not providing risk outcomes from a comprehensive approach. Because of its high potential consequences in case of failure, this case study analysis aims at assisting dam and levee owners to assess the current situation and develop future risk-informed flood management strategies.

A simplified scheme of the dam-levee system is depicted in Figure 14.

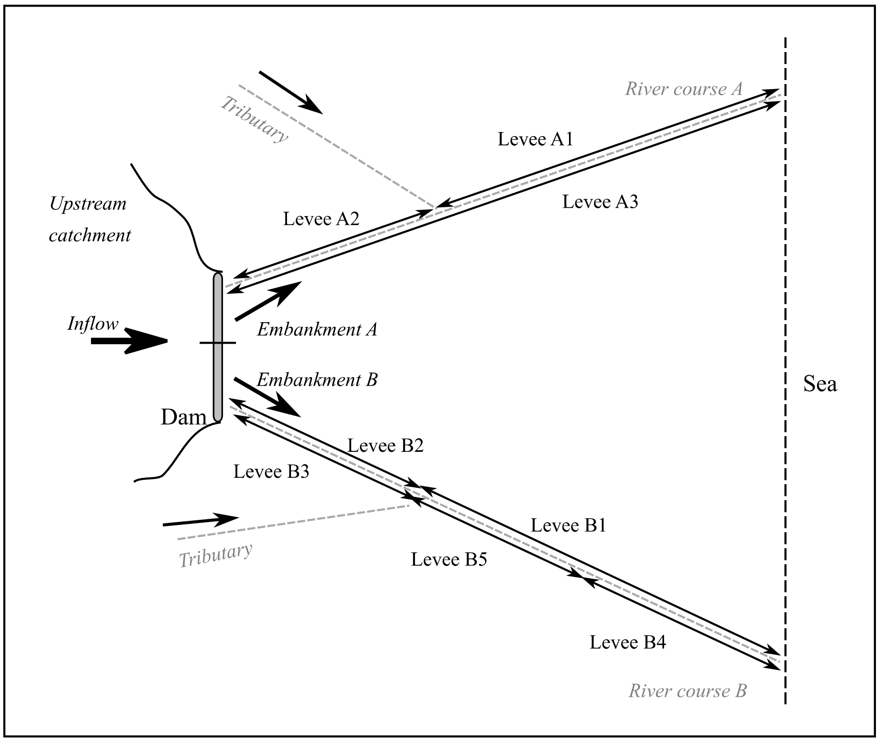

Figure 14. Scheme of case study 3.

Flood risk analysis

Two main information sources were available: a dam risk analysis conducted in 2011, including dam failure probabilities for six identified potential failure modes for hydrologic scenario and 3 in case of seismic scenario, and results from applying the LST method to all downstream levee segments.

The baseline scenario was analysed and refers to the current situation of the system, including current dam operating rules during flood events.

A combined dam-levee risk model is proposed. In addition, individual risk models for the dam and each levee segment were performed to compute risk for all sub-systems.

The risk model architecture depicted in Figure 15 is used for computing incremental dam risk, including hydrologic and seismic scenarios. Nodes in include input data on loads, system response and consequences to estimate risk from hydrologic and seismic scenarios. Details on abbreviations are provided in **Annex 3**.

Similarly, the risk model architecture shown in Figure 16 is used for computing total risk from both dam failure and non-failure cases, including hydrologic and seismic scenarios.

The risk model architecture shown in Figure 17 is used for computing flood risk from levee breach prior to overtopping and flooding due to overtopping (breach and non-breach cases) for each levee segment.

Based on the generic risk model proposed in Sect.3.2 and individual risk models depicted in Figure 15, Figure 16 and Figure 17, the combined risk model architecture used for this case study was defined and it is shown in Figure 18. This model is an ad-hoc influence diagram developed for the case study, connecting both dam and levee individual risk models, and differs from the generic structure due to the following specific conditions:

- Levee segments are divided into two subsystems, that is, distributed along two different river courses. Two distributions of outflow discharges for dam scenarios from flood routing are used.
- It is assumed that for each levee subsystem, multiple levee breaches do not occur.
- Common cause adjustment is applied over all failure modes for each levee subsystem.

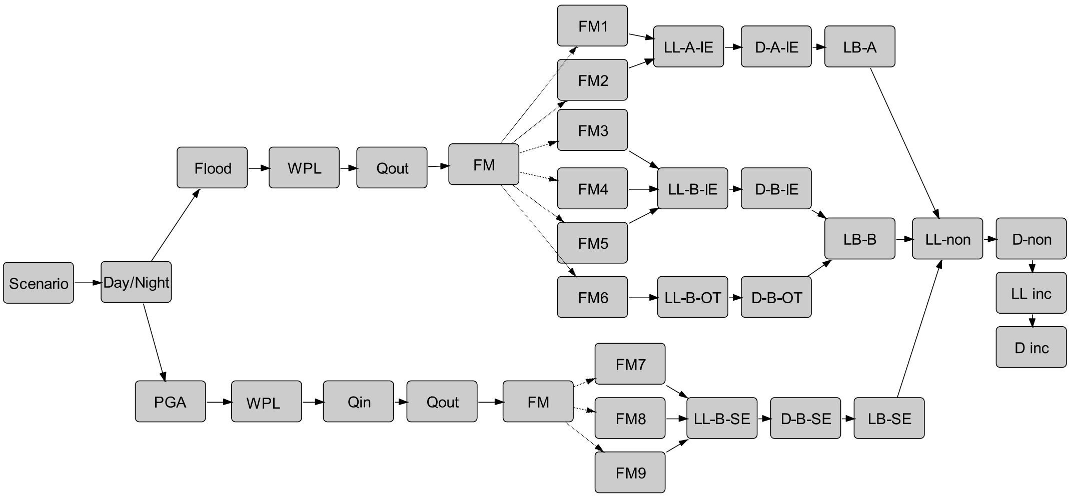

Figure 15. Risk model architecture scheme for case study 3: dam risk model (incremental risk).

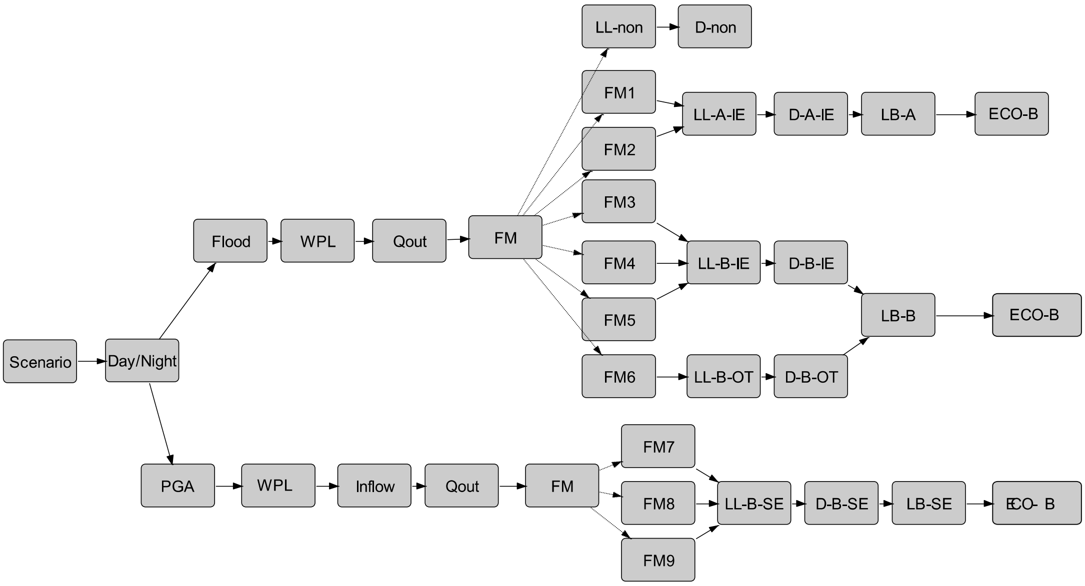

Figure 16. Risk model architecture scheme for case study 3: dam risk model (total risk).

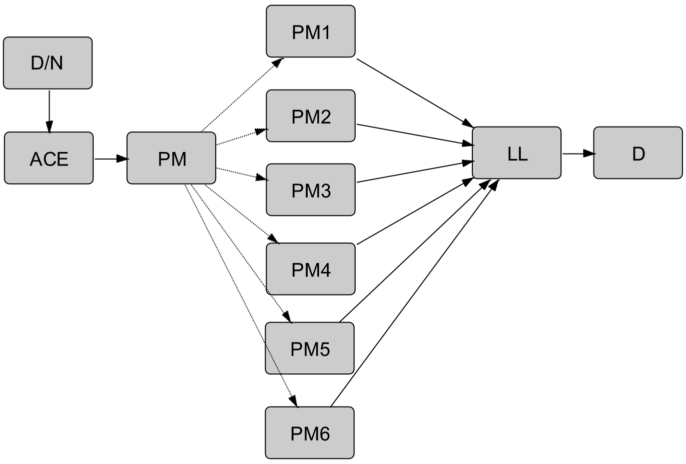

Figure 17. Risk model architecture scheme for case study 3: levee risk model.

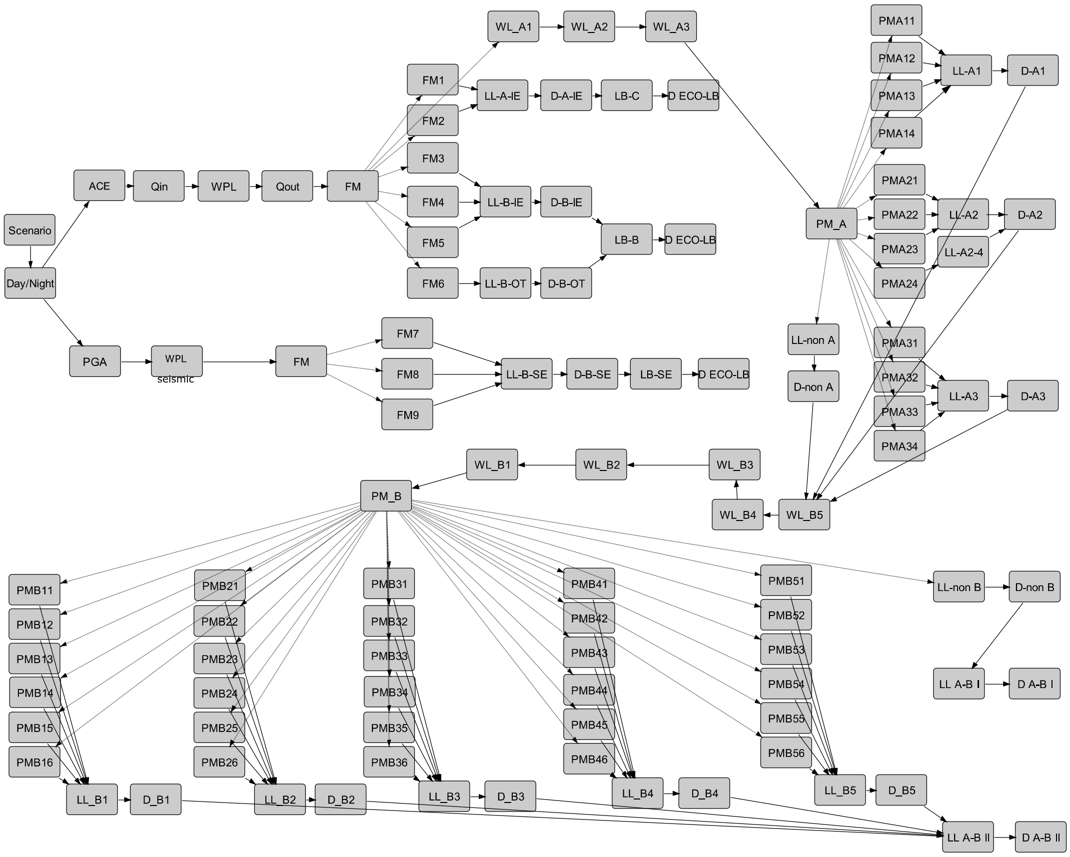

Figure 18. Risk model architecture scheme for case study 3: combined dam-levee system risk model.

Results and discussion

Results from the separate dam risk model (not including risk associated with potential breach of levees) are shown in Table 5. The estimated incremental societal risk is 0.01 lives per year and dam failure probability is about $1.34 \cdot 10^{-4}$.

Table 5. Risk outcomes for case study 3: dam risk model.

Risk model	Dam (incremental)			Dam (total)		
Scenario	Hydrologic	Seismic	Global	Hydrologic	Seismic	Global
Failure probability (1/yr)	1.34E-04	1.55E-06	1.35E-04	-	-	-
Economic risk ($/yr)	1,045,961	2,368	1,048,328	17,518,841	4,922	17,523,763
Societal risk (fatalities/yr)	0.0104	0.000012	0.0104	0.0131	0.000012	0.0131

Results from levee models are included in Table 6. Incremental risk results range from 0.1 up to 4.5 lives per year. Annual levee failure probabilities are generally greater than 10^{-4} and annualized societal incremental risk above 0.1 lives per year.

Table 6. Risk outcomes for case study 3: levee risk models.

Levee Segment	Failure probability	Economic risk ($/yr)	Societal risk (lives/yr)
A1	4.44E-03	126,500	1.05E-03
A2	1.35E-03	3,425,148	7.17E-02
A3	5.81E-03	31,032,335	4.96E-01
B1	2.26E-03	6,392,352	1.32E-01
B2	2.68E-02	238,628,175	4.50E+00
B3	6.69E-03	8,490,563	2.00E-01
B4	3.09E-04	307,445	6.27E-03
B5	2.08E-03	6,505,021	2.02E-01

Figure 19 shows the fN pairs for the dam and each levee segment. Results show that levee segments in subsystem B present, in general, higher values.

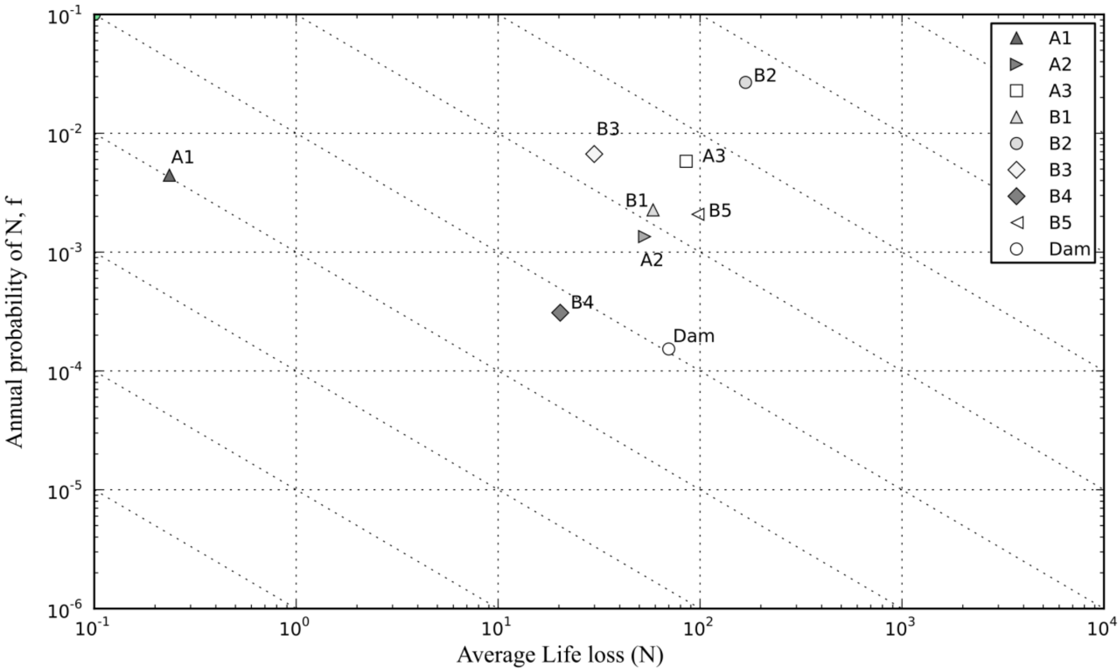

Figure 19. fN pairs from dam and levee risk models.

Finally, results from the combined model are included in Table 7. Estimated ssocietal risk is approx. 5.5 lives per year and economic risk is about $M 292 per year.

Table 7. Risk outcomes for case study 3: combined system risk model.

Model	Combined		
Scenario	Hydrologic	Seismic	Global
Economic risk ($/yr)	291,628,124	4,922	291,628,124
Societal risk (fatalities/yr)	5.55	1.24E-05	5.55

Figure 20 depicts FN-curves for both dam risk model (total risk terms) and the combined dam-levee model.

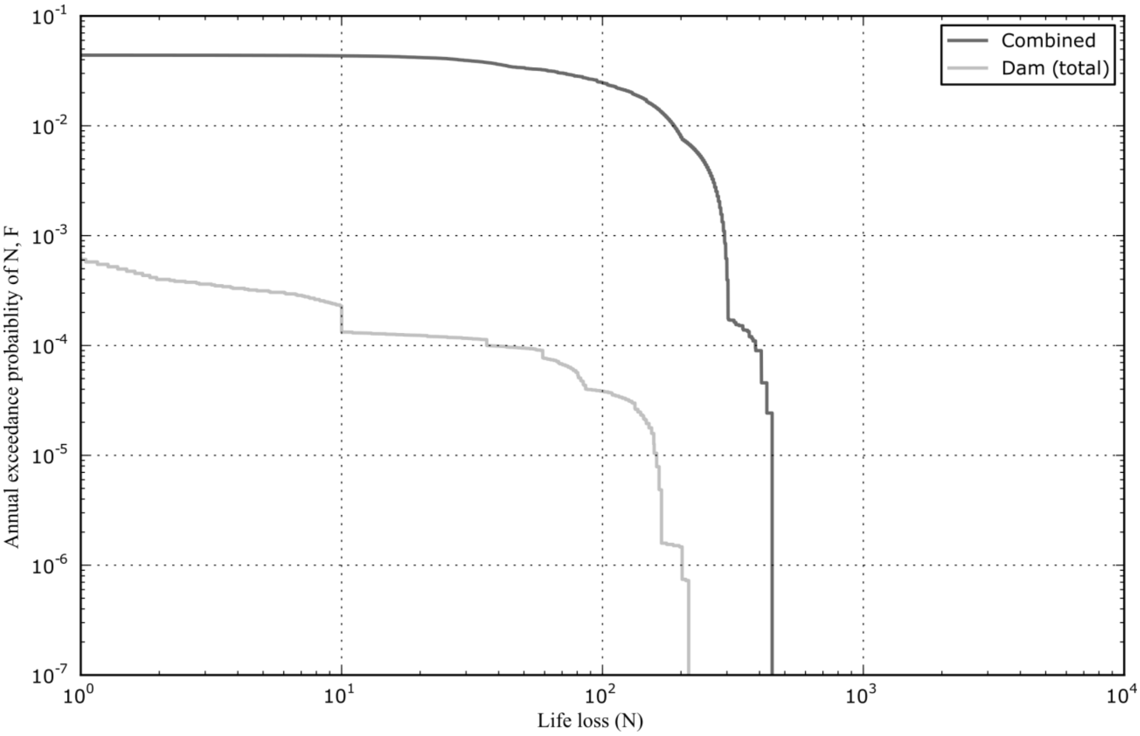

Figure 20. FN curves from dam risk model vs. combined dam-levee risk model.

Focusing only on risk analysis of the dam (Table 5), results show both the incremental societal risk and probability of failure are above tolerable risk guideline recommendations for dams used by many agencies (Munger et al., 2009). As such, measures to reduce incremental risk associated with the dam should be investigated. Typically, remediation measures should include a wide range of options, including those that reduce frequency and magnitude of loading, those that reduce probability of breach given loads, and those that reduce consequence in the case of flooding.

In total risk terms, societal risk is estimated at about 0.01 lives per year. Based on those estimates, 77% of total risk is due to incremental risk. Therefore, decreasing incremental risk by lower the probability of failure or associated consequences would also have a significant impact on total risks.

For this case study, the potential life loss is relatively high. Much of this is due to the fact that people are located directly downstream from the dam, meaning they do not have very much time to receive warning and evacuate if something goes wrong at the dam. Therefore, one potential risk reduction alternative could be installation of warning sirens directly downstream from the dam. Additional analysis with those sirens in place shows that life loss could be reduced by approximately 30% if the dam was to breach (due to larger warning times). While installation of sirens would not reduce the probability of failure (therefore not addressing that portion of the tolerability criteria), they will reduce the overall incremental and total risk for a relatively small financial investment.

Results from the levee analysis (no dam failure) show the risk is orders of magnitude higher than that associated with the dam. This is not surprising, at least in the U.S., as the typical large dam has a spillway that allows for it to safely pass very rare hydrologic events (1 in 10,000 chance per year or less frequent) without breaching, while the typical levee is designed to pass much lower frequency events, and is not designed to withstand overtopping.

Results for the case study show the overall risk for the community downstream of the dam is mainly driven by levee segment B2. Therefore, investing in remediation activities at this segment would impact on societal risk from a system perspective. For example, reducing the probability of failure for the driving failure modes (embankment seepage and floodwall stability) by an order of magnitude could reduce risk from an estimated 5.6 lives and $M 292 per year to 1.9 lives and $M 100 per year.

However, additional considerations should be taken into account when analysing efficiency of risk reduction measures, such as budget limitations, cost vs. benefit analysis for both economics and life safety.

3.4. Part III: Screening procedure to incorporate malevolent threats into dam risk analysis and flood risk assessment

3.4.1. Description

The procedure for screening of the impact of manmade threats on the overall risk management of a dam herein proposed is based on the comparison of annualized incremental safety risk analysis outcomes and conditional security risk estimates.

Figure 21 shows a flow diagram and the connections between safety and security risk analyses outcomes and how are related as proposed in this paper.

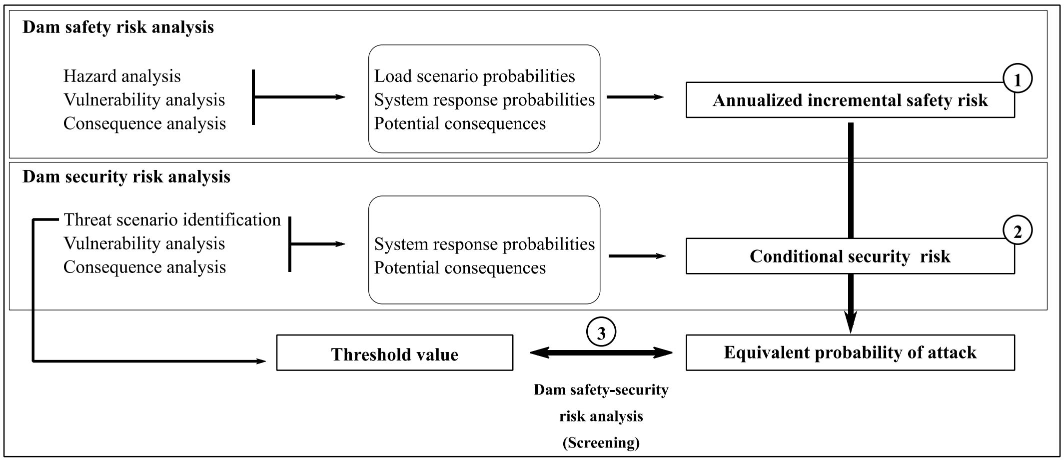

Figure 21. Screening procedure for analysing the impact of manmade threats in dam risk analysis.

The procedure includes a 3-step process including:

- Step 1 "Dam safety risk analysis": obtaining annualized incremental safety risk as the main outcome.
- Step 2 "Dam security risk analysis": obtaining conditional security risk.
- Step 3 "Comparative analysis": obtaining the equivalent annualized probability of attack and compared with a reference threshold value.

Table 8 includes actions to be undertaken in this stage of the proposed procedure and resulting outcomes.

Table 8. Steps of the screening procedure for analysing the impact of manmade threats in dam risk management.

Step	Name	Description	Main outcome
1	Dam safety risk analysis	Analysis of natural hazards, system response and consequences, including: Probability estimations of load events and system response. Estimation of incremental consequences in case of dam failure or mission disruption.	Annualized incremental safety risk.
2	Dam security risk analysis	Analysis of manmade threats, system response and consequences, including: Analysis of past incidents and context. Attack scenario identification. Probability estimations of system response. Consequence estimation in case of dam failure or mission disruption.	Conditional security risk. Threshold value.
3	Comparative analysis	Estimation of the equivalent annualized probability of attack, based on outcomes from Steps 1 and 2. Comparative analysis of threshold value and equivalent probability of attack, based on outcomes from Steps 2 and 3.	Equivalent annualized probability of attack.

In Step 3, an indicator is proposed for the comparative analysis to assess the impact of manmade threats. This indicator named equivalent annualized probability of attack, it is denoted as $\lambda_{eq,i}$, reveals the potential attack probability that would result in similar risk estimates for both natural hazards and manmade threats.

The equivalent annualized probability of attack is defined as the ratio between annualized incremental safety risk, r_N, and conditional security risk, hereafter denoted as $r_c(A_i)$:

$$\lambda_{eq,i} = \frac{r_N}{r_c(A_i)} \quad (1)$$

where $\lambda_{eq,i}$ is the equivalent annualized probability of attack; r_N is the annualized incremental safety risk, $r_c(Ai)$ is the conditional security risk and A_i is each identified attack scenario.

This ratio has units of yr^{-1} and it represents the attack probability that equals risk from natural hazard analysis and the given attack scenario.

An attack scenario with an actual probability of occurrence greater than λ_{eq} would result in a security risk level higher than the existing risk from natural hazards. If the resulting value is not plausible, then safety risk can be understood as the 'main' source of risk. On the contrary, plausible values indicate that security risk levels may be significant when compared to existing safety risk.

At asset (dam) level, this indicator can be used for screening analysis to identify if manmade threats are driving the current risk climate; thus plausible attack scenarios may lead to security risk levels that are higher than existing safety risk levels.

Following the proposed procedure, results obtained for the equivalent annualized probability of attack inform on the relative impact of manmade threats when compared to safety risk levels.

An additional indicator, $\lambda_{eq,th}$, named *threshold probability of attack*, is proposed to represent a threshold value for analysing the equivalent attack probability, $\lambda_{eq,i}$. Estimation of the threshold probability of attack requires information on past incidents, context characterization and the consideration of site-specific conditions.

The following ranges are defined for assessing the impact of manmade threats into dam risk management, based on the resulting equivalent annualized probability of attack and the asset-specific threshold probability of attack:

- $\lambda_{eq.i} > 1$: dams in which safety risk is significantly higher compared to risk from manmade threats. Consequently, such cases require the attack probabilities to be so high that, in order to make both safety and security risks somewhat equal, would require attack scenarios that may be virtually not credible.
- $\lambda_{eq,th} \leq \lambda_{eq} \leq 1$: dams in which required attack probabilities to equal both safety and security risks are relatively high (with probabilities of occurrence ranging from $\lambda_{eq,i}$ to 1).
- $\lambda_{eq,i} < \lambda_{eq,th}$: dams with high conditional security risk for the identified attack scenario when compared to existing safety risk.

Estimation of the threshold probability of attack based on information from intelligence communities would be desirable. If the equivalent annualized probability of attack might be contrasted with this information, dam owners and operators would be able to assess how credible it is that security risk becomes the major risk driver for a particular dam. However, in practice, it is not possible to access to such level of information. Data on reported past incidents against dams, or similar infrastructures, may be used if available.

3.4.2. Case study 4: Combined safety and security analysis at portfolio scale

Short description of the case study

The aim of this case study is to show how results from risk analysis for natural hazards and manmade threats can be compared to provide information for an integrated dam risk management.

The case example is provided to show how the screening procedure presented in Sect. 3.2 and described in **Annex 4** can be used by dam owners and operators to analyse risk on dams from a combined safety and security perspective.

A set of four concrete gravity dams is considered, which represents part of the portfolio managed by a public dam owner. All dams include spillway gates.

Flood risk analysis

After a preliminary identification process of potential attack scenarios, the attack scenario that presents the highest conditional security risk estimate, in terms of societal risk, is chosen. For this scenario, the spillway is the targeted element. A sequential and progressive failure of spillway gates is considered for each dam (5-10 minutes in total).

System vulnerability was estimated based on the presence of physical barriers, access to control panels, gate structure, main and supplementary energy supply, etc. It is assumed that potential attackers are terrorist groups with the capability of utilizing man-portable explosive devices and small vehicles. Their objective would be to access the gate chamber, activate control commands to open spillway gates and later block/damage them to avoid gate closure. It is considered that the water level at the reservoir is at Normal Operating Level (NOL) when the attack occurs (NOL is set at the top of the spillway gates for all dams).

Results and discussion

The proposed screening procedure has been applied and results are included in Table 9, where outcomes from both safety and conditional security risk analysis are included.

Table 9. Risk outcomes for case study 4.

Dam	**Step 1**	**Step 1**	**Step 1**	**Step 2**	**Step 2**	**Step 2**	**Step 3**
	Dam failure probability, $f_{p,j}$ [yr^{-1}]	Incremental average life-loss, N_j [lives]	Annualized incremental societal safety risk, $r_{N,j}$ [lives·yr^{-1}]	Conditional failure probability, $f_{c,j}$	Life-loss for scenario $A_{0,j}$, $N_{A0,j}$ [lives]	Conditional security risk, r_c ($A_{0,j}$)[lives]	Equivalent probability of attack, $\lambda_{eq,j}$ [yr^{-1}]
D1	$3\cdot10^{-7}$	$7\cdot10^{-1}$	$2\cdot10^{-7}$	$5\cdot10^{-2}$	1	$5\cdot10^{-2}$	$4\cdot10^{-6}$
D2	$2\cdot10^{-4}$	$1\cdot10^{2}$	$2\cdot10^{-2}$	$6\cdot10^{-3}$	10	$6\cdot10^{-2}$	$3\cdot10^{-1}$
D3	$6\cdot10^{-4}$	$1\cdot10^{2}$	$6\cdot10^{-2}$	$7\cdot10^{-3}$	5	$3\cdot10^{-2}$	2
D4	$7\cdot10^{-6}$	3	$2\cdot10^{-5}$	$2\cdot10^{-2}$	1	$2\cdot10^{-2}$	$1\cdot10^{-3}$

Results from step 1 (dam safety risk analysis) include dam failure probability, annualized incremental societal safety risk and incremental average life-loss (obtained by dividing annualized risk and dam failure probability). Results from step 2 (dam security risk analysis) include conditional dam failure probabilities, estimated life-loss for the given attack scenario and conditional security risk (obtained by multiplying the first two outcomes). Results from step 3 (comparative analysis) include the estimation of the equivalent probability of attack for each dam.

For the sake of simplicity, it is assumed that the attack scenario with the highest conditional risk for each dam, $A_{0,j}$, is the only relevant to account for (where j denotes the dam at study).

A value for the threshold probability of attack equal to $1·10^{-5}$ [yr^{-1}] is considered in this example. This value has been obtained based on reported past incidents against dams worldwide. According to the DHS report on 'Worlwide Attacks against Dams' (DHS, 2012), in the period 2001-2011, 25 attacks were conducted against dams: four in Afghanistan and Burma, three in Iraq, two in Russia, India, Nepal and Philippines, and one in Indonesia, Thailand, and in the U.S, respectively. Explosive devices, standoff weapons, and incendiary devices were used by assault teams. Based on the number of large dams (>15m high) in each country, a simplified estimate of $1·10^{-5}$ [yr^{-1}] for the probability that an individual large dam may be attacked was obtained for the U.S. (probabilities are higher in areas of ongoing armed conflicts). Despite the limitations of available data (low number of reported incidents, different scenarios and adversary goals, changing contexts, etc.), the resulting value is used for the purpose of this example.

Combining results from both safety and security analyses, Dam D1 shows an equivalent probability of attack lower than the threshold value. For this dam, plausible probability values for the given attack scenario result in higher security risk levels if compared to existing safety risk from natural hazards ($2·10^{-7}$ lives·yr^{-1}). Consequently, security risk mitigation measures along with safety risk reduction actions might be considered for this asset to conduct a balanced operation in terms of dam risk management.

However, results for Dams D2, D3 and D4 show values of the equivalent probability of attack larger than the threshold value, thus current security risk levels for the given attack scenario are low when compared to existing safety risks. It should be noted that safety risk outcomes for D2 and D3 are $2·10^{-2}$ lives·yr^{-1} and $6·10^{-2}$ lives·yr^{-1}, respectively. Consequently, safety risk would in principle stand for the main concern for the current situation. After implementing safety risk reduction measures, an updated combined safety-security analysis would be required to analyse the need for security risk reduction measures.

Figure 22 represents fN pairs obtained from individual risk models for all dams that relate annual dam failure probabilities and incremental average consequences. Results from dam safety risk analysis (left) are compared with international tolerability recommendations as proposed by ANCOLD and USACE (SPANCOLD, 2012). As observed in Figure 22, dams D1 and D4 show risk estimates in line with recommendations for existing dams, with societal risk estimates below $1·10^{-3}$ lives·yr^{-1}. Although it is common practice in the dam engineering community to use these recommendations, they should be considered as part of a comprehensive risk evaluation process, not considering minimum requirements to meet such criteria but reducing risk through prioritization based on efficiency and equity principles as suggested in (Morales-Torres et al., 2016).

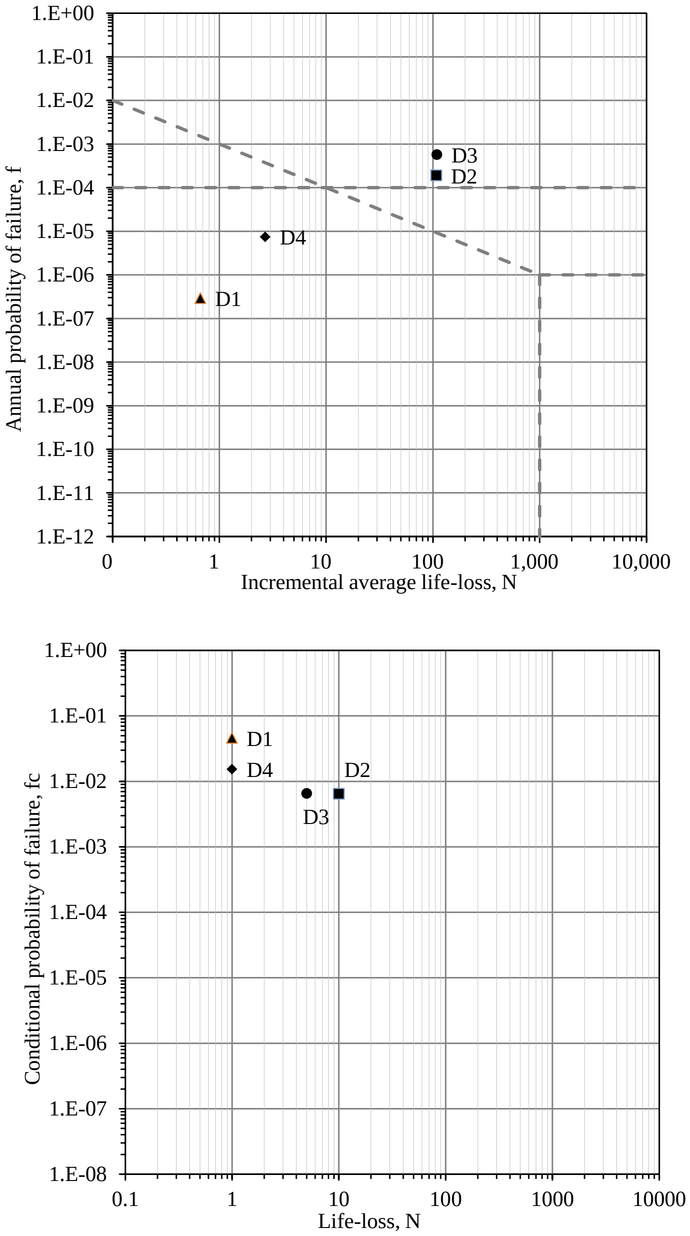

Figure 22. fN graph obtained for case study 4: (a) safety and (b) security risk outcomes.

Outcomes from security risk analysis for the given attack scenario are shown in Figure 22 (right), representing fN pairs that relate conditional system failure probabilities and estimated consequences in case of a successful attack. Risk acceptance criteria are not included in this case since there is no consensus on tolerability recommendations. Although it is out of the scope of this paper, the ALARP principle might be considered for evaluating the impact on security risk of mitigation actions, based on risk reduction up to a level that is as low as reasonably practicable in terms of cost against the benefits obtained.

As observed, dams D2 and D3 show consequence estimates lower than the average life-loss resulting from dam failure due to natural hazards. However, this graph does not include the risk component related to the threat probability then it cannot be fully compared against safety outcomes.

3.5. Towards integrative flood risk management and governance

The International Risk Governance Council (IRGC) defines “risk governance” as “the totality of actors, rules, conventions, processes, and mechanisms concerned with how relevant risk information is collected, analysed and communicated and management decisions are taken” (Renn and Graham, 2006). Examples of risk governance frameworks can be found in the literature (USACE, 2014) An example is the work conducted by the IRGC, an independent organization whose purpose is to improve the understanding and management of emerging systemic risks. IRGC developed a comprehensive framework for risk governance composed by 5 elements (Renn and Graham, 2006), including risk pre-assessment, risk appraisal, risk characterization and evaluation, risk management and risk communication.

Despite the existence of such frameworks, risk governance is not a mainstream approach in the infrastructure sector (Escuder-Bueno and Halpin, 2016), regardless existing studies, procedures, and applications. Therefore, recent efforts have been allocated to identify barriers and root causes of the relatively low degree of implementation of risk governance in the infrastructure sector, and especially in the dam sector. One of the identified barriers is the lack of consensus among key actors on risk analysis procedures and practices (Escuder-Bueno and Halpin, 2016).

Aiming at overcoming such barriers, collaborative initiatives can be found, such as the Memorandum of Understanding subscribed in 2015 by the U.S. Army Corps of Engineers (USACE) and the Spanish Ministry of Agriculture, Food and Environment (MAGRAMA), to cooperate in the field of dam safety and risk management of hydraulic infrastructures. Both institutions have responsibilities regarding a wide range of hydraulic infrastructures, including flood defences. The purpose of this cooperation was to set a framework for exchange of knowledge, best practices and lessons learned to enhance integrated water management, particularly in the field of dam safety. This agreement represented a reference example for other institutions on the benefits of collaborative work among different entities with common roles and interests, and how to boost risk governance on key infrastructure management.

Concerning flood risk management, risk issues have been incorporated into water resources management and spatial planning, mainly after the publication of both EU Water Framework Directive and EU Floods Directive. Examples are flood risk plans developed at river basin district level, including the analysis of different flood scenarios and potential consequences in terms of population at risk and/or economic damages. However, further efforts are still needed to align flood risk management actions at different administration levels. Evidences of recent quantitative flood risk analyses approaches at local scale can be found (Porta-Sancho et al., 2016), e.g. in Spain, but are not widespread conducted.

In such context, effective flood risk management can only be achieved by aligning the following three key components: *society* (including decision makers, stakeholders and citizens)*, policy (at* different scales*),* and *science*. Connections among these three components are required for boosting risk-informed flood emergency management.

This thesis, as shown in case study 1, has been conducted in close collaboration with key flood risk management actors (i.e. local authorities responsible for flood risk management and civil protection in Oliva, Spain). Stakeholder engagement is crucial for getting research findings into practice. Combining flood risk management objectives, actions and measures with outcomes from risk assessment will help to better establish efficient and effective institutional strategies for flood risk reduction (Porta-Sancho et al., 2016).

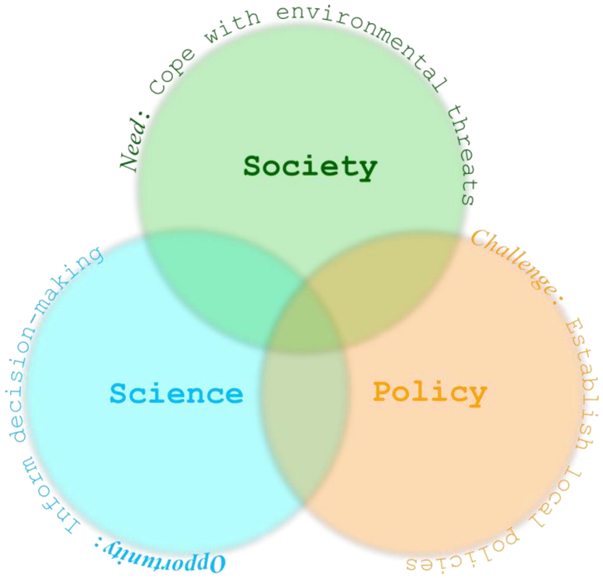

Figure 23. Connections among science, policy and society for efficient flood risk management (Porta-Sancho et al., 2016).

Consequently, this thesis aimed to provide integrative quantitative risk analysis techniques. These may boost implementation of flood and infrastructure risk governance and they may support decisions in flood risk management (FRM).

Methods and tools (*science*) are provided to quantify, analyse and evaluate risk to support decisions on risk reduction for key FRM actors (*society*) and to comply with requirements set by current FRM policies (*policy*). Outcomes from quantitative risk analyses may support decision makers on how to prioritize actions for flood risk reduction, based on multiple criteria, including efficiency and/or equity principles.

The proposed framework in this thesis and conducted case studies aimed at encouraging key actors on flood risk management (infrastructure managers, authorities, emergency action planners, etc.) on the use of QRA, and at demonstrating to what extent QRA can usefully contribute to better understanding risk drivers and inform decisions on how to act to efficiently reduce flood risk.

This PhD research provides new tools for integrative flood risk analysis and management to make our cities and regions safer against current and future hazards. This will only be possible through active and real collaboration among academia and stakeholders, since it is the only way to bring innovative solutions into practice. Outcomes of this PhD research have already been applied by local authorities for improving current flood risk management, representing key steps on the transition from vision to action.

Findings of this research will help us to strengthen our capacity as a society to cope with current and future risks and the benefits go beyond risk reduction figures. Lives behind figures may significantly be improved through effective and efficient use of resources for flood risk reduction: reducing potential vulnerability, improving flood risk management strategies and reducing existing and future societal and economic risk. Outcomes from comprehensive flood risk analyses, as those conducted in these thesis, will help to inform decisions on actions for flood risk management at local scale, resulting in direct and indirect benefits for citizens living in urban areas at risk.

4. CONCLUSIONS

4.1. Summary of research outcomes

The main results of the PhD research are summarized in this section:

- The main scope of this research was to propose a common framework for quantitative flood risk analysis by integrating multiple hazards, to be applied at local scale but not limited to micro-scale analysis.
- The basis behind the proposed methodology relies on the potential of event tree modelling to calculate and analyse risk from multiple combinations of 'load-system response-consequence' events. The use of event tree modelling has proven to be a robust and consistent method for risk calculation.
- Results from this research have proven that the use of risk models provides a logic and mathematically rigorous framework for compiling information for flood risk characterization and analysis from different natural hazards and performance of flood defences.
- Part I of the methodology, briefly presented in Sect. 3.2 and described in **Annex 1,** presents a comprehensive framework to integrate the analysis of pluvial flooding, river flooding and flooding from dam failure into urban flood risk analysis, to provide improved and more complete information to decision makers on flood risk management.
- In addition, the relevance of conducting quantitative flood risk analysis in urban areas to support flood emergency management has been proven, as described in **Annex 2**. Case study applications have shown how risk outcomes may inform decision on flood emergency management and local action planning.
- Part II of the methodology, presented in Sect. 3.3 and described in **Annex 3,** provides an approach for analysing risk in complex dam-levee systems by combining information from multiple flood defence system components, an innovative framework for combined risk modelling that may benefit from advances in dam and levee safety risk characterization (incorporating upgraded input data on loads, system response or consequences). This framework will help flood defence owners and operators, and emergency services, to better understand flood risk including multiple sources of hazard.
- Part III of the methodology, presented in Sect. 3.4 and described in **Annex 4,** provides a screening procedure of the impact of manmade threats on dam risk, allowing the integration of outcomes of dam safety risk analyses and conditional security risk analyses by using a combined indicator, named equivalent annualized probability of attack. It allows to compare safety and security risk levels and to inform decisions at asset scale. This approach will help dam owners and operators to meet the challenging task of addressing both safety and security issues. The proposed procedure takes advantage of state-of-the-art QRA practices in dam safety management (with proved robustness and

consistency, applied to real cases worldwide) to improve current security risk analysis.

- Contributions of this thesis are aligned with recent initiatives towards smart risk governance in Spain and worldwide, as described in Sect. 3.5, and represent examples of pioneer risk analysis practices for flood risk reduction (i.e. the municipality of Oliva).
- The proposed framework can be potentially applied by local authorities or flood defence infrastructure managers to perform similar flood risk analyses. For example, there is still a long way to go in the development and implementation of risk-informed action plans against flooding. This thesis aims to become a reference example for other cities and regions towards improved flood risk management.

4.2. Implications and final remarks

From the perspective on how this research will impact on flood risk management in general, and on safety management of flood defence infrastructures in particular, several implications and remarks are here included.

- This thesis provides procedures, supported by case studies, to demonstrate the **usefulness of quantitative risk results for flood risk management** and the need to integrate different sources of hazards to inform flood risk governance.
- The proposed approaches can be adapted to other cases, dam and levee systems. The presented risk model architectures are generic and can be **adapted to site-specific characteristics** as shown in its application to case studies.
- Risk model architectures proposed in this thesis can be used to estimate risk by integrating information from different sources of information in nature and **level of detail**.
- The level of detail of the analysis should match the **needs of decision makers**. Having an overall picture of quantitative flood risk for the whole system, able to capture the contribution of each element, will help decision-makers to better understand risks and define actions for risk reduction.
- Results from case studies show that societal and economic risks, while considerably reduced from planned **structural measures** (dams or levees), both can be further reduced through **non-structural measures** such as emergency action planning.
- There is still a long way to go in the development and implementation of local action plans for flood risk management. The framework described in this thesis, aims to become a **reference example** for other cities and flood defence systems towards improved flood risk management.
- FRM key actors are facing different **challenges**: lack of resources, climate change impact; a changing socio-economic context; and new technologies that change the way we communicate. Therefore, performed flood risk analyses have shown the benefits of risk-informed flood emergency management and the impact of local action planning on societal and economic risk.

- Potential users of research outcomes presented in this document are dam and levee owners, operators, regulators, local authorities responsible for flood emergency action planning, and FRM decision makers. All of them are required to prioritize and allocate investments for flood risk reduction in a more effective and efficient way. The main purpose of this thesis is to provide them with tools for a more integrative and risk-informed dam safety and flood emergency management.
- In the next years, on-going urban transitions (e.g. from "grey" to "green" solutions for flood risk reduction) and ageing population will modify the current urban landscape. Hence, it is important to adapt flood risk management strategies to this changing urban environment. **Updating and upgrading risk analyses** will help local authorities and flood defence managers to define actions in a more efficient and effective way.
- Manmade threats deal with higher **uncertainty** since are directly related to a changing socio-political context. For this reason, the screening procedure proposed in this thesis will help to analyse the need for detailed studies in terms of security risk reduction. The index proposed in this research has the advantage of informing dam safety and security governance on a first stage, allowing to analyse both sources of risk and helping on solving knowledge gaps.

4.3. Future research lines: the way ahead

Based on the main findings of this thesis, the following research lines are foreseen, aiming at boosting integrative flood risk management at local scale.

- Methodological frameworks and case studies of this thesis are focused on flood risk from pluvial flooding, river flooding and failure of flood defences. Future research could also be based on analysing integration of **coastal flooding** in urban flood risk analysis from multiple hazards.
- In addition, following the risk model architecture developed for dam-levee systems, a similar procedure could be developed to analyse flood risk from failure of **other flood defences** such as storm surge barriers.
- Current concerns on how to deal with manmade threats is one of the main identified barriers for risk governance in large dams and other flood defence infrastructures. This thesis helps to overcome such barriers when detailed information on **manmade threats** is not available. A future research line is finding a consistent manner to quantify threat probabilities from manmade threats, to be incorporated into QRA and then balance present safety and security risk analyses.
- A major challenge to be addressed when evaluating risk in complex systems is the application of **tolerability recommendations** at local or system scale. Although recent efforts have been allocated on defining tolerability guidelines for levee safety (in line with current dam safety practices), there is still a need for defining criteria to evaluate risk at different scales (e.g. district, region scale). Examples can be found in the literature for regional flood risk studies (Jonkman et al., 2011; Voortman et al., 2003). However, the acceptable level of flood risk in a given study area may differ among regions and countries since

economic, societal and environmental criteria considered for defining tolerability limits may be different (depending on existing risk aversion, risk component to be considered or risk dimension, e.g. incremental or total terms). As stated in (Castillo-Rodríguez et al., 2014) tolerability standards at local scale based on the use of FN-curves are still under debate (e.g. on the consideration of a maximum base point, the slope of the tolerability criterion or the influence of risk aversion). This discussion falls outside the scope of this research. Further investigation might focus on developing standards and tolerability recommendations to assess urban flood risk.

- The methodology itself allows to incorporate advances and improvements on methods for risk component characterization that can be merged into this framework and proposed risk model architectures. Thesis outcomes are capable to integrate results from complementary techniques, e.g. up-to-date hydrologic studies and models, consequence estimation methods, etc.

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ANNEXES

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ANNEX 1: The value of integrating information from multiple hazards for flood risk analysis and management

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TITLE

The value of integrating information from multiple hazards for flood risk analysis and management

ABSTRACT

This article presents a methodology for estimating flood risk in urban areas integrating pluvial flooding, river flooding and failure of both small and large dams. The first part includes a review of basic concepts on flood risk analysis, evaluation and management. Flood risk analyses may be developed at local, regional and national level, however a general methodology to perform a quantitative flood risk analysis including different flood hazards is still required. The second part describes the proposed methodology, which presents an integrated approach – combining pluvial, river flooding and flooding from dam failure, as applied to a case study: an urban area located downstream of a dam under construction. The methodology enhances the approach developed within the SUFRI project ('Sustainable Strategies of Urban Flood Risk Management to cope with the residual risk', 2009-2011). This article also shows how outcomes from flood risk analysis provide better and more complete information to inform authorities, local entities and the stakeholders involved in decision-making with regard to flood risk management.

KEYWORDS

Flood risk, risk analysis, risk models, dams, flood defence infrastructures

1 INTRODUCTION

Flooding may occur as a combination of meteorological and hydrological extreme occurrences (WMO/GWP, 2008) or as the result of human-induced threats such as terrorism, vandalism or sabotage that may cause the failure or collapse of flood defence infrastructures. In most cases, floods are additionally influenced by human factors, such as flood protection planning, urban planning, emergency management, etc.

Urban areas may be affected by flooding from river courses, mountain torrents, flash floods, coastal floods, pluvial flooding, sewer flooding, groundwater flooding (in permeable areas), Mediterranean ephemeral water courses, and failure of drainage systems and flood defence infrastructures. Urban areas may present high flood risk levels due to high population density rates, multiple economic activities, infrastructure and property values (Pelling, 2003). Furthermore, present requirements of residential and industrial areas have resulted in new urban developments in flood-prone areas, increasing risk for people and inducing significant economic costs in case of flooding.

An analysis of global statistics (Jonkman, 2005) showed that inland floods (including drainage floods, river floods and flash floods) caused 175 000 fatalities and affected more than 2.2 billion people worldwide from 1975 to 2002. An example of these events is the disastrous flood in the Elbe River basin in August 2002 (Engel, 2004) that accounted for 58 fatalities and thousands of people evacuated. Coastal floods were not included in these statistics, but they may cause even more catastrophic floods in terms of loss of life, such as the flooding caused by hurricane Katrina in 2005 (Jonkman et al., 2009), with more than 1100 fatalities in the state of Louisiana (United States).

As a result of past flood events and their consequences, social demand for higher levels of safety has become a major challenge for the governments of European countries. This demand requires methods to identify the areas that can be potentially affected by floods and to estimate societal as well as economic flood risk. Moreover, flood risk management should be addressed including not only structural but also non-structural measures such as flood forecasting, early warning procedures, emergency management, etc.

In the European context, three Directives have been approved in recent years to establish the basis for present and future actions in the field of flood risk and critical infrastructure management: the EU Water Framework Directive (2000/60/EC), the EU Floods Directive (2007/60/EC) and the EU Critical Infrastructure Directive (2008/114/EC). According to the EU Floods Directive, all EU Member States must undertake the necessary actions to develop preliminary flood risk assessments, flood hazard and flood risk maps, and flood risk management plans at river basin district level before 2011, 2013 and 2015, respectively.

In addition, flood risk research activities have focused on the development of improved methodologies and strategies for an effective flood risk management, taking into account sustainability, public participation, risk awareness and risk communication (Thieken and Beurton, 2012). The ongoing efforts on flood risk research aim at developing methodologies to assess the existing flood risk in urban areas by integrating different sources of hazard. These methodologies should provide tools to compare and analyze measures for flood risk reduction.

In this context, this paper presents a comprehensive methodology for urban flood risk analysis, integrating pluvial flooding, river flooding and flooding from dam failure. It represents an enhancement of a methodology for urban flood risk analysis presented in Escuder-Bueno et al. (2012), incorporating potential flooding due to the existence of small or large dams as flood defence infrastructures (in case of failure or flood routing), allowing a step forward towards an integrated and comprehensive flood risk assessment and management by considering multiple flood hazards.

This paper proposes the use of risk models for flood risk analysis as they provide a logical and mathematically rigorous framework for compiling information to estimate flood risk. The proposed methodology describes the process for combining all necessary information to estimate, analyze and evaluate flood risk, obtaining an integrated flood risk outcome which includes probabilities and consequences of all potential flood events resulting from several sources of hazard. This integrated outcome provides better and more complete information to decision makers (e.g. by analyzing flood risk for the current situation and the impact of different risk reduction measures).

This article is structured as follows. Section 1 provides the introduction and a brief overview on the legal framework and research needs in current flood risk management. Section 2 includes a summary of basic concepts and tools for estimating and analyzing flood risk. Section 3 describes the proposed methodology for flood risk analysis integrating three sources of flood hazard: pluvial flooding, river flooding and flooding from dam failure. The application of the methodology to a case study is presented in Section 4. Concluding remarks and further research lines are described in Section 5.

2 BASIC CONCEPTS IN FLOOD RISK ANALYSIS AND MANAGEMENT

2.1 Risk concepts

The term risk is widely used in different fields (e.g. engineering, industry, economy, etc.). Thus, different definitions can be found depending on the field of research. Efforts have been allocated in recent decades to reach a common vocabulary within the flood risk management context (e.g. Gouldby and Samuels, 2005) as a guidance for researchers and experts. The following definitions are used in this paper:

- Risk, hazard and vulnerability

Based on the commonly adopted 'Source-Pathway-Receptor-Consequence' model (Gouldby and Samuels, 2005), *risk* can be defined by the following components: the nature and probability of a source of hazard, the degree of exposure of the receptors (e.g. property, people, environment) to the hazard, the susceptibility of the receptors to the hazard, and the value of the receptors. This definition can be represented by the expression shown in Eq.(1).

Risk = Hazard × Exposure x Susceptibility x Value (1)

For a risk to arise, there must be a hazard that consists of a 'source' or initiator event (e.g. high rainfall or high river water discharge). A *hazard* is then considered as any physical event, phenomenon or human activity with the potential to result in harm. However, a hazard does not necessarily lead to harm.

Research literature identifies *vulnerability* as an umbrella term for a number of vulnerability-types and it can be formulated, from a traditional systems perspective (Gouldby and Samuels, 2005) as composed of two components: susceptibility and value. Thus, vulnerability is a sub-function of risk and includes the characteristics of a system that describe its potential to be harmed. Therefore, is common practice to define also risk by the expression given in Eq.(2).

Risk = Hazard × Exposure x Vulnerability (2)

In practice, exposure and vulnerability are often captured in the assessment of the *consequences*; thus risk is commonly viewed in simple terms as the combination of probability and consequences, as shown in Eq.(3).

Risk = Probability × Consequences (3)

However, attention should be paid since there is no univocal relationship between hazard and probability. In general, probability includes not only probabilities of potential hazards (e.g. exceedance probabilities of river water levels) but also the conditional probabilities of the system response given such hazard (e.g. probability of failure of a flood defence system for a certain river water level).

Probability can be defined as the chance of occurrence of one event compared to the population of all events. In this definition, probability is dimensionless. In flood risk analysis, probability is often referenced to a specific time frame, for example, as an annual exceedance probability (then probability has units of yr^{-1}).

The second risk component, *consequences*, represents an impact (or improvement) such as economic, social or environmental impact and may be expressed quantitatively (e.g. monetary value), by category (e.g. High, Medium, Low) or descriptively. Consequences can include the impact of flooding to different sectors such as housing, industry, transport, agriculture, the environment and human health (Meyer et al., 2013). Some descriptions of potential flood consequences are, for example, economic impact, number of people/properties affected, harm to individuals (fatalities, injury, etc.), environmental or ecological impact.

Flood consequences can be, in general, classified into direct and indirect impacts (Merz et al., 2010). Direct impacts are those which occur due to the physical contact of flood water with humans, property or any other objects. Indirect impacts are induced by the direct impacts and occur – in space or time – after the flood event. Both types of impacts can be classified into tangible and intangible impacts, depending on whether or not they can be assessed in monetary values. Different classifications of flood consequences can be found in the literature, such as the classification proposed by the CONHAZ project ('Costs of Natural Hazards'), including five categories (Meyer et al., 2013): (1) direct costs, (2) business interruption costs, (3) indirect costs, (4) intangible costs, and (5) risk mitigation costs. Reviews on assessment of societal and economic flood impact can be found in Jonkman (2007) and Merz et al. (2010), respectively.

- Individual and societal risk / economic risk

In flood risk analysis, two concepts are widely used: individual risk and societal risk. *Individual risk* can be defined as the probability of an individual at a certain location getting killed by an accident (Jonkman et al. 2011); in the flood risk analysis context, the probability of being killed by flooding. *Societal risk* concerns the probability of an accident with a large number of fatalities. In the case of considering potential economic impacts, then the term *economic risk* is used.

- Flood risk analysis

In this paper, a *system* is considered as the assembly of elements or components (i.e. natural, human, social, etc.) and the interconnections between them within an area under study. Flood risk can be analyzed for systems of different size and complexity, such as a city, a province, a hydrological subsystem, or a country. In general, system boundaries are aligned with institutional boundaries (e.g. provinces, municipalities, etc.) or hydrological systems (e.g. river basin districts).

In this paper, the term *characterisation* is used for the process of expressing the observed and predicted behaviour of a system and its related components, with the aim of obtaining probabilities of potential flood events and resulting consequences.

As shown in Eq. (3), risk can be expressed by two components: probability and consequences. *Flood risk analysis* is defined as the process of objectively determining risk by analysing and combining probabilities and consequences. The combining process is also called risk calculation.

Accordingly to Eq. (3), tools for flood risk analysis can be classified as partial or complete depending on whether they obtain one component of risk or both (Escuder-Bueno et al., 2010). In addition, they can be classified as quantitative or qualitative depending on whether or not they provide a numerical value of risk. Among these four groups, complete and quantitative tools may be the most convenient option to provide information for decision makers. However, robustness and reliability of results will depend not only on the type of tool but also on uncertainty of input data.

- Flood risk assessment

Flood risk assessment comprises understanding, evaluating (flood risk evaluation) and interpreting risk and existing societal tolerances of risk to inform decisions and actions for flood risk management.

The process of flood risk evaluation requires the comparison of risk with tolerability criteria to assess the current situation of the system and the need for risk mitigation measures.

- Flood risk mitigation

Flood risk mitigation includes the reduction of the level of risk, by either reduction in the probability of a flood occurring or a reduction in consequences. With that purpose, different risk mitigation measures can be established (although distinction between risk reduction and risk mitigation measures could be drawn, both terms are used indistinctly in this paper, as proposed in Gouldby and Samuels, 2005).

In general, these measures are classified in two categories: structural and non-structural measures. Structural measures refer to any physical construction to reduce or avoid possible impacts of floods, which include engineering measures and construction of hazard-resistant and protective infrastructures. Non-structural measures may include urban planning, flood forecasting, advanced early warning systems, aids and insurance, increase of risk awareness, knowledge development, methods and operating practices for flood emergency management, etc. (Escuder-Bueno et al., 2011; Schanze et al., 2008).

In general, risk cannot be entirely eliminated since structural measures handle the consequences of a specific severe event, typically called a design event. Even in the case of perfect behaviour of the flood defence infrastructure, there is always a residual risk. Although non-structural measures may reduce part of this risk, residual risk relates to the consequences that cannot be absolutely prevented by the combination of existing structural and non-structural measures. Therefore, risk analysis and assessment should focus on obtaining the existent risk and analyse the impact of risk reduction measures.

- Flood risk management

The definition given by the FLOODsite project (Gouldby and Samuels, 2005) for *flood risk management* is ‘the continuous and holistic societal analysis, assessment and mitigation of flood risk’. In addition, flood risk governance is considered as the process of decision making and implementation of risk mitigation measures. Nevertheless, flood risk management involves a wide range of considerations that cannot be easily reproduced in a concise statement.

Among other aspects, flood risk management should consider structural and non-structural measures similarly, turning into a continuing cycle of assessing, implementing and maintaining measures to achieve acceptable residual risk and aiming at a sustainable development (Klijn et al., 2008). Hence, flood risk management combines results, information and recommendations from risk analysis and assessment practices, which are used as key information for the definition and prioritization of risk reduction measures.

Prioritization of risk reduction measures is required to achieve an efficient flood risk management. This prioritization may be based on equity and efficiency principles (ICOLD, 2005): (1) *equity* refers to the right of individuals and society to be protected, and the right that the interests of all are treated with fairness, with the goal of placing all members of the society on an essentially equal footing in terms of level of risk that they face, and, (2) *efficiency* refers to the need for society to distribute and use available resources so as to achieve the greatest benefit.

As stated by Halpin (2010), there can be conflict in achieving equity and efficiency. Achieving equity justifies the establishment of maximum tolerable risk limits for individual risk (e.g. the maximum failure probability of a flood defence infrastructure), regardless of the lack of economic justification or the magnitude of the cost. Efficiency is defined by the risk level where marginal benefits equal or exceed the marginal cost. Flood risk management should consider both equity and efficiency principles for evaluating risk and for defining risk mitigation measures. Further discussion and some considerations on the tension between equity and efficiency in setting standards for flood protection can be found in Van der Most (2010).

All agents involved in flood risk management (e.g. flood defence designers, operators, authorities, stakeholders, etc.) should promote and achieve an integrated and broad vision of risk management towards good flood risk governance, taking into account the context, the objectives and restrictions inherent to the flood risk management process (SPANCOLD, 2012). With that purpose, flood risk governance should cover all aspects (e.g. technical, societal, cultural, financial, etc.) related to the development, prioritization and application of risk mitigation actions to be carried out before, during and after a flood disaster event.

2.2 The use of risk models and FN-curves for flood risk analysis

Among existing tools for flood risk analysis, the use of risk models, influence diagrams, event trees and FN-curves is proposed in this paper. Risk models arise as robust, complete and quantitative flood risk analysis tools that enable the integration of all information for estimating risk. Outcomes from risk modelling can be used to represent FN and FD-curves.

The following definitions are provided since the terms are widely used in this paper:

- *Risk model:* a risk model is a simplified representation of the system. By characterizing system processes and variables, all relevant elements of the system are considered in the risk model. Several tools can be used to represent risk models. In this paper, influence diagrams and event trees are proposed.

- *Event tree:* an event tree is a detailed representation of all events that may lead to flooding in a system. The event tree starts with an initiating event (e.g. a rainfall event) and splits into several branches based on the characteristics of the initiating event (e.g. the range of possible rainfall events). For each resulting branch, the event tree splits into new branches taking into account possible subsequent events given that the previous event has occurred (e.g. river water levels at a certain location for a given rainfall event, failure and non-failure events for such river water level, different evacuation scenarios, etc.). Each new subsequent event is then related to a conditional probability of occurrence. Once all combinations of events that may lead to flooding and their related consequences have been captured within the event tree, each path of the event tree represents a potential flood event and it is related to a joint probability, resulting from the combination of all events that compose that path.

Depending on system complexity, event trees may have thousands of paths. Therefore, influence diagrams are used as a compact representation of event trees.

- *Influence diagram:* an influence diagram is composed by nodes and connectors. Each node includes input data on the system (loads to the system, system response or consequences) regarding one or several system variables. Connectors are used to define the relationships between nodes. The influence diagram incorporates the necessary information to define the number of branches in which the event tree splits in each node and to estimate the probability of taking each branch given that the previous events have occurred.
- *FN-curves:* a FN-curve is a form of presentation of the frequency and the distribution of the number of fatalities in case of flooding. The FN-curve plots F(n) against n, where F(n) is the cumulative exceedance probability of events with n or more fatalities (Evans and Verlander, 1997). Accordingly, f(n) is the exceedance probability of events with exactly n fatalities. When representing potential economic flood damages, the term FD-curve is used. The following general properties of FN-curves can be considered: (1) because $f(n) \geq 0$ for all n, FN-curves are always flat or falling; (2) FN-curves are usually plotted on double logarithmic scales (to represent events with a large number of fatalities but very small frequencies, so called ‘low probability-high consequence’ events), and, (3) the lower the curve is, the better (i.e. a lower curve implies a lower frequency of events with n or more fatalities).

Event trees are particularly applicable for risk calculation and analysis (IEC, 2009), as they allow the user to obtain and combine probabilities and consequences, but not for risk evaluation. FN-curves provide a comprehensive and robust tool to represent societal and economic risk quantitatively, thus these curves are helpful tools to support risk evaluation.

The basis of the use of FN-curves for urban flood risk analysis was presented in the ‘SUFRI Methodology for pluvial and river flooding risk analysis in urban areas to inform decision making’, developed within the SUFRI project (‘Sustainable

Strategies of Urban Flood Risk Management to cope with the residual risk'), 2nd CRUE ERA-Net funding initiative, in the period 2009–2011 (Escuder-Bueno et al., 2011).

Figure 1 shows the FD-curve for a hypothetical case study as proposed in Escuder-Bueno et al. (2012). Both axes show theoretical but typical values. When representing flood risk including the potential failure or collapse of flood defence infrastructures, FN-curves may show steps (as shown in Fig.1). These steps represent flood events resulting from failure of one or more flood defence infrastructures.

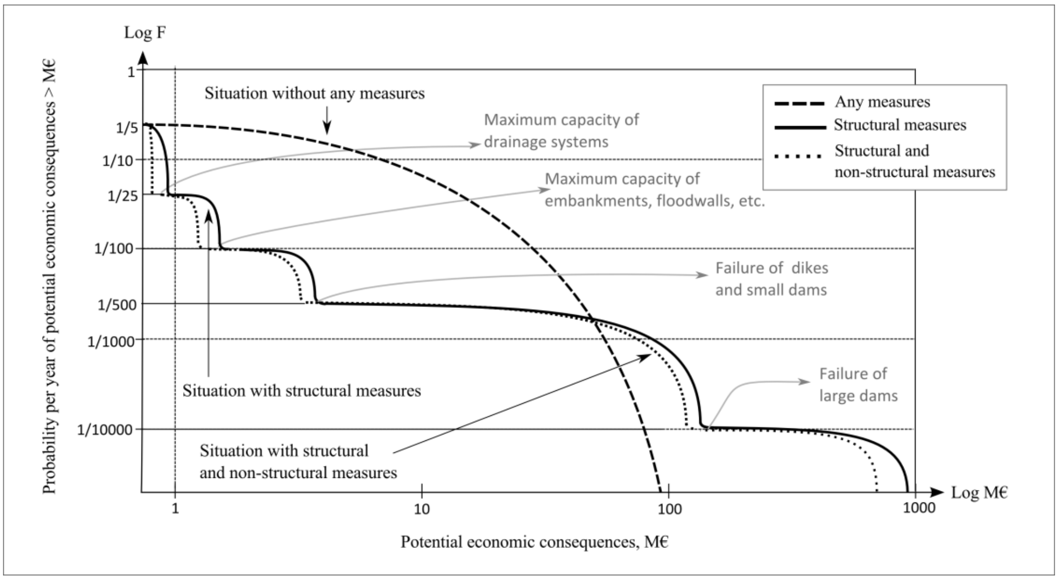

Figure 1. Example of FD-curves of a hypothetic case study (Escuder-Bueno et al., 2012).

In general, these infrastructures protect an area from flooding up to a certain load level (e.g. runoff discharge, river water level). Once this level is exceeded, if failure occurs, then the resulting flooding is, in general, related to a higher number of potential fatalities when compared with the non-failure situation. Therefore, flood events which include potential failure of flood defence infrastructures show higher N values than non-failure flood events, but associated with lower probabilities ('low probability-high consequence' flood events).

As FN-curves show the probability distribution of the number of fatalities, they can be used for the evaluation of fatality risks from a societal perspective. To facilitate the evaluation of FN-curves, several criterion lines might be defined and an FN-curve should, in principle, not exceed the criterion line. An FN-criterion line is generally defined by three variables (Jonkman et al., 2011): (1) its base point or the exceedance probability of one fatality (so called C-value); (2) its slope (generally equal to minus 1 or minus 2), and, (3) its probability and/or consequence cutoff (i.e. a maximum tolerable value for probability and/or consequence). Some discussion on FN-criteria can be found in the literature (Vrijling, 2001; Jonkman et al., 2011; SPANCOLD, 2012).

In addition, the use of FN-curves enables the representation of results from sensitivity and uncertainty analysis to identify the variables that contribute the most to flood risk (e.g. by incorporating different input data for load variables from different samples of Monte Carlo simulations).

Risk models are a simplified representation of the system. Consequently, results from the risk model are inherently uncertain. Sensitivity analyses can be conducted to analyze the impact on the estimated flood risk of each model variable and, thus, on the choice between alternatives for risk mitigation. For example, the use of expected, median or worst-case values can affect the results when important parameters are highly variable. There exist several reviews on sensitivity analysis methods (e.g. Frey and Patil, 2002). Among them, some examples can be found in the field of flood risk (e.g., Pappenberger et al., 2008). Different methods can lead to a difference in ranking of importance of model variables. Procedures for sensitivity analyses may include, for example, one-at-a-time methods (varying one part of the input while other parts keep the same value) or variance-based techniques (e.g. Gouldby, 2007).

Uncertainty arises principally from lack of knowledge of the system or of ability to measure and to calculate risk and gives rise to potential differences between the risk estimate and its actual value. Two types of uncertainty can be defined (Gouldby and Samuels, 2005): natural variability and knowledge uncertainty. *Natural variability* refers to inherent variability of the real world (also called aleatory or random uncertainty), and, *knowledge uncertainty* refers to incomplete knowledge of the system (also called epistemic uncertainty).

Different procedures and techniques can be used to reduce random and epistemic uncertainty. In general, natural variability can be characterised as random or stochastic, and probabilistic models are adopted, which involve the definition of probability distributions for stochastic variables (Gouldby, 2007). Among them, Monte-Carlo techniques are the most comprehensive and robust methods.

However, epistemic uncertainty is also frequently described by probability distributions, although with a different interpretation: probability distributions for natural variables represent the relative frequency of values within an interval, whereas probability distributions for epistemic parameters (e.g. model parameters) represent the degree of knowledge or belief of the analyst that a value is within a specific interval (Merz and Thieken, 2005).

The use of uncertainty analysis has several advantages, such as the identification of weak points and critical assumptions on the model (Merz and Thieken, 2009) and may guide the required efforts for obtaining more information to improve our knowledge about the system and, consequently, to improve the risk model.

Based on the aforementioned potential use of risk models and FN-curves as robust and comprehensive tools for flood risk analysis, the proposed methodology is described in Sect.3.

3 PROPOSED METHODOLOGY

The proposed methodology is divided into 11 phases. These phases are based on the methodology proposed in Escuder-Bueno et al. (2012) that has been adapted to incorporate the analysis of small and large dams as common flood defence infrastructures, including potential flooding from failure and non-failure cases (i.e. flooding due to discharges from flood routing). In addition, it includes aspects of risk uncertainty, risk reduction, risk management and governance.

The proposed methodology describes how to estimate flood risk from the three considered flood hazards, compiling information that is used as input data for a risk model, whose architecture definition is also part of the methodology. The model is used to perform risk calculations providing risk outcomes that can be plotted on FN and FD-curves. Representations are then used to visualize different situations (e.g. existent risk or situations with new risk reduction measures), and propose risk reduction measures based on an integrated and comprehensive risk analysis.

3.1 Phase I: definition of the scope and aim of the study

Phase I focuses on the definition of the scope of the study. The complexity of the risk model will depend on the scope of the analysis (e.g. screening, preliminary analysis or detailed study and micro-scale, meso-scale or macro-scale).

3.2 Phase II: review of available data

Data gathering and review of all existing information is necessary for the analysis, such as information from rainfall data, hydrologic studies, hydraulic models, historical data, dam characteristics, urban characteristics (e.g. urban typology, population, economy, land uses), etc.

3.3 Phase III: definition of the current situation

Phase III includes the definition of the current situation, also called *Base Case*, that is, the characterization of the system and the definition of the necessary assumptions to analyze the current situation.

3.4 Phase IV: risk model architecture

In Phase IV, the risk model architecture for the *Base Case* is established. This model will remain the reference for the subsequent analysis of the impact of risk reduction measures.

As described in Sect.2, an event tree starts with an initiating event. Depending on the characteristics of the case study, two situations may be distinguished: Situation A and Situation B. First, Situation A represents urban areas where initiating events, i.e. rainfall events within the urban and the river catchment areas, can be considered as independent phenomena thus potential flooding from these sources of hazard are assumed independent. In this case, different influence diagrams (and the corresponding event trees) may be used to analyze each flood hazard separately. Results can be later combined to obtain total flood risk. In this methodology, two generic schemes for defining the required influence diagrams are provided in Figures 2 and 3 (Schemes A1 and A2, respectively), which correspond to the analysis of pluvial and river flooding (including the existence of dams), respectively. Second, Situation B represents urban areas where rainfall events within the urban and the river catchment areas are related (including, for example, the river catchment area upstream of the dam), i.e. potential flood events are the result of the same initiating event.

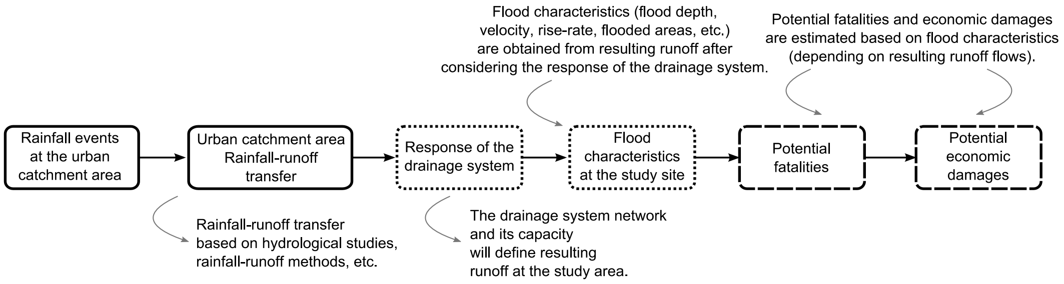

Figure 2. Generic influence diagram: Independent initiating event (Scheme A1).
Note: Nodes outlined with solid, dotted and dashed lines refer to loads, system response and consequences, respectively.

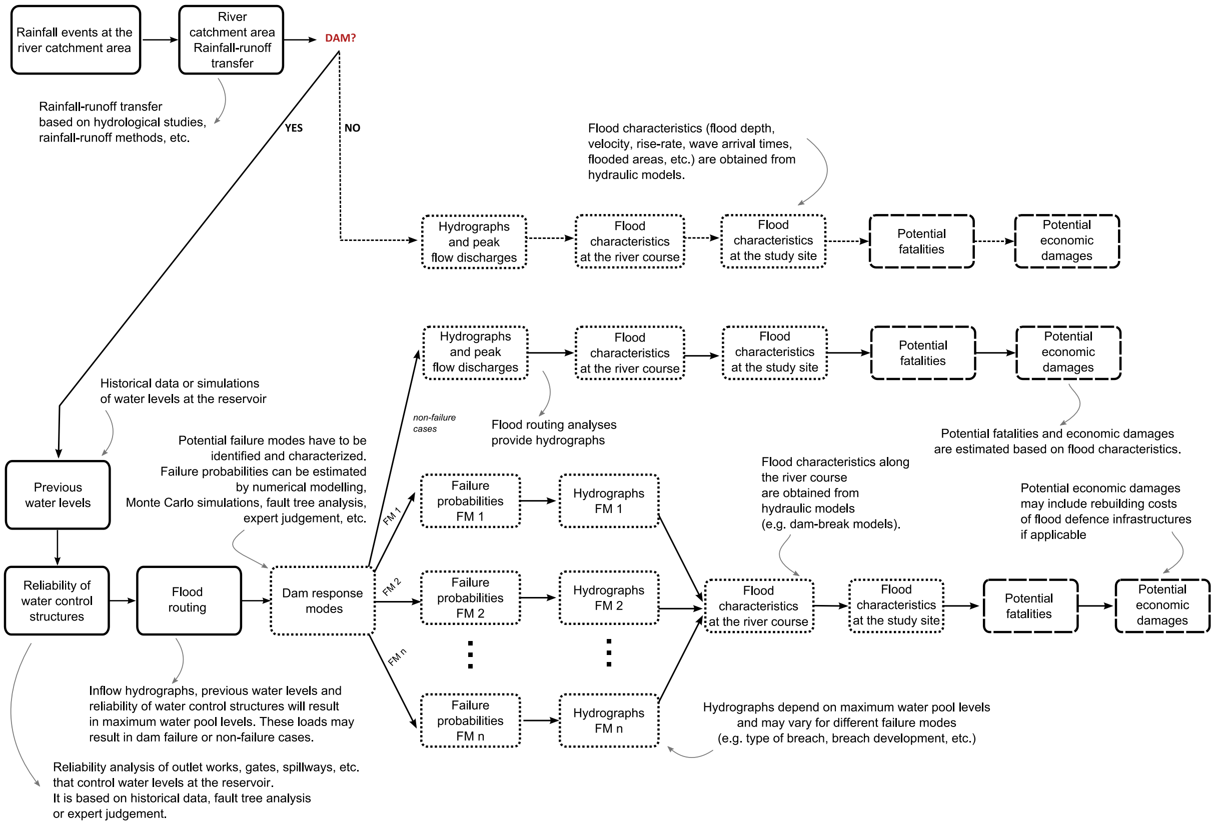

Figure 3. Generic influence diagram: Independent initiating event (Scheme A2).
Note: Nodes outlined with solid, dotted and dashed lines refer to loads, system response and consequences, respectively.

Therefore, a unique influence diagram to represent the risk model can be used for the analysis. Figure 4 shows the (simplified) generic scheme for the risk model architecture (and the corresponding influence diagram) for this situation (Scheme B). The same architecture shown in Schemes A1 and A2 can be used for Situation B, by adding a common initiating event and two connectors: one linking the node for the initiating event to the first node of Scheme A1 shown in Fig. 2, and, the second, linking the last node of Scheme A1 to the first node of Scheme A2.

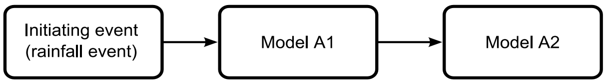

Figure 4. Generic influence diagram: Common initiating event (Scheme B).

The schemes given in Figs. 2-4 are proposed as reference risk model architectures but they should be adapted for each case study.

3.5 Phase V: input data

Phase V includes all necessary estimations to provide the risk model with input data on three main categories: loads (nodes with solid line in Figs. 2-4), system response (dotted nodes) and consequences (dashed nodes).

In most cases, outcomes from existing hydrological, hydraulic, structural or probabilistic models may be used to provide information for the risk model. However, in general, additional studies or ad hoc estimations may be required to characterize all necessary variables which are involved in the process for estimating conditional probabilities and consequences of potential flood events.

First, for nodes referring to loads, information from hydrological studies, previous water levels at reservoirs or river courses, reliability of water control structures of dams and flood routing studies are required.

Next, nodes referring to system response will require the identification of potential dam failure modes (e.g., dam break due to overtopping, internal erosion, sliding, etc.), quantification of failure probabilities, characterization of failure characteristics (e.g., breach development time, type of breach, etc.) and the analysis of non-failure cases (e.g., flow discharges due to overtopping of small dams, discharges from flood routing in large dams, etc.). All these aspects can be studied based on structural models, hydraulic models, fault tree analysis, Monte Carlo simulations, expert judgement, etc. (SPANCOLD, 2012).

Finally, nodes referring to consequences will include information based on estimation of potential economic damages and casualties (potential fatalities and economic damages are considered in this methodology). These estimates may be obtained using different methods that include the use of hydraulic models to obtain flood characteristics at the river course (i.e. river water levels) and at the site under study (e.g. flood depths). Flood depths, velocities, arrival wave times, flood severity levels, flood exposure, etc. are used to estimate potential consequences.

Schemes shown in Figs. 2 and 3 are two independent schemes that start with different (and independent) initiating events:

- Rainfall events at the urban catchment area that result in runoff at the study site depending on the response of the drainage system; and,
- Rainfall events at the river catchment area that result in inflow discharges at reservoirs, and/or floods along the river course that may lead to flooding at the study site.

Regarding pluvial flooding, the first scheme (Fig. 2) shows a generic diagram that can be used to analyze flooding from rainfall events at any urban catchment area.

Regarding river flooding and dam failure, the second scheme (Fig. 3) shows a generic diagram that can be used to analyze flooding from rainfall events at the river catchment area. The scheme diverges in different branches depending on the existence of dams upstream of the urban area. In this scheme, dam failure and non-failure cases are considered (e.g. flood routing discharges). Potential consequences have to be estimated for all cases, including rebuilding costs in case of dam failure.

In some cases, it can be assumed that rainfall events in both catchment areas (urban and river catchment area) do not occur independently, then a unique influence diagram can be established, starting with a common initiating event. This approach can be used in systems where rainfall events at the urban and river catchment area are correlated, i.e. local or regional rainfall distributions do not differ substantially and spatial and temporal variability on rainfall patterns is not significant.

Different input data can be used to analyse one or several scenarios (e.g. the current situation and the situation with risk reduction measures).

3.6 Phase VI: risk calculation

In Phase IV and V, the definition of the risk model architecture provides the framework for compiling information to estimate flood risk. With that purpose, the defined influence diagram is the compact representation of the event tree that includes all possibilities that can lead to flooding. The event tree allows the estimation of conditional probabilities and consequences in a mathematically rigorous way.

The risk model is a conceptual representation of the system, taking into account hazard(s), exposure to the hazard(s) and vulnerability of the system to that hazard(s). If several sources of hazard are considered, a unique influence diagram integrating information for all hazards can be used (Fig. 4). However, if hazards are considered independent, then different influence diagrams can be used to represent the system for each source of hazard separately (Figs. 2-3).

For Situation A (Figs. 2-3), independent influence diagrams for analyzing each flood hazard are considered. In this case, outcomes can be later incorporated to an overall scheme which obtains total flood risk due to the three sources of flood hazard, adapting input data to avoid double counting in areas potentially affected by several flood hazards. A simplified assumption is considered and potential damages in these areas are obtained by taking into account the maximum value from results for all hazards.

Figure 5 shows a general scheme of the process for combining results from three independent risk models.

The outcomes from Risk Models 1, 2 and 3 (represented by the FN curves shown in Fig. 5) are used as input for an overall 3-node influence diagram. 'Probability-consequence' pairs of all flood events from Risk Models 1, 2 and 3 are incorporated into the overall diagram in each node, respectively.

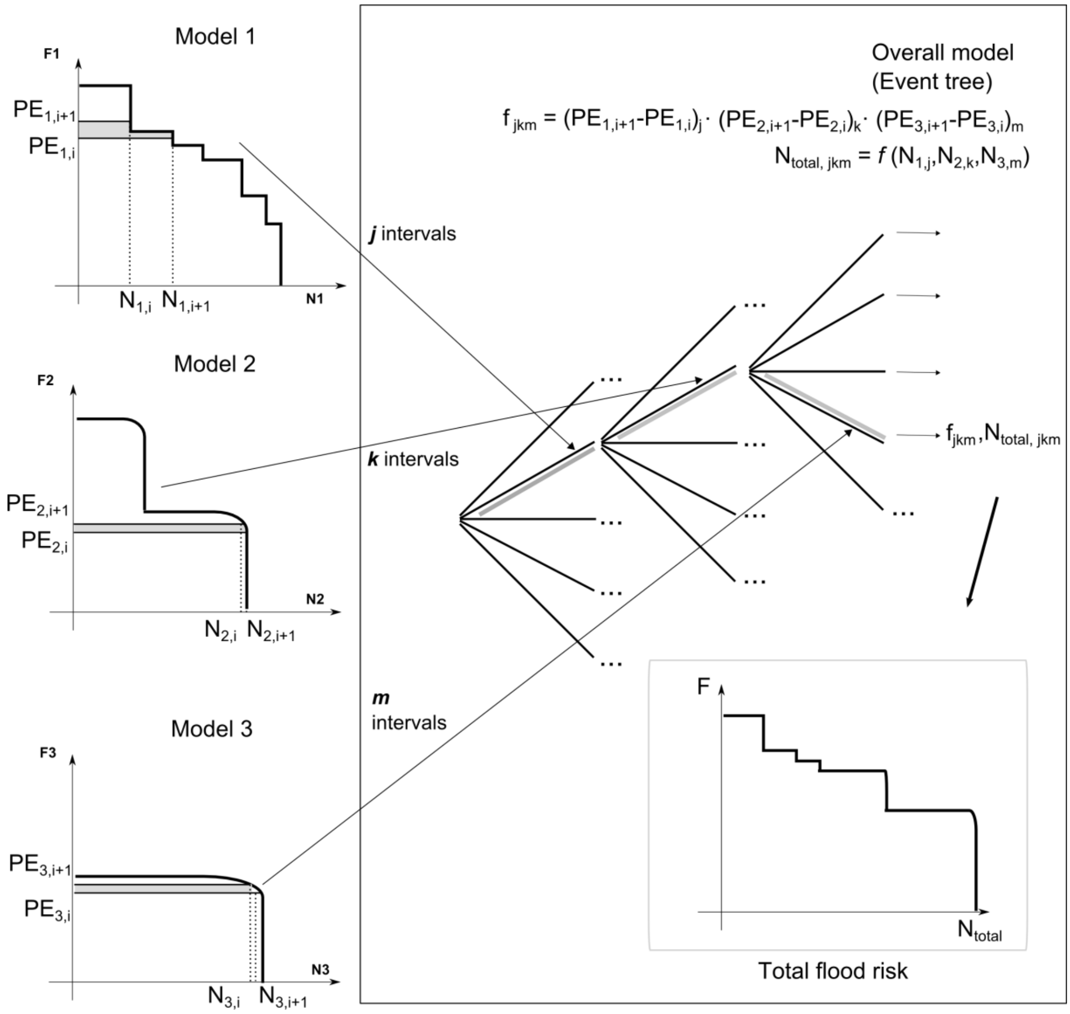

Figure 5. Combination of outcomes of different risk models.

The exceedance probability functions that result from each independent risk model (Models 1, 2 and 3 in Fig. 5) are discretized into a number of intervals. Each interval has two endpoints defined by the values of the damage variable (N_i, N_{i+1}) and their corresponding exceedance probabilities (PE_i, PE_{i+1}). Intervals are generally evenly spaced in the exceedance probability axis. For each interval, the N value for the range i will be computed as the average of the pair N_i, N_{i+1} and the probability as *prob* = $PE_{i+1} - PE_i$.

The joint event tree (shown in Fig. 5) resulting from this diagram includes all possible combinations of events in Risk Models 1, 2 and 3. If events in Risk Models 1, 2 and 3 are considered independent, the probability of the combined event (f_{jkm}) is obtained by multiplying the three probabilities of the corresponding events from Models 1, 2 and 3, respectively.

Finally, the overall model obtains the FN (or FD) curve that represents flood risk by integrating the three sources of flood hazard.

For Situation B (Fig. 4), the analysis may be carried out by defining a unique risk model architecture which starts with a common initiating event and combines the three sources of flood hazard. Hence, only one event tree is necessary to obtain flood risk and it provides all FN (or FD) pairs that represent all potential flood events from pluvial flooding, river flooding and flooding from dam failure and non-failure cases.

3.7 Phase VII: risk representation

The use of FN and FD-curves is proposed in this methodology to represent outcomes of the risk model based on the schemes provided in Phase IV and outcomes from Phase VI. The basis of the use of FN and FD-curves has been described in Section 2.

3.8 Phase VIII: sensitivity and uncertainty analyses

Sensitivity and uncertainty analyses may improve our knowledge of the system and help to identify key factors and reduce random and epistemic uncertainty. Results from sensitivity and uncertainty analyses may be compared with the *Base Case* to evaluate confidence of obtained outcomes and identify the need for further information.

When analyzing the risk model for the *Base Case* using input data mainly from existing studies (e.g. hydrologic or hydraulic models) and minor additional estimations, sensitivity and uncertainty analyses will help to allocate efforts to develop more detailed analyses of specific variables (e.g. flood hydraulic characteristics, life-loss estimations, etc.).

3.9 Phase IX: risk evaluation

The risk outcomes obtained for the *Base Case* can be compared with standards or tolerability recommendations, if available. The use of FN and FD-curves allows the comparison among current risk and tolerability recommendations and, therefore, enables a determination as to whether or not societal and economic risks are acceptable. Nevertheless, there is still a lack of tolerability recommendations for evaluating urban flood risk, except for some specific and regional studies (Jonkman et al., 2011).

3.10 Phase X: risk reduction measures

The analysis of the impact of risk reduction measures (e.g., structural or non-structural measures) is developed in Phase X by analysing different situations and by comparing new outcomes with the results of the *Base Case*. Based on the *Base Case* risk model, risk reduction measures can be analyzed by estimating new input data. Variations will depend on the type of measure. On the one hand, structural measures may need new nodes and information to characterize system response and failure modes within the risk model architecture. In general, structural measures act by reducing flood probability and modifying system response in case of flooding. On the other hand, non-structural measures affect generally flood potential consequences, reducing vulnerability of people exposed to the flood and potential economic consequences.

3.11 Phase XI: risk management and governance

The aim of analyzing and evaluating current flood risk is to support decision making on flood risk management and governance. Outcomes from risk analysis and the comparison of existent flood risk with other situations that capture the impact of risk reduction measures may help local authorities, emergency services and action forces to develop improved flood emergency action plans.

Prioritization of risk reduction measures based on equity and efficiency principles is required to allocate investments and establish risk reduction programmes.

Different risk indicators can be found in the literature to analyze and justify prioritization of risk reduction measures, e.g. individual risk (Jonkman et al., 2011), the 'Adjusted Cost per Statistical Life Saved' ACSLS indicator (Bowles, 2004), or the Life Quality Index (Rackwitz, 2002). These indicators consider either efficiency and/or equity principles. The analysis of different indicators for a set of risk reduction measures may support decision-making on flood risk management. In addition, there exist software tools to analyze and compare risk results based on some of the aforementioned indicators (SPANCOLD, 2012).

4 CASE STUDY

This section presents and summarizes the application of the proposed methodology to a real case study. The urban area is suitable for the analysis since a river crosses this town (the name of the town is not explicitly provided as requested by the river authority). The urban area is located 8 km downstream of a dam under construction. A simplified scheme of the location of the urban area is shown in Fig. 6.

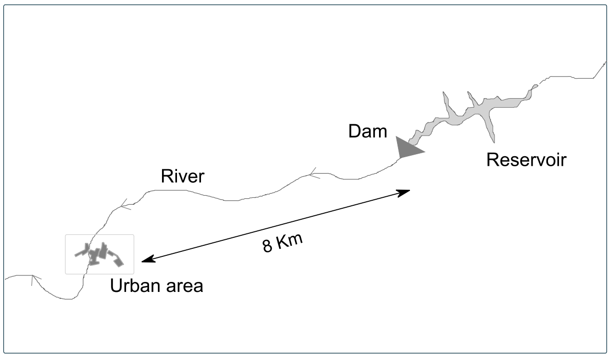

Figure 6. Overall scheme of the urban area downstream the dam.

The analysis followed the phases presented in Sect. 3 and it is summarized hereafter.

4.1 Phase I: definition of the scope of the study

The purpose of this analysis is to provide information on flood risk in an urban area located downstream of a dam under construction. Therefore, the scope of this analysis is to analyse societal and economic flood risk for three different situations: the current situation, the situation after dam construction, and, after implementing non-structural measures of public education and warning.

In this context, the following questions will be answered: first, what the current flood risk in this urban area is, and, second, how risk reduction measures would change flood risk. Results are shown to answer these questions.

The three analysed situations for the case study are:

- the current situation before dam construction (natural flow regime of the river and existence of the current drainage system), denoted as *Base Case*;
- the situation after the construction of the dam, including implementation of the Dam Emergency Action Plan (*DEAP-Case*), and,
- the situation with new non-structural measures, denoted as *NonSt-Case*, which includes a program on public education and warning that complements the Dam Emergency Action Plan (DEAP).

Concerning the estimation of potential consequences, potential loss of life and economic damages are obtained for residential and industrial areas. Neither the potential consequences in rural areas nor those for infrastructure are considered. Potential consequences are only estimated within the urban area and not at the whole municipality.

4.2 Phase II: review of available data and description of the case study

4.2.1 Location

This town is located in Spain. The municipality is divided into five urban areas. The main urban area, a traditional agricultural village with a population of about 2004 inhabitants in 2011 and an area of 31.3 km^2, will be considered for this analysis.

4.2.2 General description of the system

The river and the dam are managed by the Duero River Authority. A previous analysis was carried out in 2010 at the Universitat Politècnica de València (Sanz-Jiménez et al., 2012) and provides the necessary information to estimate input data for the risk model in terms of dam failure modes, peak flow discharges, maximum water pool levels, flood depths, flooded areas, etc. It also provides data regarding the natural flow regime of the river that is used further in this analysis to define the situation for the *Base Case*.

4.2.3 Demography

Population increases during the day and in summer. Data from the Spanish National Statistics Institute showed a total amount of residents for the whole municipality of 2150 inhabitants in 2011 (2004 inhabitants in the urban area), with an expected increase of 800 inhabitants in summer due to the existence of secondary households and 256 inhabitants during the day due to working populations.

4.2.4 Economy and land use

The land in the municipality is mainly devoted to residential, industrial and rural uses, as listed in Table 1.

Table 1. Land uses.

Land use category	Area (m^2)	Area (ha)
Urban areas (residential and industrial uses)	744 813	74.5
Developable land	437 826	43.8
Rural areas	32 922 195	3292.2
Protected rural areas	3 985 166	398.5
TOTAL (Rural areas)	36 907 361	3690.7

4.3 Phase III: study of the current situation - Definition of the *Base Case*

In this phase, the system and the *Base Case* are described. Flood risk is analyzed by considering the following sources of flood hazard: pluvial flooding due to rainfall events at the urban catchment area and river flooding from the natural flow regime of the river.

Therefore, flood events are related to two main sources of hazard:

- Event 1: floods due to rainfall events that occur at the urban catchment area, which result in runoff from the combination of both urban topology characteristics and current drainage system capacity;
- Event 2: floods due to rainfall events that occur at the river catchment area, which result in flow discharges along the river course.

Due to climate and topographic conditions of the study area, it can be assumed that both rainfall events are related. Consequently, the overall scheme shown in Fig. 4 has been used as reference scheme to develop the risk model architecture for this case study.

4.4 Phase IV: definition of the risk model architecture

Two influence diagrams have been developed ad hoc for the case study. The first diagram (Fig. 7) is used to analyze the current situation (i.e. the natural flow regime of the river and considering the existence of the drainage system).

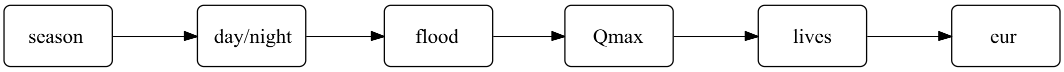

Figure 7. Risk Model 1. *Base Case* (natural flow regime of the river and drainage system).

The second diagram (Fig. 8) makes possible the incorporation of all information regarding pluvial flooding and river flooding including the existence of the dam (Phase X). Figs. 7 and 8 show the defined influence diagrams.

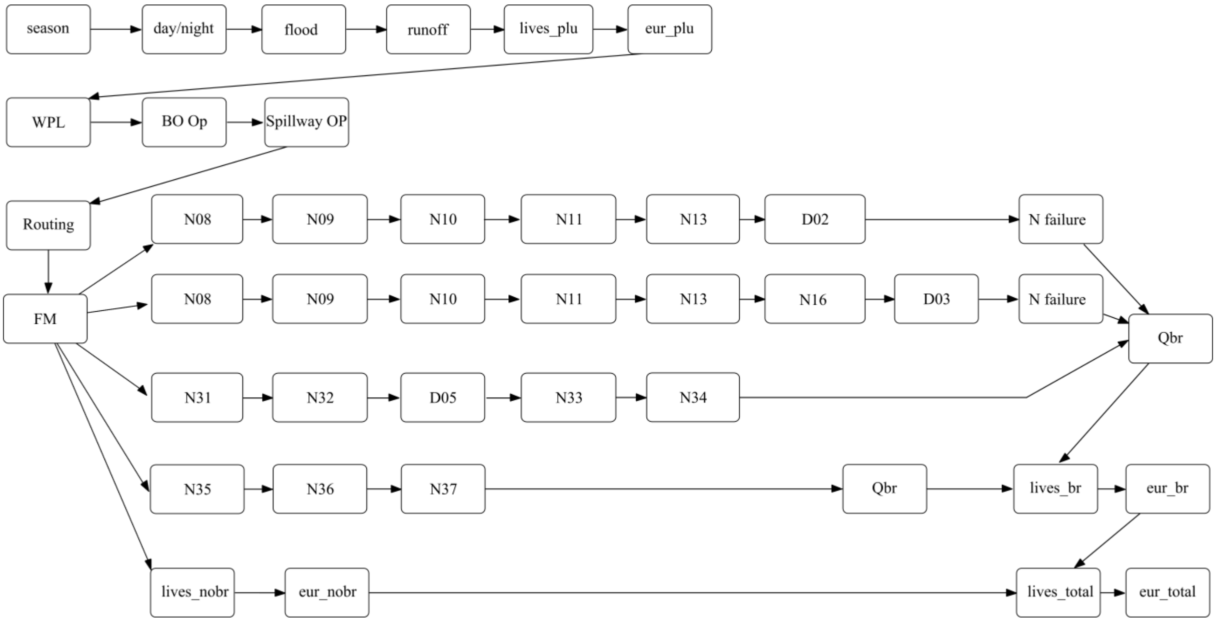

Figure 8. Risk Model 2. Pluvial flooding and river flooding including the existence of the dam.

Tables 2 and 3 define the information provided for each node of the influence diagrams. This information is combined to estimate probabilities and consequences of all flood events.

Table 2. Nodes for Risk Model 1.

Node	Definition
season; day/night	include probabilities to incorporate seasonal and daily variations of population at risk
flood; Qmax	include return periods of rainfall events and resulting peak discharges at the river course and runoff rates at the study site
lives; eur	include estimations of potential loss of life and economic damages

Table 3. Nodes for Risk Model 2.

Node	Definition
season; day/night	Probabilities of different time categories (e.g., summer/day, winter/night) to incorporate seasonal and daily variations of population at risk
flood	Range of return periods related to inflow hydrographs into the reservoir and rainfall events at the urban area
runoff	Runoff characteristics at the study site
lives_plu; eur_plu	Consequence estimations in case of pluvial flooding (life-loss and potential economic damages, respectively)
WPL; BO Op; Spil.Op	Previous water pool levels (WPL) and reliability of dam outlet works
Routing	Maximum water levels and peak flow discharges obtained from flood routing analyses based on previous information on water pool levels, gate reliability, etc.
FM	Four failure modes are characterized and conditional failure probabilities are included in nodes denoted as N or D.
N08	FM2 and FM3 First node: Existing sliding plane
N09	FM2 and FM3 Second node: Degradation surface
N10	FM2 and FM3 Third node: Loss of efficiency of drain wells
N11	FM2 and FM3 Forth node: Hydraulic connection
N13	FM2 and FM3 Fifth node: Permeability injections
D02	FM2 Sixth node: No detection
Nfailure	FM2 and FM3 Last node: Failure probabilities based on water pool levels
N16	FM3 Sixth node: Silting of drains
D03	FM3 Seventh node: No detection
N31	FM5 First node: Stilling basin erosion
N32	FM5 Second node: Stilling basin breach
D05	FM5 Third node: No detection
N33	FM5 Forth node: Scouring
N34	FM5 Last node: Failure probabilities based on discharges at the stilling basin
N35	FM6 First node: Foot erosion
N36	FM6 Second node: Upwards erosion
N37	FM6 Last node: Failure probabilities based on water pool levels (overtopping)
Qbr	Peak flow discharges in case of dam failure based on water pool levels
lives_br; eur_br	Estimations of potential loss of life and economic damages in case of dam failure
lives_nobr; eur_nobr	Estimations of potential loss of life and economic damages in case of flood routing
lives_total; eur_total	Overall results including the three sources of flood hazard

Potential consequences are estimated by combining inputs from the two types of flood events (pluvial flooding and river flooding from the natural flow regime of the river), avoiding double counting by considering the maximum number of potential fatalities and economic damages from both sources of flood hazard for each flood event.

4.5 Phase V: estimation of input data for the risk model

Input data for the risk model can be generally classified in three categories: loads, system response and consequences. In this section, information to characterize the *Base Case* is summarized (natural flow regime of the river and existing drainage system).

Information has been mainly obtained from existing hydrologic and hydraulic models and additional calculations have been carried out to estimate potential consequences.

4.5.1 Loads

Input data regarding pluvial flooding includes information of flood events resulting from rainfall episodes for return periods up to 100 yr. This upper value is based on the characteristics of the urban catchment area where it is assumed that rainfall rates for higher return periods do not exceed significantly the obtained estimates for the rainfall event of 100 yr of return period. Maximum annual daily rainfall rates are listed in Table 4.

Table 4. Maximum annual daily rainfall rates at the case study.

Return period (yr)	Maximum annual daily rainfall rate (mm)
5	70.8
10	84.1
25	101.0
50	113.4
100	125.8

These values have been obtained from hydrological studies based on a rainfall gauge located 20 km from the urban area, using a Gumbel distribution (PGOU, 2009).

Concerning the natural flow regime of the river (with a mean annual peak discharge of 29.3 m^3s^{-1}), hydrographs resulting from rainfall events for return periods that range from 2 to 10 000 yr are used. Simulations from a 1D hydraulic model in HEC-RAS for 12 different hydrographs (return periods from 2 to 10 000 yr) are used for analysing flood extent, flood depth, arrival wave time, etc. in downstream areas.

4.5.2 System response

Regarding pluvial flooding, the urban catchment area can be divided into 4 zones based on urban topology (e.g., building typology, slope and width of streets, etc.) and land-use distribution. From existing hydrologic studies, runoff rates, flood depths and velocities are obtained in streets of all zones to estimate flood severity levels for each flood event (Escuder-Bueno et al., 2012).

Concerning the natural flow regime of the river, flooded areas, flood depths, peak discharges, and arrival wave times provided by the analysis carried out in 2010 (Sanz-Jiménez et al., 2012) and a 1D hydraulic model are used.

4.5.3 Potential consequences

The estimated population in this case study is 2004 inhabitants. However, daily and seasonal variations exist according to the available demographic data. Therefore, four time categories are set as shown in Table 5 in order to reflect that variability (where summer season ranges from 1 July to 15 September and day-time category ranges from 8:00 UTC+1 to 22:30 UTC+1). Probabilities for each category are listed in Table 5.

Potential fatalities for each time category and flood event are obtained by multiplying population exposed to the flood by fatality rates. For the analysis, fatality rates proposed in Escuder-Bueno et al. (2012) are used for estimating potential loss of life in case of pluvial and river flooding (natural flow regime of the river).

Potential economic damages are obtained by estimating direct and indirect costs from flooding. For estimating direct costs of flooding, the urban area is divided into sub-areas with similar urban characteristics (mainly building typology and land use). Then, direct costs of flooding are obtained for each sub-area by multiplying three factors: (1) a reference value (in euros per square meter) based on the land use category (two categories are considered: residential or industrial); (2) the extent of the flooding within the sub-area, and (3) a percentage of damages based on flood depth.

According to existing studies (COPUT, 2002), the reference values shown in Table 6 are considered, based on a scale ranging from 0 to 100, where 100 is equivalent to an economic value of 82 € m^{-2}. Values are calculated based on Consumer Price Index values for 2011.

Table 5. Time categories and probabilities.

Time category	Population (inhabitants)	Season probability	Time category probability
TC1 Summer/day	3060	0.208	0.208·0.604=0.126
TC2 Summer/night	2804	0.208	0.208·0.396=0.077
TC3 Winter/day	2260	0.792	0.792·0.604=0.478
TC4 Winter/ night	2004	0.792	0.792·0.396=0.292

Note 1: 'Summer'-'Winter' time categories refer to different consequence estimations, where the 'Summer' category implies higher population at risk: it is considered that this increment on population occurs 2.5 months per year (2.5/12=0.208), from July until mid-September.
Note 2: 'Day'-'Night' time categories refer to different consequence estimations where 'Day' category implies higher exposure and higher population at risk (mainly in the industrial area): a value of 9.5 hours (9.5/24=0.396) is assumed as the average number of daily working hours.

Table 6. Reference costs for estimating potential economic damages.

Category	Rate	Value, year 2002 (€ m^{-2})	Value, year 2011 (€ m^{-2})
Residential areas	56.3	46.2	58.5
Industrial areas	18.8	15.4	19.5

Note: A rate of 100 is equal to 82 € m^{-2} (2002).

Generic depth-damage curves were proposed by USACE (2000). Values for properties of two or more stories without basements are used for this case study, based on average urban typology for each sub-area within the urban area. Damage to content is not considered as the reference value (in euros per square meter) proposed by COPUT (2002) for different land uses does include not only the value of the structure but the content also. Therefore, the reference value differs depending on the land use to which the flooded area under consideration is assigned (two land-use categories are considered: residential and industrial).

Finally, potential economic damages are estimated for each flood event by adding direct costs among all sub-areas. The resulting total direct cost is multiplied by a factor 1.27 to incorporate indirect costs. This factor includes disruption of public services, general costs of flood control intervention or disruption of secondary activities. Values for this factor are proposed in COPUT (2002) for different municipalities in Spain, based on total population, affected area, population density, and rate of employment, among other variables. Total costs for the *Base Case* in case of pluvial flooding and the natural flow regime of the river are shown in Table 7.

Table 7. Example of estimated potential fatalities and economic damages for the *Base Case*.

Time category	River flooding $Q_{max}=1097\ m^3s^{-1}$	Pluvial flooding T=100 yr
Potential fatalities (TC1)	11.1	3.3
Potential fatalities (TC2)	19.7	0.3
Potential fatalities (TC3)	8.2	2.4
Potential fatalities (TC4)	14.1	0.2
Potential economic damages (€)	9 899 692	6 911 030

4.6 Phase VI: risk calculation

All previous information on loads, system response and consequences in case of pluvial and river flooding is incorporated in the risk model, represented by the influence diagram shown in Fig. 7. Risk calculations are performed using the iPresas software (Serrano-Lombillo et al., 2009), developed at the Universitat Politècnica de València.

4.7 Phase VII: risk representation

Risk outcomes from iPresas software are obtained to represent FN and FD-curves for the situation before dam construction (*Base Case*). Results show that the total societal and economic risks (area under the FN and FD-curve) have been estimated as 0.097 lives yr^{-1} and 3.86 M€ yr^{-1}, respectively (Figs. 9 and 10). Total societal and economic risk can be obtained by considering the area under the FN and FD-curves.

4.8 Phases VIII: flood risk evaluation

There are no applicable standards or tolerability criteria in terms of urban flood risk to evaluate this case study. The main objective is to analyze the situation after the construction of the dam, including the implementation of the DEAP, and the situation after additional non-structural measures of public education and warning.

4.9 Phase IX: sensitivity and uncertainty analyses

A sensitivity analysis of the established conditional probabilities for all dam failure modes is further described in Phase X, after the study of the situation after dam construction. Uncertainty analysis is not considered for this case study.

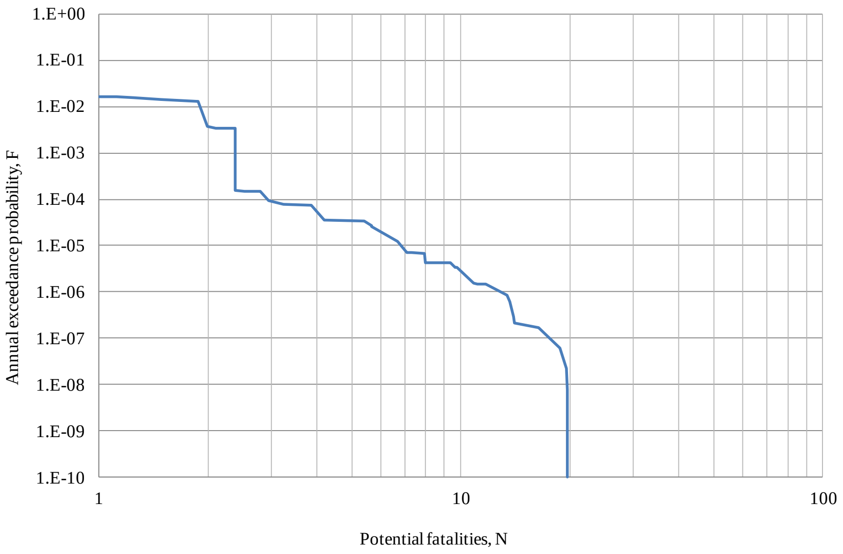

Figure 9. FN-curve for the *Base Case*.

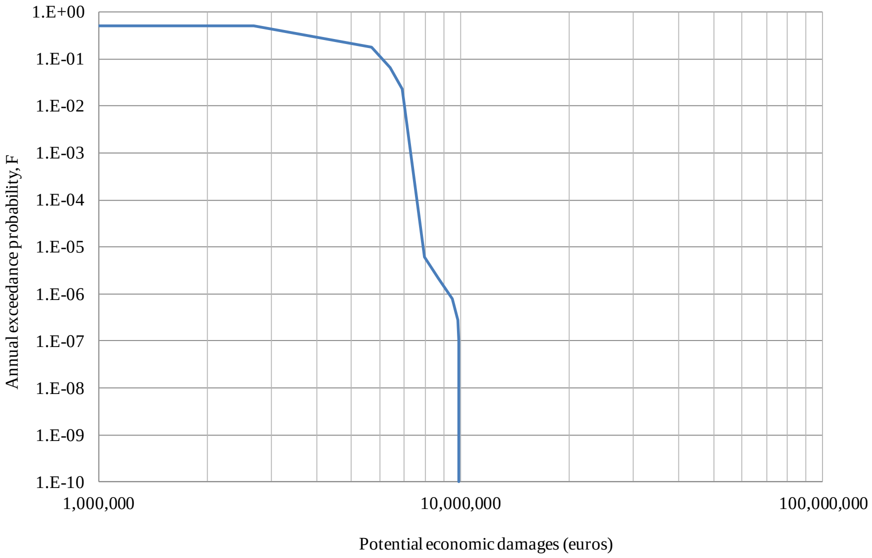

Figure 10. FD-curve for the *Base Case*.

4.10 Phase X: risk reduction measures

In addition to the *Base Case*, other two situations are analyzed:

4.10.1 Situation after dam construction, including the EAP (DEAP-Case)

Based on the *Base Case*, the situation after dam construction, denoted as *DEAP-Case*, includes also the implementation of the Dam Emergency Action Plan. Its impact can be incorporated into the risk model by estimating new loads, system response and consequences.

Dam construction costs are established as 100 M€ and DEAP annual maintenance costs as 0.03 M€.

Input data for pluvial flooding do not vary from the *Base Case.* The DEAP provides the necessary information to characterize loads, system response and consequences for this case.

Risk model architecture

Figure 8 shows the influence diagram for this case. The risk model includes four dam failure modes (San-Jiménez et al., 2012): two failure modes related to structural-geotechnical aspects (slippage of dam blocks) and two failure modes related to failure of outlet works (e.g., stilling basin erosion or undermining of the toe of the dam).

Loads: River flooding including the dam

Annual exceedance probabilities of different inflow rates at the reservoir are considered. Figure 11 shows inflow discharge distributions at the reservoir for five different annual exceedance probabilities (PAE, with units of yr^{-1}). Dam failure is analyzed based on inflow rates at the reservoir for return periods up to 100 000 yr. Estimations of feasible previous water pool levels at the reservoir are also obtained (Fig.12). Gate reliability of bottom outlet works is estimated as 85% (the spillway is uncontrolled).

System response: River flooding including the dam

A multidisciplinary group of professionals (33 participants), covering different areas of knowledge such as geology, hydrology, seismicity, materials, dam design, construction, monitoring, hydrology, etc. was actively involved in 2010 in the development of the different risk assessment activities to characterize loads, system response and consequences in case of failure of this dam (Jiménez-Sanz et al., 2012). Four failure modes are considered in this analysis (denoted as FM2, FM3, FM5 and FM6). These failure modes are related to potential sliding due to the existence of the *San Fermín* fault or failure of outlet works in a hydrological event.

Table 8 gives a short description of each failure mode. Different assumptions on the uplift distribution were made to account for three different hypotheses on the permeability of San Fermín Fault (very low, intermediate, and very high) and two on the performance of the drainage system (good, bad). Depending on the definition of the failure mode, either 3 or 6 (3 times 2) possible uplift resulting laws had to be then considered to account for all the combinations. The conditional probabilities that characterize each failure mode were obtained by expert judgement.

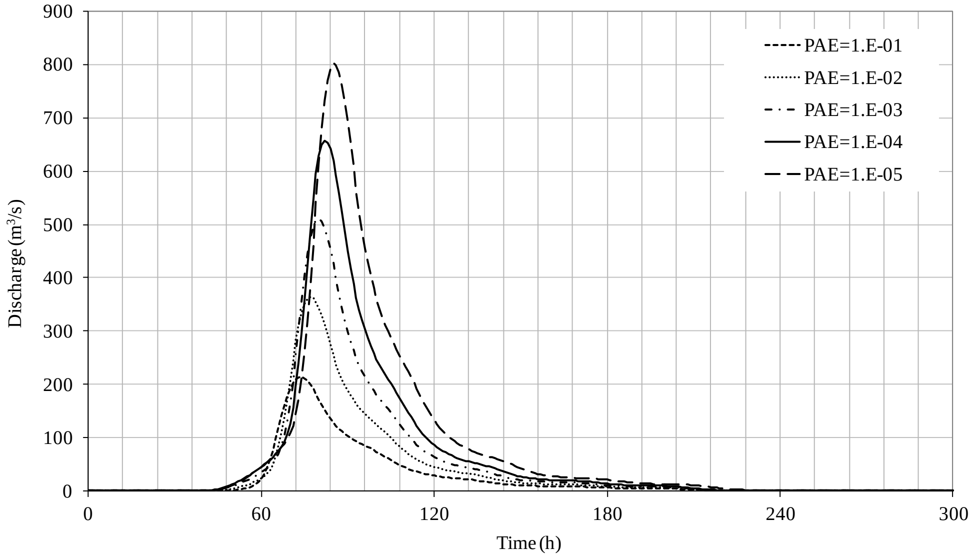

Figure 11. Inflow rates at the reservoir for several annual exceedance probabilities (PAE).

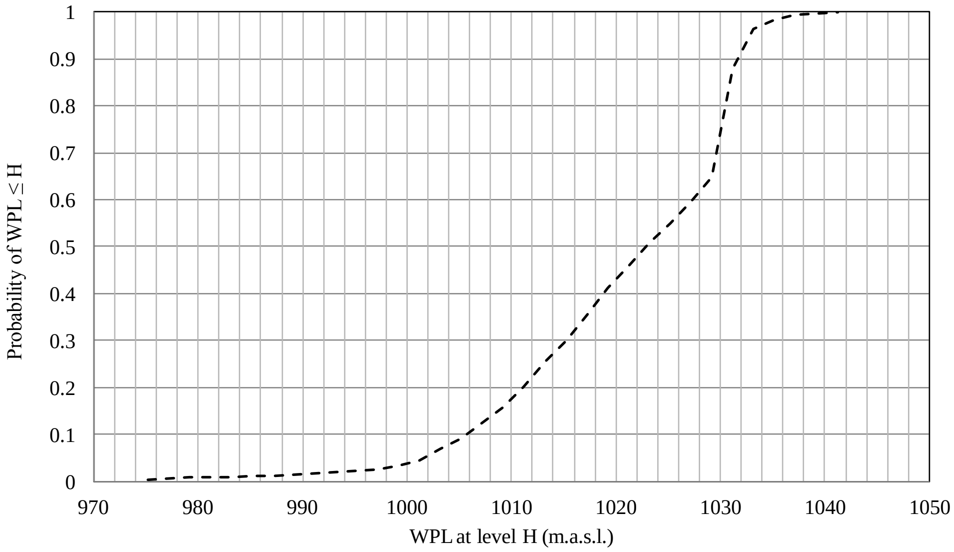

Figure 12. Exceedance probabilities of water pool levels (WPL) at the reservoir.

Table 8. Failure modes considered for the analysis.

Failure mode	Description
FM2	Given a certain water pool level, on the embankment of a block close to the centre but not included in the overflow section. It starts from the existence of a sliding surface with enough continuity through the San Fermín fault and a degradation of the surface (which could include a limonite-sandstone contact), giving rise to a loss of effectiveness of the drainage wells, together with feasible influences from San Fermín fault (three uplifts laws). The dam fails finally by sliding.
FM3	Given a certain water pool level, on the embankment of one of the baffle blocks, it starts from the existence of a sliding surface with enough continuity through the San Fermín fault and the existence of degradation of the surface (which could include a limonite-sandstone contact), giving rise to a loss of efficiency of the drainage wells, together with feasible influences from San Fermín fault and the possibility of drain silting and its break (six uplift laws). Finally, the dam fails by sliding.
FM5	Related to a continuous discharge through the stilling basin, and involves erosion of the basin itself or the downstream toe of the basin takes place, by headcutting or continuous concrete degradation. The stilling basin loses its structural integrity and leaves the ground uncovered. Erosion continues and reaches the toe of the dam and it is undermined. Finally, dam failure occurs due to a hybrid mechanism of settlement, overturning and sliding.
FM6	Related to continuous overtopping, erosion on the toe of any block. This process takes place until the downstream toe is uncovered. Erosion continues undermining the toe of the dam and, finally, dam failure takes place by a hybrid mechanism of settlement, overturning and sliding.

Two series of flow discharges are considered: discharges due to failure cases and flood routing cases (Table 9). Flooded areas are obtained based on inundation maps from hydraulic simulations using the software tool MIKE11. Flood depths and arrival wave times are also obtained from hydraulic modelling.

Table 9. Selected flow discharges in dam failure and non-failure cases for estimating consequences.

Dam failure cases Q (m^3s^{-1})	574	15 034	37 629	56 878	81 039	107 162	116 871	121 323
Non-failure cases Q (m^3s^{-1})	99	122	245	352	633	783	-	-

A sensitivity analysis of established conditional probabilities for all failure modes was also conducted. With that purpose, lower and upper estimates obtained from expert judgement are also incorporated into the risk model and results are denoted as Case L and Case U, respectively (best estimates were used in the *DEAP-*

Case). Table 10 shows the established values from expert judgement for all nodes of the risk model associated with failure modes (Nodes N and D, where *a,b,c* denote different estimates for the same node based on discharges or overtopping heights).

Table 10. Probability estimates for all failure modes (lower, best and upper estimates).

Node	Failure mode	Lower estimate	Best estimate	Upper estimate
N08	FM2	0.1800	0.2800	0.3550
N09	FM2	0.1050	0.1583	0.3083
N10	FM2	0.0543	0.1229	0.2143
N11	FM2	0.0683	0.1500	0.2333
N13	FM2	0.3786	0.4714	0.5857
D02	FM2	0.0686	0.1429	0.2429
N16	FM3	0.0700	0.1429	0.1929
D03	FM3	0.1071	0.2357	0.3786
D05	FM5	0.6214	0.7000	0.8264
N31a	FM5	0.0143	0.0343	0.0629
N31b	FM5	0.0271	0.0586	0.0843
N31c	FM5	0.0571	0.1100	0.1500
N32a	FM5	0.0100	0.0300	0.0729
N32b	FM5	0.0171	0.0557	0.1214
N32c	FM5	0.0286	0.0743	0.1429
N33a	FM5	0.0229	0.0486	0.0900
N33b	FM5	0.0471	0.0957	0.1571
N33c	FM5	0.0729	0.1214	0.2071
N34	FM5	0.1629	0.2571	0.4214
N35a	FM6	0.2050	0.2300	0.4083
N35b	FM6	0.2550	0.4083	0.5083
N35c	FM6	0.4143	0.5571	0.6729
N36a	FM6	0.1357	0.1614	0.2386
N36b	FM6	0.1686	0.2457	0.3286
N36c	FM6	0.2429	0.3143	0.3929
N37	FM6	0.0671	0.1714	0.3143

Potential consequences: River flooding including the existence of the dam

Potential affected elements (e.g., households, industrial areas, etc.) are identified from hydraulic simulations. Based on flood characteristics (e.g., flooded area, flood depth, peak discharge at the study site, arrival wave time, etc.), population at risk is obtained by quantifying the number of affected households and the number of inhabitants.

Fatality rates are obtained from reference fatality rates proposed in Escuder-Bueno et al. (2012) based on available warning times and flood severity. The number of potential fatalities (N) for the *DEAP-Case* is given in Table 11 for the largest flood events in failure (Q_{br8}) and non-failure cases (Q_{nbr6}).

Table 11. Example of estimated potential fatalities and economic damages for the *DEAP-Case* (river flooding including dam failure and flood routing).

Results	**River flooding** **Dam failure case** Q_{br8} = 121 323 m^3 s^{-1}	**River flooding** **Non failure case** Q_{nbr6} = 783 m^3 s^{-1}	**Pluvial flooding** T=100 yr
Potential fatalities (TC1)	187	0.1	3.2
Potential fatalities (TC2)	361	0.1	0.3
Potential fatalities (TC3)	138	0.1	2.4
Potential fatalities (TC4)	258	0.1	0.2
Potential economic damages (€)	27 980 109	2 522 812	6 911 030

Note: TC denotes 'time category'.

Results

Figures 13 and 14 illustrate the results for the three cases with lower (Case L), upper (Case U) and best estimates (DEAP-Case) of probabilities for failure mode characterization.

As it can be observed in both graphs, the FN and FD-curves for both cases move upwards or downwards as the dam failure probabilities shifts in comparison with the DEAP-Case.

However, if total societal or economic risk is considered (area under the FN-curve and F-D curve, respectively), then risk results do not show significant differences in comparison with the DEAP-case since these values are more influenced by the impact of pluvial flooding in the urban area (high probability events).

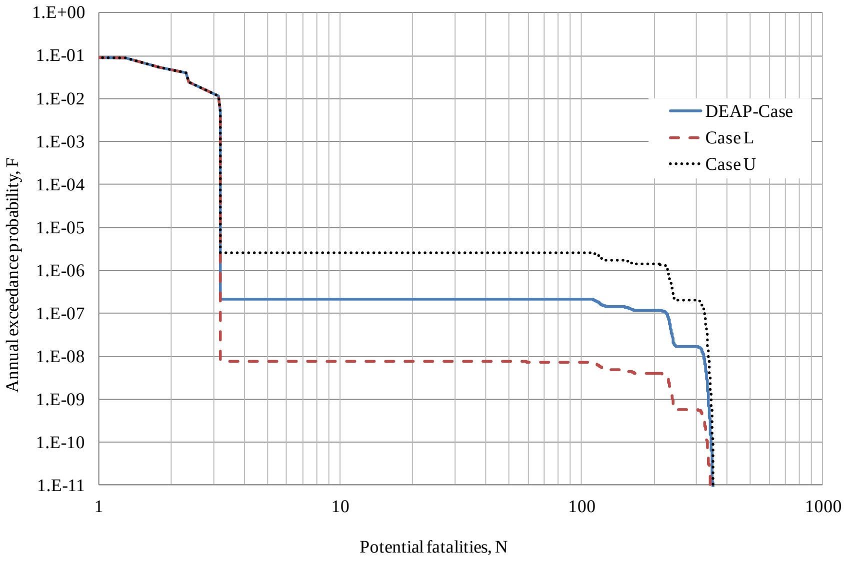

Figure 13. FN-curves for the DEAP-Case and sensitivity analysis.

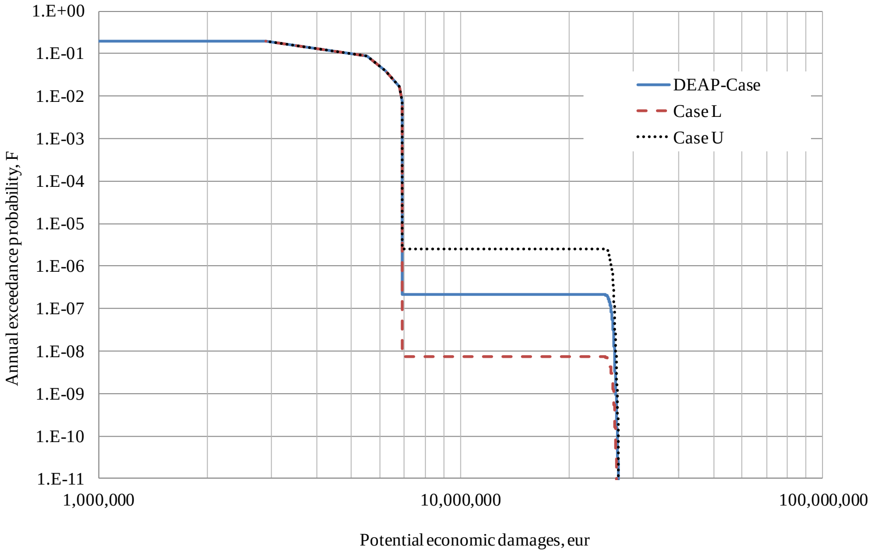

Figure 14. FD-curves for the DEAP-Case and sensitivity analysis.

4.10.2 Situation with non-structural measures of public education and warning (NonSt-Case)

Based on the *DEAP-Case*, the situation with new non-structural measures, denoted as *NonSt-Case*, includes a Public Education and Warning Programme (PEWP). The implementation cost of this Programme is 50 000 € (annual maintenance costs of 15 000 €). Its impact can be incorporated into the risk model by estimating new consequences.

With regard to potential fatalities, lower fatality rates can be used for analyzing pluvial flooding for situations with advanced warning systems. In case of river flooding including the dam, fatality rates associated with this situation are established at level 10 (highest level of flood severity understanding from advance risk communication and public education programmes and highly-coordinated emergency services) from the classification proposed by Escuder-Bueno et al. (2012).

In general, the impact of non-structural measures on potential economic damages is estimated by considering the state of knowledge on the relationship between lead warning times and reduction on potential damage depending on flood depth (Messner et al., 2007, Parker et al., 2005, Penning-Rowsell et al., 1978). However, it is considered that a measure involving warning systems should be implemented along with public education actions, as it is assumed that warnings are only effective if population at risk have a certain level of knowledge on how-to-act in case of a flood. Therefore, reduction of potential economic damages (e.g., from installation of waterstops to prevent water from entering households) can only be considered if public educational activities are in place. In this case, a reduction of the estimated damages can be achieved.

The annualized cost of the Public Education and Warning Programme (PEWP) is obtained based on implementation and maintenance costs and the expression given in Eq.(4).

$$C_A = C_{man} + \frac{C_{\text{int}}}{(1+r)} \cdot \frac{r\cdot(1+r)^n}{(1+r)^n - 1} \tag{4}$$

where C_A is the annualized cost of the risk reduction measure, C_{int} is the implementation cost, C_{man} is the maintenance cost, r is the discount rate and n the dam lifespan. It is considered that this measure is implemented in one year, the lifespan of the dam is 75 yr and the discount rate is 5%. As a result, the annualized cost for the program is 17 441 € yr^{-1}.

Annualized costs are obtained to calculate an indicator of the economic risk reduction generated by the implementation of the measure. The ACSLS (Adjusted Cost per Statistical Life Saved) indicator is used in this article (ANCOLD, 2003) and it follows the expression given in Eq.(5). This indicator can be used to figure out whether measures reduce risk in an efficient and equitable way. Bowles (2004), in a preliminary way, proposed that a measure is very justified with an ACSLS lower than \$3 million and is not much justified with an ACSLS higher than \$140 million. This indicator is defined as:

$$ACSLS = \frac{C_A - (E[R_E] - E[R_R]) - (O[R_E] - O[R_R])}{(E[N_E] - E[N_R])} \tag{5}$$

where C_A is the annualized cost of the risk reduction measure, $E[R_E]$ and $E[R_R]$ are the estimates of total economic risk before and after implementing the measure, $O[R_E]$ and $O[R_R]$ are the operational costs of the dam, and, $E[N_E]$ and $E[N_R]$ are the estimates of total societal risk. In this case study, dam operational costs are considered constant.

Figures 15 and 16 show the FN and FD-curves, which represent societal and economic flood risk for the analyzed situations: the *Base Case* (solid line), the *DEAP-Case* (dashed line) and the *NonSt-Case* or situation with non-structural measures (dotted line).

Results for the *DEAP-Case* show that approx. 360 fatalities result for an annual cumulative exceedance probability (F) of $1\cdot10^{-8}$ for the situation after dam construction. Results show that the total probability of failure is $3.7\cdot10^{-7}$, which corresponds to the horizontal part of the FN-curve. The combination of pluvial flooding and flood routing cases reach a maximum number of approx. 3 fatalities. This value is only exceeded by dam failure cases.

By comparing the *DEAP-Case* with the situation with non-structural measures (*NonSt-Case*), it can be observed that the whole FN-curve moves to the left as the level of consequences is reduced due to the existence of improved warning systems and higher flood severity understanding, when all sources of hazard are considered. In this case, the maximum number of potential fatalities is approx. 70 casualties.

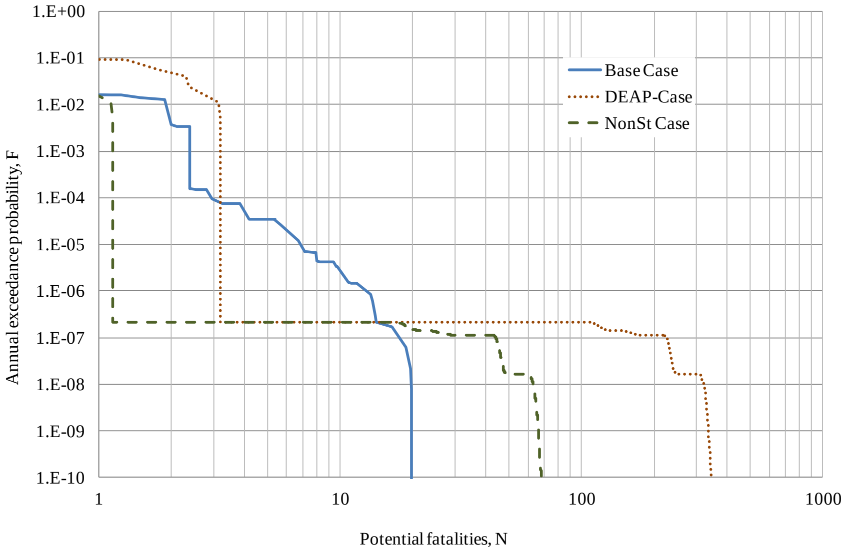

Figure 15. FN-curves for all analyzed situations.

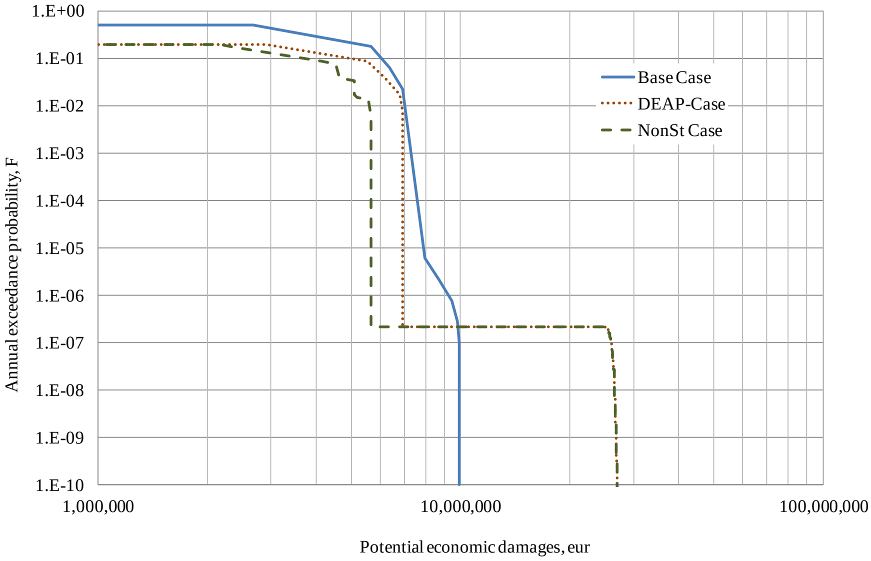

Figure 16. FD-curves for all analyzed situations.

Reduction of economic damages for flood events with low flood depths (e.g., pluvial flooding) is considered for the situation with non-structural measures of public education and warning. Therefore, the FD-curve varies for the *NonSt-Case* (dashed line). Economic damages for 'high-probability' flood events are higher for the *Base Case* as it includes river flood events from the natural flow regime of the river. As it is observed from the FD-curve, dam failure increases the expected level of potential economic damages for the *Base Case*.

Table 12 shows the results of total societal and economic flood risk for each situation (*Base Case*, *DEAP-Case* and *NonSt-Case*). These values are obtained from FN and FD-curves where they represent the area under each curve. Therefore, values are given in terms of lives·yr^{-1} and € yr^{-1} (or M€ yr^{-1}).

Results show that a risk reduction of, approximately, 0.13 lives·yr^{-1} may be obtained after implementing non-structural measures of public education and warning based on the proposed program. In addition, both ACSLS indicators for the *DEAP-Case* and *NonSt-Case* are negative thus the implementation of both measures (dam construction and public education and warning program) are justified in terms of efficiency.

Table 12. Total flood risk for the case study.

ID	Case	Societal flood risk (lives yr^{-1})	Economic flood risk (€ yr^{-1})	ACSLS indicator (€ lives^{-1})
Base Case	Drainage system and natural flow regime of the river	0.097	3 846 323	Not applicable
DEAP-Case	Drainage system and dam, including EAP	0.194	835 093	-19 591 730 (<0)
NonSt-Case	Drainage system and dam, including EAP and non-structural measures of public education and warning (Public Education and Warning Program)	0.069	672 897	-1 158 041 (<0)

4.11 Phase XI: risk management and governance

From the risk outcomes shown in Figs. 15 and 16, it has been demonstrated that potential fatalities in case of dam failure are significant but related to low probabilities. The implementation of non-structural measures of public education, warning and improved coordination schemes in case of flood emergency may reduce existent risk by improving the implementation and impact of the Dam Emergency Action Plan.

The guiding principle for flood risk management and governance to protect this urban area should be ensuring effective communication mechanisms among dam operators, emergency services and local authorities to ensure a quick response in case of emergency (i.e. increasing available warning times).

Annual education programs on flood risk, improved warning systems and training exercises require relatively low economic and technical resources (the annualized cost for the program is 17 441 € yr^{-1}) when compared to their potential for risk reduction. Results show that societal risk would decrease from 0.194 lives yr^{-1}, for the situation with only a Dam Emergency Action Plan, to 0.069 lives yr^{-1}, for the situation with improved public education and warning. In addition, results show that economic risk would decrease from 0.835 M€ yr^{-1}, for the situation with only a Dam Emergency Action Plan, to 0.673 M€ yr^{-1}, for the situation with improved public education and warning (i.e. the estimated reduction on economic risk is larger than the annualized cost of the proposed risk reduction measures).

5 CONCLUSIONS AND FURTHER RESEARCH LINES

In the first part of this article main concepts on flood risk analysis, assessment and management are presented and discussed.

This article presents a comprehensive methodology to integrate the analysis of pluvial flooding, river flooding and flooding from dam failure into urban flood risk analysis to provide better and more complete information to decision makers on flood risk management. The methodology starts from a methodological piece developed within the SUFRI project and includes the analysis of dam failure and non-failure cases (flood routing) to quantify and evaluate flood risk in urban areas. The goal of this methodology is to provide a tool for flood risk analysis that integrates all information regarding several sources of flood hazard. Reinforcement of best policies (e.g., urban planning, emergency management, civil protection, etc.) and good governance may be achieved by using the outcomes of flood risk analysis.

The use of risk models provides a logic and mathematically rigorous framework for compiling information. In addition, integrated societal and economic quantitative risk outcomes can be obtained. The relevance of quantitative flood risk analysis in urban areas is supported by the obtained results, indicating that FN and FD-curves are helpful and comprehensive tools to represent flood risk. These curves are the basis to illustrate risk quantification and the effect of different measures on flood risk reduction. Thereby, they prove to be helpful in comparing and analyzing mitigation measures. Furthermore, FN and FD-curves may be used to compare estimated risks against tolerability criteria or historical data.

The proposed methodology has been applied to a case study to analyze flood risk after dam construction and the impact of the non-structural measures of public education and warning. The results suggest that, for the case study site, flooding from the river and pluvial sources results in a low number of fatalities, whereas flooding from dam failure results in a high number of fatalities. The results of the analysis of non-structural measures confirmed that current risk is sensitive to warning times. Therefore, the implementation of the Dam Emergency Action Plan along with additional non-structural measures of public education and warning would reduce considerably the number of potential fatalities at the urban area in case of dam failure. Based on the existent flood risk and the potential of non-structural measures on risk reduction, it is confirmed that the implementation of an ‘upgraded’ DEAP (including annual education programs and improved warning systems) would reduce societal risk. Accordingly, the results show that it is of high importance to implement this plan before operation of the dam is initiated, as established in current regulation on dam safety at a national scale.

The methodology has been applied for a case study but it has been developed to be potentially applicable to any urban area. Flood risk analyses can support decision making by providing information to prioritize risk reduction measures. Hence, it is important to measure not only the impact but also the efficiency of the different measures. The results have shown that the proposed non-structural measures of public education and warning are highly justified in terms of efficiency. However, it has to be remarked that equity (Bowles et al., 2005) is another fundamental principle from which alternatives can be prioritized and conflict should be avoided achieving both equity and efficiency (Munger et al., 2009).

Regarding tolerability risk guidelines, there is still a lack of general standards for flood risk analysis in urban areas. Applicability of FN-curves for flood risk evaluation at local, regional or national level has been under discussion during recent years (e.g. Evans and Verlander, 1997) and it is still a matter for debate in the flood community, as results vary when considering load interdependencies among flood defence systems (i.e. the impact of failure of a flood defence infrastructure in the loading conditions of downstream systems). Tolerability standards based on the use of FN-curves are still under debate (e.g. on the consideration of a maximum base point, the slope of the tolerability criterion or the influence of risk aversion). This discussion falls outside the scope of this paper. An example and some considerations on the use of individual and societal risk for the national flood safety policy in The Netherlands can be found in Jonkman et al., 2011. Further investigation might focus on developing common standards to assess urban flood risk.

The proposed methodology goes one step forward in the process towards a comprehensive flood risk management that integrates all sources of flood hazard (natural and man-made threats), analyzing all related flood defence infrastructures (e.g., dams, dikes, levees, etc.) and involves all phases from risk analysis to risk governance (Fig. 17). Within this framework, there are further research opportunities to integrate human-induced hazards and to incorporate potential failure of other flood defence infrastructures such as fluvial dike systems into quantitative flood risk analysis.

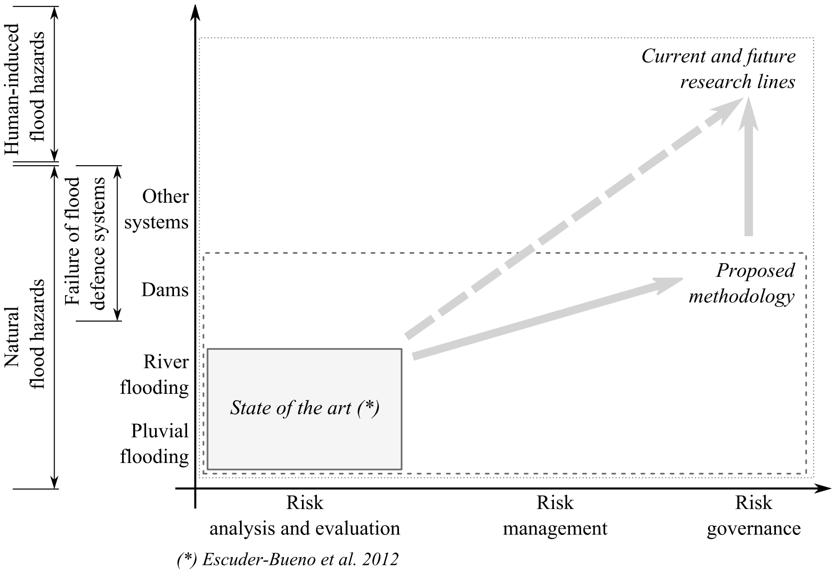

Figure 17. Current and future research lines within the risk analysis-governance framework.

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ANNEX 2: Enhancing local action planning through quantitative flood risk analysis: a case study in Spain

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TITLE

Enhancing local action planning through quantitative flood risk analysis: a case study in Spain

ABSTRACT

This article presents a method to incorporate and promote quantitative risk analysis to support local action planning against flooding. The proposed approach aims to provide a framework for local flood risk analysis, combining hazard mapping with vulnerability data to quantify risk in terms of expected annual affected population, potential injuries, number of fatalities, and economic damages. Flood risk is estimated combining GIS data of loads, system response and consequences and using event tree modeling for risk calculation. The study area is the city of Oliva, located in the Eastern coast of Spain. Results from risk modeling have been used to inform local action planning and to assess the benefits of structural and non-structural risk reduction measures. Results show the potential impact on risk reduction of flood defences, and improved warning communication schemes through local action planning: societal flood risk (in terms of annual expected affected population) would be reduced up to 51% by combining both structural and non-structural measures. In addition, the effect of seasonal population variability is analyzed (annual expected affected population ranges from 82% to 107%, compared with the current situation, depending on occupancy rates in hotels and campsites). Results highlight the need for robust and standardized methods for urban flood risk analysis replicability at regional and national scale.

KEYWORDS

River flooding, vulnerability analysis, risk analysis, flood risk management

1 INTRODUCTION

Floods are among the most damaging natural disasters in Europe and worldwide. In this paper, the need for improved quantitative flood risk analysis is identified, current and future challenges on flood risk reduction are acknowledged and a framework for flood risk analysis is presented and applied to a city as an example for enhanced local flood risk management.

1.1 The need

In the period 1985-2015, Europe has suffered nearly 481 major flood events, with 3,136 fatalities, more than 12 million affected people and more than 123 US$ billion economic losses (Université Catholique de Louvain, 2015). Flood risk assessments for future scenarios in several countries show that risks might rise due to climate or socioeconomic changes. Examples of analyses and projections of future exposure and risk at national scale can be found, e.g. in The Netherlands (Jongman et al., 2014), United Kingdom (Sayers et al., 2015) and Austria (Fuchs et al., 2015). In addition, analyses at European scale can also be found (Barredo, 2009), which show that the increase observed on flood risk is mainly due to socioeconomic shifts. However, future risks are influenced by both climate and socioeconomic projections and these may significantly vary for each region or country.Urban areas concentrate population and economic activities thus presenting high flood vulnerability. Mediterranean cities are particularly affected by flooding as they are located next to rivers, in low-land areas and affected by flood events in ephemeral streams. In many Mediterranean cities, the combination of basin physical characteristics and intense and irregularly distributed rain generates frequent floods.

As an example, the Valencian region in Spain has suffered severe flood events in the last decades (Université Catholique de Louvain, 2015), highlighting the 1957 Turia river flood (with 77 fatalities) and the 1982 flood from failure of Tous dam (with 43 fatalities and more than 226,000 affected people).

As a result of the impact of past flood events and the need for reducing existent flood risk, the European Commission published the Directive 2007/60/EC on 6 November 2007 (European Parliament, 2007), aiming at reducing and managing the risks that floods pose to human health, the environment, cultural heritage and economic activity. This Directive requires all Member States to assess risks related to water courses and coastlines, to develop hazard and risk maps and to apply measures to reduce flood risk.

This Directive was transposed into Spanish law by Royal Decree 903/2010, "Flood risk evaluation and management", which requires the definition of all areas with potential flood risk within the territory. This Decree establishes the content of hazard and risk maps, along with flood risk management plans at river basin scale.

More particularly, in the Valencian region, the regional government developed PATRICOVA (Territorial Action Plan for Flood Risk Prevention) in 2003, a preventive tool with recommended actions for urban planning and flood risk reduction. Municipalities classified at medium and high flood risk levels are required to develop local action plans for flood risk management (in Spanish, 'Planes de Actuación Municipal ante el Riesgo de Inundaciones', herein denoted as PAMRI by its acronym). PATRICOVA has been recently updated in 2015, incorporating new legislation and integrating recent advances in cartography.

Despite recent legislation and work conducted on flood risk management, there is still a need for local flood risk analyses to complete those developed at regional scale, to inform action planning and to better orientate risk reduction actions at urban scale. In most cases, despite some exemptions found in the literature such as guidance and examples of micro-scale flood risk assessment carried out e.g. in England and Wales (Penning-Rowsell et al., 2013), there is a lack of applications of risk analysis techniques at local scale or the required level of detail to support decision-making on local flood risk reduction and planning.

1.2 The challenge

Flood risk management has acquired an important role since the European Floods Directive (Directive 2007/60/EC) and global strategies for flood risk reduction have evolved from focusing mainly on reducing the hazard (structural measures) to more holistic approaches including the combination of both hazard and impact mitigation.

Different approaches for flood risk analysis can be found in the literature, including societal (Jonkman et al., 2008) and economic risks (Merz et al., 2010), and ranging from local (Marcotullio and McGranahan, 2006) to global scale (Winsemius et al., 2013).

'Think globally, act locally', the famous phrase attributed to René Dubos during the UN Conference on the Human Environment in 1972, emphasizes the importance of scale in dealing with environmental challenges. Unique physical, climatic, and cultural conditions appear at local scale and site-specific flood risk management is needed.

In the Valencian region, only 18 out of 136 local action plans for flood risk management have been developed and approved up to date. Despite the publication of some recommendations by civil protection on how to perform these plans, local authorities do not have the information, know-how or experience on the required flood risk analyses to be developed.

The city of Oliva, located in the Eastern coast of Spain, belongs to the group of municipalities within medium to high flood risk levels. Located 70 km from Valencia, Oliva is affected by pluvial, river and coastal flooding and it is characterized by a complex and wide-ranging geography (e.g. hills up to 460 m.a.s.l., plains, coastal areas and wetlands). In addition, there is high seasonal variation in population (with 27,127 and 55,174 inhabitants of resident and seasonal population, respectively, distributed across 60.1 km^2).

After 28 years of the largest flood event in modern times in Oliva (accounting for the highest recorded rainfall rate at the Iberian Peninsula with 817 mm in 24 hours), local authorities face the challenge of mitigating flood risk through the development and implementation of a local action plan (as required by regional legislation), in line with other existent and ongoing structural measures for flood risk reduction.

Local and regional authorities stand at the frontline of reducing the vulnerability of their territory to natural hazards and impacts of climate change (Mayors Adapt, 2015). In such context, quantitative flood risk analysis arises as a helpful tool to support management actions and strategies.

1.3 The opportunity

Flood risk is commonly expressed in terms of expected annual damage (in terms of potential affected population, number of fatalities or economic damage), obtained from the combination of three key components: flooding probability, exposure determinants and vulnerability of receptors (Klijn et al., 2015). Generally, risk is conceptualized as the multiplication of flood probability and consequences. In this paper, we propose flood risk analysis through the use of risk models, capable of estimating annual risk for different scenarios and performed for a real case study, based on results from flood hazard characterization and consequence estimations. This paper aims to present a framework for local flood risk analysis and its application to a real case to show how local flood risk management strategies may benefit from risk analysis. This paper analyses the city of Oliva (Spain) as an example. Although flood hazard mapping is available, a quantitative flood risk analysis had never been performed. The presented study is being used as a basis for developing a local action plan against flood risk.

This ‘science for policy’ paradigm can be considered as a ‘lighthouse’ example for other cities in Spain that are required to develop their corresponding plans. Examples can be found in the literature on examples of the benefits of research for policy and practice for flood risk management (Frans Klijn and Schweckendiek, 2012). The study shows how flood probability, exposure and vulnerability analyses provide valuable information for the development of a local action plan against flooding, for example by characterizing the impact on risk of improved warning systems and public education campaigns.

2 APPROACH

In this section, the applied framework (including tools and methods) for flood risk analysis is described. This framework for flood risk analysis is based on the method proposed by (Escuder-Bueno et al., 2012), through the use of a risk model which incorporates all information regarding loads, system response and flood consequences, and adapted to integrate GIS data into risk modelling. Figure 1 shows the flowchart summarizing data, methods and tools within the presented framework.

Potential applications include local flood risk assessments such as those required by regional and national legislation in Spain after the 2007 European Floods Directive.

Examples of such structured frameworks for flood risk analysis for other hazard types such as flooding from mountain rivers or landslides can be found in the literature (Fell et al., 2008; Mazzorana et al., 2013), as a means to enhance flood risk analysis processes.

The steps of the proposed framework include:

- Phase I: Scope of the case study
- Phase II: Review of available data
- Phase III: Study of the system situation: definition of the Base Case
- Phase IV: Flood events to be analyzed
- Phase V: Risk model architecture
- Phase VI: Input data for the risk model
- Phase VII: Risk calculation
- Phase VIII: Risk representation
- Phase IX: Risk evaluation
- Phase X: Study of risk reduction measures

2.1 Phase I: Scope of the case study

The proposed framework aims at estimating flood risk in urban areas in terms of affected population, potential injuries, fatalities, and economic costs resulting from damage to assets and infrastructure. It can be applied to analyze existent risk or to compare different scenarios to evaluate the impact of risk reduction measures.

The level of detail of the required analysis will depend on the scope and scale of decisions for flood risk management.

2.2 Phase II: Review of available data

Information on hydrologic studies, hydraulic modelling, flood defence response, population and land use data is required for characterizing loads, system response and estimating consequences from flooding.

GIS data on flood characteristics (e.g. flood depth, velocity, flooded area, etc.) and population and land uses is required to apply the procedure proposed in Fig.1. In recent years, more detailed and up-to-date GIS-based data is available, then allowing a more accurate estimation of flood hazard, exposure and vulnerability.

2.3 Phase III: Study of the system situation: definition of the Base Case

The Base Case corresponds with the benchmark scenario. The benchmark scenario should represent the system situation, incorporating existing structural and non-structural measure for flood risk reduction and system characteristics in terms of exposure and vulnerability. Therefore, it is of high important not only to define the benchmark scenario but also those after implementing planned risk mitigation actions, to be compared with the Base Case. Examples of scenario building processes for flood risk analysis from mountain rivers are found in (Mazzorana et al., 2012, 2013).

2.4 Phase IV: Flood events to be analyzed

The range of all potential flood events should be considered, obtained from hydrologic studies, and analyzed through hydraulic simulations to characterize system response and flood characteristics.

Flood defence reliability should be incorporated, when possible, into hydraulic modelling to analyze the existent protection level and the impact on flood characteristics of their performance (failure and non-failure cases of flood protection infrastructure).

This range will be divided into intervals, as shown in Fig.2, to incorporate data on flood hazard probabilities into the risk model performed in Phase V. Each flood event interval is characterized by a representative annual exceedance probability (AEP).

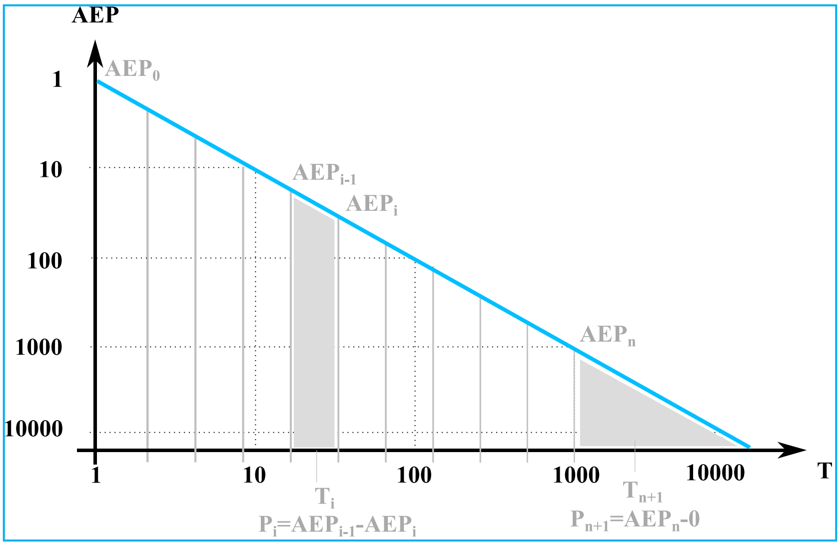

Figure 1: Generic division of the analyzed range of flood events.

2.5 Phase V: Risk model architecture

The use of risk models provides a logic and mathematically rigorous framework for compiling information of the system to estimate flood risk (Castillo-Rodriguez et al., 2014).

The risk model can be represented by an influence diagram composed by nodes and connectors (Serrano-Lombillo et al., 2011). Nodes include information on loads (e.g. annualized probabilities of flood events), system response (failure probabilities of flood defence infrastructures, e.g. dam or levee breach) or consequences (e.g. results from consequence estimations in terms of affected population or economic damages).

In this paper, two generic schemes for defining the risk model architecture are proposed and shown in Fig.3. The first scheme (model "a") can be used for analyzing flood risk for urban areas affected by river flooding from non-regulated systems. The second scheme (model "b") should be used if potential failure of a flood defence (e.g. a dam) is incorporated into the analysis.

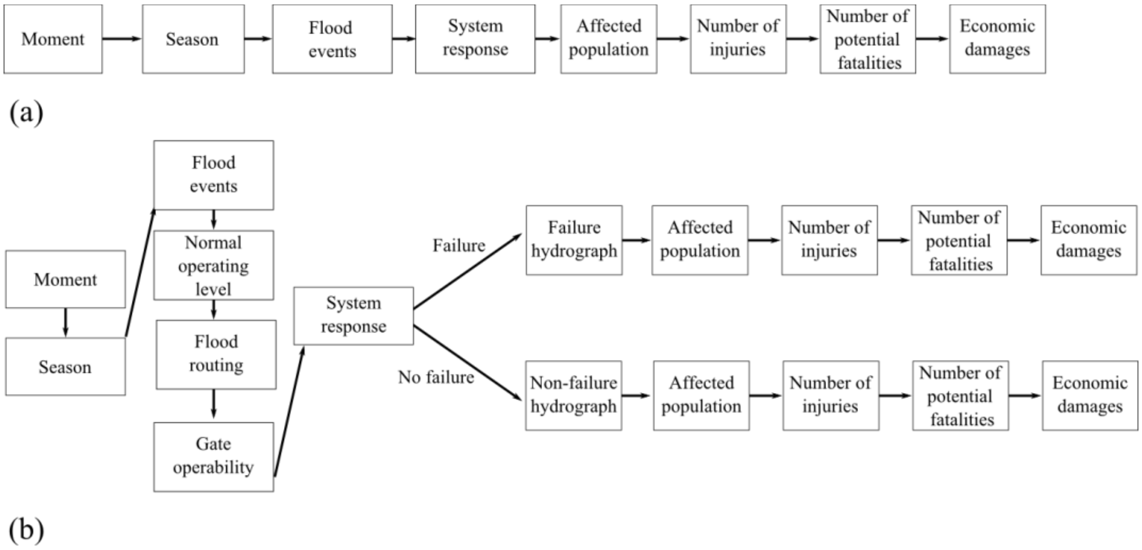

Figure 2: Generic risk model architecture: non-regulated river system (a) and regulated river system (b).

These two generic influence diagrams are an adapted version of those proposed by (Castillo-Rodriguez et al., 2014). These schemes allow to include the analysis of societal risk in terms of affected population, potential injuries, fatalities and economic costs due to damages from flooding (assets, infrastructure and services).

For the first influence diagram (model "a"), proposed to analyze flood risk in non-regulated systems, the following nodes are considered:

- Moment: this node includes information on probabilities for different time periods during the day (i.e. the probability of being during the day or at night). It can be used to later incorporate daily variability on potential consequences (e.g. affected population in industrial areas might change depending on the moment of the day).
- Season: this node includes information on probabilities for different seasonal periods during the year (i.e. the probability of being in summer or winter season). It can be used to later incorporate seasonal variability on potential consequences (e.g. affected population in urban areas might change if resident or potential population during summer is considered).
- Flood events: this node includes information on probabilities for different flood events. A range of flood events is established, defined by minimum and maximum return periods. This range is divided into a number of intervals (e.g. 10, 20, etc.). Figure 2 shows how the range of plausible flood

events is divided into intervals for risk calculations. These intervals are equally spaced in logarithmic scale along the given range of return periods. Each interval is represented by an annual exceedance probability (AEP), obtained by deducting AEP values of low and high interval limits. The example shows a range from 1-yr to 1000-yr flood events into 10 intervals. An additional interval is added to include flood events that exceed the 1,000-yr return period.
- System response: this node includes information on system response (e.g. peak flow river discharges).
- Affected population, number of injured people, potential fatalities and economic costs: these nodes include information on consequence estimation in terms of affected population (AP), injuries (NI), fatalities (N) and economic damages in the urban area (D), respectively. Estimations for different flood events are obtained and incorporated into the risk model in each node.

For the second influence diagram (model “b”), proposed to analyze flood risk in a regulated river system with a dam, the following nodes are considered:

- Moment, Season, Flood events: these nodes are equivalent to the aforementioned described for the first influence diagram.
- Normal Operating Level (NOL): this node includes the water level at the reservoir in normal situation. For simplicity, it is assumed that this level is constant.
- Gate operability: this node includes probabilities for each possible combination of gate operability (number of gates functioning correctly for flood routing when the flood arrives) for dams with controlled outlet works.
- Routing: refers to results from the technique used to estimate evolution of water levels at river course and reservoirs during the flood event, based on initial conditions (water level when the flood arrives). Results from flood routing are included in this node for each flood event and gate operability combination. Two outcomes from flood routing analysis are required: the maximum water pool level at the reservoir and resulting peak flow discharge through outlet works for each combination.
- System response: for each load combination (represented by a maximum water pool level from flood routing), this node is used to consider two possible situations: failure and non-failure of the flood defence system, with complementary conditional probabilities of occurrence for each load combination. Hence, two branches emerge from this node to consider both options.
- Failure and non-failure hydrographs: these nodes include information on peak flow discharges resulting from flood defense failure or non-failure cases (i.e. peak flow discharges from flood routing).
- Affected population, number of injured people, potential fatalities and economic costs: these nodes include information on consequence estimation in terms of affected population (AP), injuries (NI), fatalities (N) and economic damages in the urban area (D) for flood events resulting from flood defense failure (upper branch) and non-failure cases (lower branch).

2.6 Phase VI: Input data for the risk model

A GIS-based tool is proposed for input data processing. The tool, named gvSIG Desktop (www.gvsig.com), is an open source software, GNU / GPL license, with free use, distribution, study and improvement. Recently, gvSIG has been graduated as an OSGeo project (Open Source Geospatial Foundation). This GIS software tool was first developed by the regional government of the Valencian Autonomous Region (to be widely implemented in their regional and local systems) and now is further developed and promoted by the gvSIG Association.

The use of other available GIS tools can be applied within this framework (e.g. qGIS). In this paper, gvSIG has been applied since it is being used by local governments in Spain.

In this paper, the procedure shown in Fig.1 is proposed to integrate GIS data into the risk model in Phase VII. This procedure shows the required steps to estimate flood consequences and to provide input data for the risk model in terms of affected population, potential injuries and fatalities and damage costs at local scale. This GIS-based procedure aims at boosting implementation of risk-informed local action plans through standardized consequence estimation and risk calculation.

The information required includes:

- Hydrological and hydraulic modeling. Flood characteristics should be estimated for each cell on the map representing the study area for different floods (a range of flood events with return periods up to, at least, 500- year is recommended). Two maps are required showing inundation depths and flow velocities for each cell.
- Consequence estimation. Several types of consequences per cell on the map are obtained. The impacts are then aggregated at municipality scale. The impacts include population exposed to flooding, injuries, potential fatalities and economic damages.
    - Affected population. Affected population should be obtained using census data (resident and seasonal population) and information on occupancy rates in hotels, campsites, etc. Accuracy and precision on population distribution is of high importance to enhance risk estimates. Detailed knowledge of population distribution and variability will help to better define potential scenarios (day/night, seasonal and/or spatial variability).
    - Life-loss estimation. The life-loss estimation method proposed by MAGRAMA (Spanish Ministry of Agriculture, Food and Environment) for developing risk analysis at river basin scale is used. This method is based on the methodology proposed by DEFRA (Department for Environment, Food and Rural Affairs). Recent flood risk analyses have been conducted in Spain by applying this methodology, as for example in the Ebro River Basin (PREEMPT project "Policy-relevant assessment of socio-economic effects of droughts and floods"). For a detailed description on the method for estimating potential fatalities, the reader is referred to Wallingford et al (2006).

    - Economic damage estimation. It is based on the method used in PATRICOVA (Generalitat Valenciana, 2015). Potential direct economic damage costs are obtained using information on land use categories to define asset values and applying a depth-damage function, which estimates the expected damage for a given inundation depth.
- Risk modeling.
    - Input data on floods (exceedance probabilities), river discharge (system response) and estimated consequences (aggregated outcomes at municipality scale from GIS-data) is incorporated into the risk model to estimate societal and economic risk in terms of annual expected impacts.

Table 1 shows a summary of most relevant variables and data sources for flood risk analysis based on the presented framework in Fig.3.

Table 1. Summary table of main variables and outcomes used in the presented framework for flood risk analysis.

Risk component	Main variables	Data source	Risk outcome
Flood probability	Annual exceedance probability (AEP)	Hydrologic studies	Annual Expected Affected population (AEAP) Annual Expected Number of injured people (AENI) Annual Expected Number of potential fatalities (AEN) Annual Expected Economic damages (AED)
Exposure	Failure probabilities (system response)	System reliability analysis	
	Flood depth (y) Flow velocity (v) Flooded areas (AF) Debris factor (DF) Hazard ratings (HR)	Hydraulic modelling	
Vulnerability	Area vulnerability (AV) People vulnerability (Y) Affected population (AP) Percent of damages (PD) Reference costs (CR) Number of injured people (NI) Number of potential fatalities (N) Economic damages (D)	Land use distribution Census data distribution Consequence analysis	

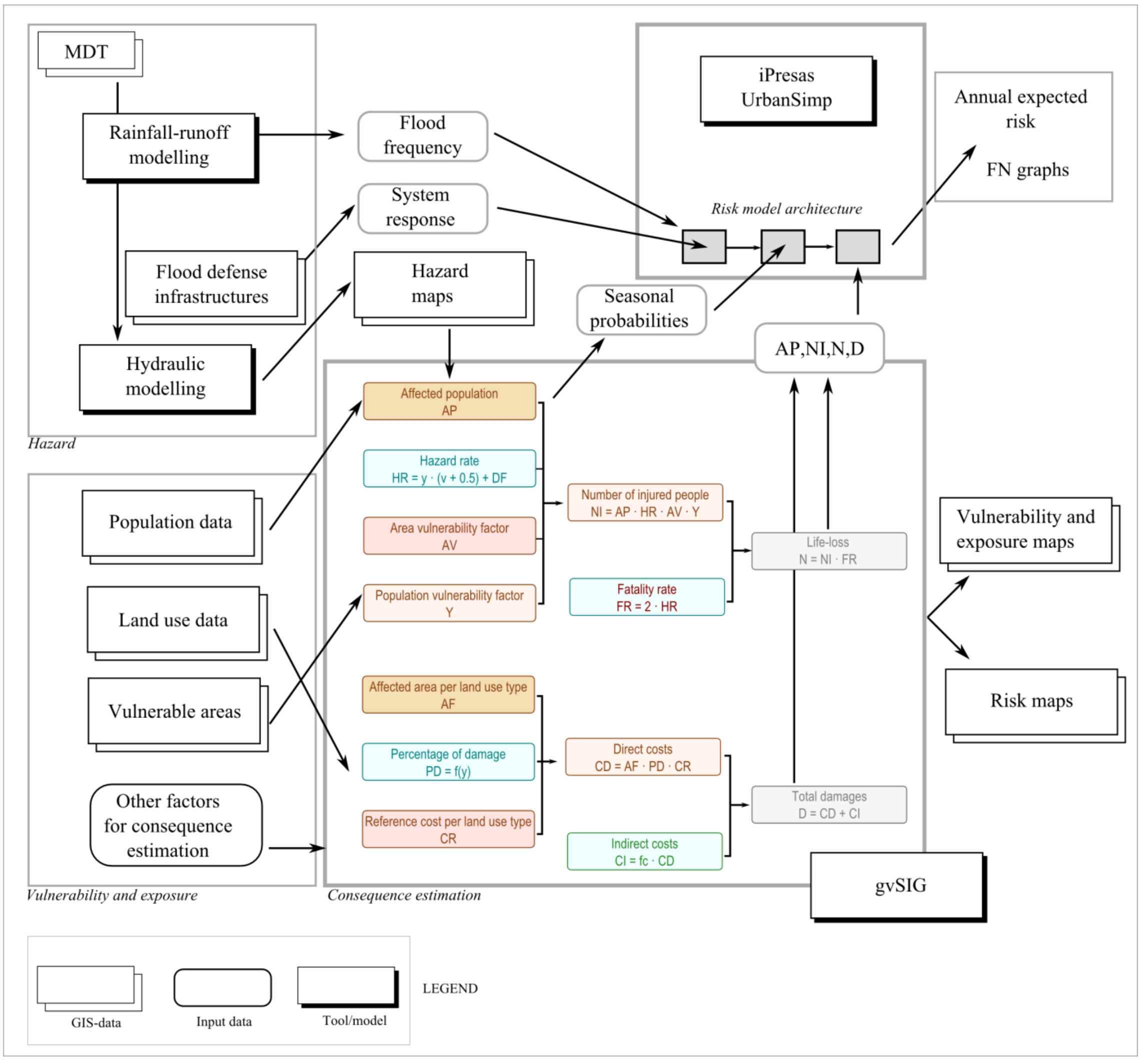

Figure 3: Flowchart of data and models.

2.7 Phase VII: Risk calculation

Aggregated data on consequence estimation per flood event, from Phase VI, is incorporated into the risk model, proposed in Phase V. The iPresas UrbanSimp (www.ipresas.com) software tool is used for risk calculation and modelling. This tool is a simplified version of iPresas Calc, first developed by the Polytechnic University of Valencia (UPV) and now by iPresas Risk Analysis (Spin-off UPV). iPresas Calc is a software tool that combines input data on flood hazard and impact to obtain expected annual risk (Serrano-Lombillo et al., 2011). Risk, in terms of expected annual societal or economic risk, is calculated by developing the event tree that considers all combinations of events that may lead to flooding.

In this paper, flood risk is defined as the combination of the probability of a damaging flood event and potential consequences (Gouldby and Samuels, 2005; Schanze, 2006). Risk is estimated as the expected annual average damage of flooding in terms of societal or economic consequences. Hence, risk is obtained in terms of expected annual population affected (EAPA), number of injuries (EANI), fatalities (EAF) and damage costs (EAD). The iPresas UrbanSimp software tool estimates risk by developing the event tree that includes all combinations of flood events, system response and related consequences.

Although there are examples of flood risk analysis approaches which include economic, social and environmental risks (Meyer et al., 2009), conducting a quantitative analysis of environmental risks was out of scope of this research work. On the other hand, societal risk is considered based on a three-fold perspective: potential affected population, injured and fatalities.

2.8 Phase VIII: Risk representation

Risk can be represented in F-N curves. The area under the curve is the annual expected number of fatalities, where the horizontal axis represents the level of consequences (e.g. number of fatalities, denoted as N) and the vertical axis represents the annual cumulative probability of exceedance (F) of each level of consequences.

Other type of consequences can be represented. These curves are then called F-D or F-AP, by representing economic costs due to damages (D) or affected population (AP), respectively.

2.9 Phase IX: Risk evaluation

Risk outcomes can be compared with tolerability recommendations (if available), thus enabling to analyze whether risk reduction measures are justified or not when evaluated in contrast with proposed criteria. Generalized frameworks for risk evaluation can be found in the literature (UK Health and Safety Executive, 2001). However, there still is a lack of tolerability criteria applied at local scale, although some recent examples can be found (Miller et al., 2015).

Tolerability recommendations for individual and societal risk have been published by several authors and organisations (Vrijling, 2001). As an example, the United States Bureau of Reclamation suggests a limit of 0.01 fatalities per year for annualized societal risk when analysing incremental risk from flooding due to dam failure (Hennig et al., 1997). However, this limit, proposed for analysing incremental risks (attributed to the failure of the infrastructure), may not be applied when analysing flood risks in total terms (due to all potential flood events from both failure and non-failure cases).

2.10 Phase X: Study of risk reduction measures

Once risk is obtained for the Base Case, other scenarios can be analyzed to evaluate the impact of risk reduction measures. New input data on loads, system response or consequences should be required and incorporated into the risk model. Risk outcomes for the new scenario are then compared with results for the Base Case.

Regarding evaluation of risk reduction measures, approaches such as Cost-Benefit Analysis (CBA) and Multi-Criteria Analysis (MCA) are commonly used for analyzing investment projects, required by law or promoted through guidelines (EC, 2008). In contrast to CBA, which is legally prescribed in some countries (for example in the Netherlands or the United Kingdom), MCA is not widely established, although some examples can be found. For example, project selection for public works in Italy and acquisition of data-processing equipment or consulting services by public administration in Spain have to be conducted based on MCA (Gamper and Turcanu, 2007).

In dam safety management, the use of risk indicators that consider efficiency and equity principles is common, evaluating societal and economic risk reduction and costs of measures. The Adjusted Cost per Statistical Life Saved (ACSLS) indicator is commonly used for evaluating dam risk reduction measures (Morales-Torres et al., 2016).

3 CASE STUDY ANALYSIS

An example of how the framework described in Sect.2 can be applied is included in this section. The results have been used to guide the development and implementation of a local action plan for flood risk management.

3.1 Phase I: Scope of the case study

The municipality of Oliva is located in the eastern coast of Spain (Fig. 4), has about 27,127 inhabitants (distributed in several urbanized areas) and covers a total area of 60.1km^2.

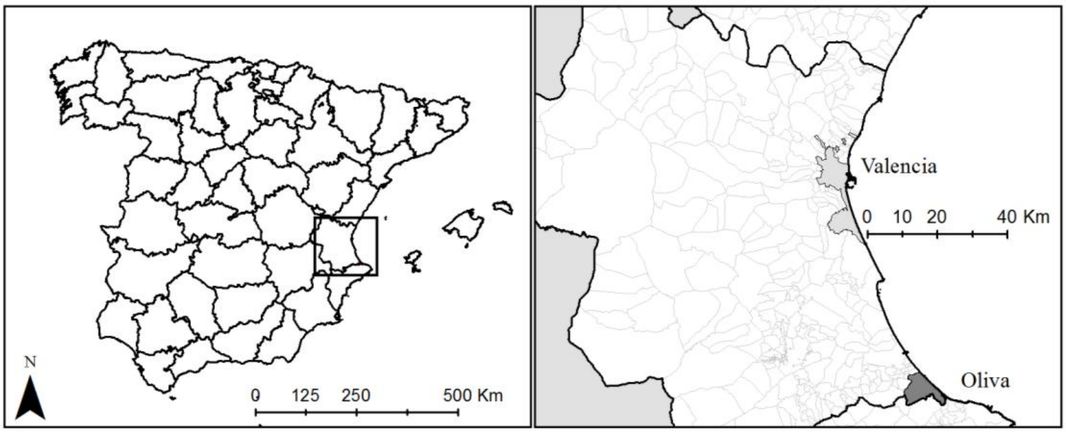

Figure 4: Location of the case study area at national (left) and regional (right) scale.

The heaviest daily precipitations historically observed in Spain concentrate mainly on the coastal Mediterranean zone. Indeed, Oliva accounts for the most extreme daily precipitation record in the Iberian Peninsula with 817 mm on 3rd November 1987 (Ramis et al., 2013). The mean annual precipitation reaches 850 mm. Flood events concentrate mainly during the rainy season from August to November. Table 2 shows a summary of most relevant flood events in Oliva.

Table 2. Summary of recent (most relevant) flood events for the case study.

Date (yyyy-mm-dd)	Precipitation in 24 h (mm)
1987-11-03	817
1997-12-04	378
1972-11-29	354
1997-06-18	288
2002-03-30	220
1996-09-11	197
2002-05-05	188

The system is characterized by multiple river courses and brooks, with complex interconnections and a varying topography, including low-land areas and hills up to 460 m.a.s.l.

A dam is currently under construction in Rambla Gallinera river course (a 62.5 m high concrete gravity dam, with a total reservoir capacity of 6.13 hm^3 at dam crest level). Civil works started in 2010 (including river embankments, diversion of secondary brooks to Rambla Gallinera river course and dam construction), but are not finished yet. The dam will provide flood protection up to a return period of 10 yr (Hijós Bitrián et al., 2010) and significant reduction on the peak flow discharges at this river course up to 56% (50-yr flood event). Discharges are also attenuated for floods with higher return periods, with a minimum reduction of 8.6% (5,000-yr flood).

Oliva is composed by several urbanized areas distributed within the municipality. The main area is located in the north-western part, concentrating 84.6% of resident population (59.6% of seasonal population). However, other areas located along the coast are relevant as population may increase by 23 times in some districts.

The selection of this study area is based on several reasons. First, the intensity and frequency of past flood events in the region are relevant. Second, good quality and up-to-date data are available on hazard, population and land use mapping. Additionally, the impact of structural and non-structural flood risk reduction measures has not been quantified so far. Finally, local authorities are currently involved in the process of developing the Municipal Action Plan against Flood Risk (denoted as PAMRI).

3.2 Phase II: Review of available data

Population and land use data are GIS-based. These data, provided by local government, is based on a yearly survey promoted by the regional government for all municipalities with less than 50,000 inhabitants (hereafter, EIEL database, by its acronym in Spanish). The municipality is distributed in 9,324 and 16,131 parcels of urban and rural land, respectively.

The EIEL database includes resident and seasonal population: “resident population" is obtained from census data and “seasonal population" is estimated from demographic trends observed in the last years during the summer season. It includes both resident and occasional population (but does not include hotel and campsite occupancy). For this analysis, the summer period ranges from mid-April to mid-September.

This database is completed with observations during site visits and other inputs from local authorities.

3.3 Phase III: Study of the system situation: definition of the Base Case

Four scenarios are considered for flood risk analysis as follows:

- Current situation (Scenario 0): this scenario represents the current situation of the system and it is used for benchmarking (to compare with results of Scenarios 1 to 3). This scenario is considered as the Base Case.
- Implementation of structural measures (Scenario 1): this scenario represents the situation after implementing structural measures for flood risk reduction, including dam construction. Differences in peak flow discharges in Rambla Gallinera are shown in Table 3 (e.g. from 282 to 182 m^3/s for a 25-yr flood event).

- Implementation of a local action plan (Scenario 2): this scenario represents the situation after implementing a local action plan against flooding (PAMRI), which includes improved warning and communication schemes, public education campaigns and training of all actors involved in emergency management.
- Implementation of both local action plan and structural measures (Scenario 3): this scenario represents the situation after implementing both structural and non-structural measures.

Table 3. Simulated peak flow discharges per river course (SOBEK model) [m^3/s].

	Current situation (Scenario 0)			**Structural measures (Scenario 1)**		
	Return period (yr)					
River course	25	100	500	25	100	500
Piles	84	153	247	84	153	247
Fonts	54	107	186	54	107	186
Algepsar	7	11	23	7	11	23
Frares	4	7	16	4	7	16
Alfadalí	21	34	82	21	34	82
Cementeri	2	4	8	2	4	8
Gallinera	282	462	1025	182	284	829
Benirrama	16	28	63	16	28	63
Bullent	102	173	399	102	173	399
Molinell	84	146	318	84	146	318

3.4 Phase IV: Flood events to be analysed

The regional plan PATRICOVA defines 6 flood hazard levels (denoted from NP1 to NP6) based on probability of flood occurrence (return periods of 25, 100 or 500 yr) and inundation depth (above/below 0.8 m). Flood hazard levels in Oliva were obtained in 2002 from an inundation study at regional scale and reviewed in 2013 (adding a new level to identify geomorphological hazards). However, resolution of GIS data used for the regional plan is too low (scale was 1:50,000 in 2002 and 1:25,000 for the updated version in 2013). In addition, the recent review did not consider new and ongoing structural actions for flood risk reduction.

In this paper, we used inundation data from a hydraulic model developed in 2010 by ACUAMED (Aguas de las Cuencas Mediterráneas S.A., public corporation and instrument of the Ministry of Agriculture, Food and Environment for Mediterranean River Basin Development Programme) and updated by TYPSA (consulting firm) in 2012 with a DEM (Digital Elevation Model) with a 5m horizontal resolution derived from LiDAR (Light Detection and Ranging o Laser Imaging Detection and Ranging) and corrected by site measures. However, only 3 flood events were modelled (return periods of 25, 100 and 500 yr). Table 3 shows peak flow discharges for two scenarios: current situation (Scenario 0) and after implementing structural flood risk reduction measures including the dam under construction (Scenario 1).

3.5 Phase V: Risk model architecture

For this case study, the risk model architecture shown in Fig.5 is used. Dam failure flood events are not modelled. Flood characteristics after dam construction (Scenario 1) are considered based on flood routing analysis. In order to determine societal or economic risk, the choice of a wide range of flood events is important. However, availability covers from 25 to 500 yr. Vulnerability was estimated for 25-, 100-, and 500-year flood events, based on the proposed framework in Sect.2. Given the discrete set of flood events, the range of plausible flood events is divided into 20 intervals, obtaining expected damage for each interval by interpolating input data for the 3 available events. The impact of a 1-year-flood event is assumed to be zero for the current situation (Scenario 0). A flood protection level of 10-yr is considered for Scenarios 1 and 3.

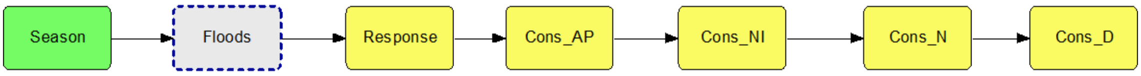

Figure 5: Risk model architecture for the case study of Oliva using iPresas UrbanSimp software tool.

3.6 Phase VI: Input data for the risk model

Concerning flood probability estimation, inundation maps with results from a 2D hydraulic model in SOBEK (a modeling suite developed by Deltares), with runoff rates from HEC-HMS (developed by the U.S. Army Corps of Engineers, USACE) are used. These maps are raster-based, with a spatial resolution of 20 m×20 m. Data on flood depth and velocity are available at each grid-cell for the three return periods. Inundation map for the 500-yr flood event and hazard level map as defined by PATRICOVA are included in supplementary material for the current situation. The hazard level map for the current situation is also shown in Fig.6.

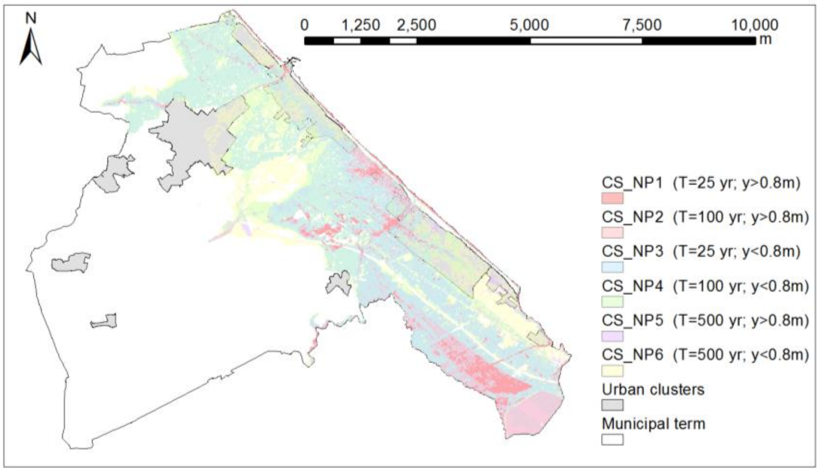

Figure 6: Hazard level map for Scenario 0 (Current situation).

Results from hazard analysis show that 10% of resident population is located in low frequency flood areas, against a 15% of resident population located in high frequency areas (25-yr flood event). Around 14,000 are located in NP1 areas, "high frequency-high flood depth" category (flood depth greater than 0.8 m for the 25-yr flood event).

Regarding consequence estimation, the municipality is divided into urban and rural parcel sub-areas and information from EIEL database is available in GIS format.

The number of resident and potential (seasonal) inhabitants in each parcel is obtained by multiplying the number of registered households and the corresponding density value (inhabitants/household). In addition, population in camping areas and hotels is considered based on the maximum capacity and hotel occupancy rates in the Valencian region (2013 Database from National Statistics Institute). These rates are assumed to be, in average, 35% and 75% in winter and summer seasons, respectively. Table 4 summarizes the results of affected population. A 500-year flood has a 0.2 % probability of occurring in any given year, and could cause roughly 22,890 affected population during summer season for Scenario 0.

Table 4. Summary of land use types for the case study (non-urbanized areas were also analysed but not included in this table).

Land use type	Area (m^2)	Percentage of urban area (%)	Reference value (EUR/ m^2)
Commercial	19,348	0.4%	34.55
Cultural	47,916	1.0%	34.55
Health services	23,672	0.5%	34.55
Industrial	687,372	14.9%	11.25
Institutional	17,288	0.4%	34.55
Office building	14,573	0.3%	34.55
Other uses	131,249	2.8%	0
Residential	3,043,656	66.0%	68.7
Restaurants	8,512	0.2%	34.55
Sports facilities	614,618	13.3%	34.55
Warehouse	58,112	1.3%	11.25

Estimation of potential life-loss is based on the method proposed by DEFRA (DEFRA, 2006). The number of fatalities is a function of the number of injuries and the hazard rating, where the number of injuries is estimated by combining the following factors:

- Number of people within the hazard zone.
- Hazard rating: factor which combines flood characteristics (flood depth, flow velocity and debris factor).

- Area vulnerability: function of effectiveness of flood warning, speed of onset of flooding and nature of area (including types of buildings); and
- People vulnerability: function of presence of people who are very old and/or infirm/disabled/long-term sick.

The following assumptions for the case study analysis are considered:

- An average debris factor (DF) equal to 0.5 is used to estimate hazard rates.
- A vulnerability area factor (AV) equal to 6, 7 and 8 is used for multi-storey buildings, residential areas and campsites, respectively.
- A population vulnerability factor (Y) of 0.2 is used based on census data (i.e. percentage of population aged 65 years and over).

We calculated the potential direct economic damage using information on land use classes (a summary is included in Table 5), reference asset values and a generic depth-damage function (denoted as CS in Fig. 8), which estimates the expected damage for a given inundation depth. Direct costs are obtained by multiplying percent of damage (based on flood depth), flooded area (in m²) and reference cost (in monetary terms per m²).

Table 5. Estimated impact per scenario and flood event.

Season	Return period (yr)	Current situation (Scenario 0)				Structural measures (Scenario 1)			
		AP	NI	N	D (M€)	AP	NI	N	D (M€)
Summer (seasonal population)	25	7795	85	2	10.86	5596	59	1	5.27
	100	13269	158	3	22.20	9850	109	2	12.15
	500	22890	341	9	52.03	18754	270	7	42.39
Winter (resident population)	25	1873	25	1	10.86	1572	22	0	5.27
	100	3428	51	1	22.20	2539	35	1	12.15
	500	6282	110	3	52.03	4497	80	2	42.39
Season	**Return period (yr)**	**Local action plan (Scenario 2)**				**Structural measures and local action plan (Scenario 3)**			
		AP	NI	N	D (M€)	AP	NI	N	D (M€)
Summer (seasonal population)	25	7795	73	1	9.91	5596	51	1	4.73
	100	13269	136	3	20.26	9850	94	2	10.95
	500	22890	293	8	47.61	18754	232	6	38.92
Winter (resident population)	25	1873	22	0	9.91	1572	19	0	4.73
	100	3428	44	1	20.26	2539	30	1	10.95
	500	6282	95	3	47.61	4497	69	2	38.92

Note: AP=Affected population; NI=number of injured people; N=fatalities; D=damage costs in M EUR.

It is essential to adjust asset values to the regional economic situation and property characteristics (Jongman et al., 2012). Therefore, asset values and a generic stage-damage function used in regional studies for flood risk planning are considered in this case study (Generalitat Valenciana, 2015). A sensitivity analysis has been included to analyze their impact on results. Different stage damage functions would impact on consequence estimation results as later described in Sect.4.

Other direct costs such as destruction of vehicles, damage to infrastructure, livestock or business interruption are not considered. Indirect costs are considered based on factors used by regional planning (Generalitat Valenciana, 2015), set as 7% of direct costs for the city of Oliva (it includes aspects such as population, employment and number of households within the urban area). Total costs are obtained by adding direct and indirect costs for each affected parcel.

Table 6 summarizes the results of consequence estimation. A 500-year flood could cause roughly 9 potential fatalities and 52M€ for Scenario 0.

Table 6. Results from risk model per scenarios CS, BC and effect of local action plan.

	Current situation (Scenario 0)	Structural measures (Scenario 1)	Local action plan (Scenario 2)	Structural measures and local action plan (Scenario 3)
Societal risk (AEAP) [inhabitants/yr]	2370	1168	2370	1168
Societal risk (AENI) [injured inh./yr]	28	21	24	18
Societal risk (AEN) [fatalities/yr]	0.56	0.28	0.48	0.24
Economic risk (AED) [Million EUR/yr]	6.11	2.10	5.57	1.89

Note: AE=annual expected; AP=Affected population; NI=number of injured people; N=fatalities; D=damage costs.

The impact of implementing a local action plan against flooding (PAMRI) is analyzed based on the following changes on consequence estimation from improved warning systems and communication schemes:

- A lower rate of vulnerability area factor (AV) is considered. Hence, values change to AV=5 in urbanized areas with multi-storey buildings, AV=6 in residential areas and AV=7 in campsites.
- A reduction on economic damages is assumed based on damage avoided when a warning lead time of, at least, 2 hours is provided. For a 80% rate of warning coverage (proportion of covered properties), 100% rate of service effectiveness (proportion of flooded serviced properties that were sent a timely, accurate and reliable flood warning), 80% rate of availability (proportion of flooded services properties that received warning), 85% rate for ability (proportion of residents able to understand and respond to such a warning), and 85% rate for effective action (proportion willing to take effective action or which have actually taken effective action), a percentage

of damage reduction of 18% is assumed for flood depths below 1.2 m (Parker et al., 2005).

3.7 Phase VII: Risk calculation

The iPresas UrbanSimp software tool is used to estimate risk by developing the event tree that includes all combinations of flood events, system response and related consequences.

Table 6 shows results in terms of expected annual population affected (AEAP), number of injuries (AENI), fatalities (AEF) and damage (AED). Risk outcomes for the current situation show societal risk levels up to 2,370 of annual expected affected population and 0.56 fatalities per year. Considerable risk reduction can be achieved by implementing planned structural measures (Scenario 1) thus societal risk would be reduced to 1,168 inhabitants per year (AEAP) and 0.28 fatalities per year (AEF). Affected population remains equal after implementing local action planning (Scenario 2) but societal risk in terms of potential fatalities would be reduced to 0.48 fatalities per year.

In addition, results reflect the combined effect of both structural and non-structural measures (Scenario 3). Societal risk after dam construction and implementation of the local action plan might change from 0.56 to 0.24 fatalities per year. Economic risk in terms of annual expected damages would vary from 6.11 to 1.89 M€ per year.

It is noted that at this stage, only direct benefits (such as the reduction in flood damage and improved warning systems) are included in the analysis of the impact of implementing a local action plan. Other benefits such as improved risk awareness or reduction on economic damages to vehicles and local businesses could be considered in future analyses.

3.8 Phase VIII: Risk representation

Figure 7 shows F-AP, F-N and F-D curves for all scenarios. The first graph depicts the cumulative annual exceedance probability (F) of each level of potential affected population (AP). Results show that there is a probability of 10^{-2} of exceeding 8,300 affected people due to flooding for the scenario with structural measures. This value is higher when considering the current situation, with approx. 11,300 affected people for the same probability. The second graph depicts the cumulative annual exceedance probability (F) of each level of potential fatalities (N).

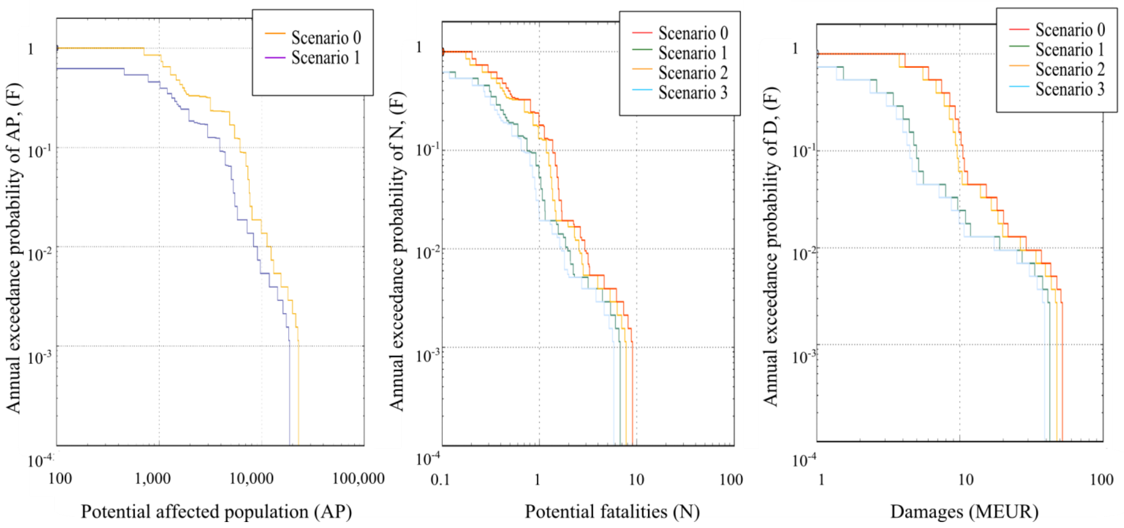

Figure 7: Extract of F-AP, F-N and F-D curves for the case study: scenarios 0 (current situation), scenario 1 (PAMRI=local action plan), scenario 2 (structural measures), and scenario 3 (PAMRI plus structural measures).

Results show that there is a probability of 10^{-2} of exceeding 3 fatalities for the current situation (Scenario 0). This value decreases after implementing structural measures (Scenario 1) to approx. 2 and up to 1.6 for combined structural and non-structural measures (Scenario 3). The third graph shows potential economic damages (D) with a probability of 10^{-2} of exceeding 28 M€ for the current situation (Scenario 0). This value might decrease up to approx. 17 M€ after implementing combined structural and non-structural measures (Scenario 3).

Finally, results from risk analysis were represented in different hazard and risk maps to support local action planning against flood risk. Recommendations published by the RISKMAP project (Fuchs et al., 2009; Meyer et al., 2012) have been considered for elaborating these maps. An example is provided as supplementary material to this paper (affected population for the 500-yr flood event for the current situation).

3.9 Phase IX: Risk evaluation

Tolerability recommendations are not considered for this case study since there are no proposed criteria or guidelines at regional or national level in Spain.

3.10 Phase X: Study of risk reduction measures

The ACSLS indicator is obtained to evaluate cost-efficiency of analyzed measures. Table 7 shows implementation, maintenance and annualized costs for considered measures (local action plan and structural measures including dam construction). Results show that any of these measures would be justified in terms of efficiency on risk reduction since results show negative values (reduction of economic risk is higher than annualized costs). After implementing the local action plan (lowest ACSLS value), the resulting ACSLS indicator still remains negative when risks before and after implementing structural measures are compared, thus supporting the decision of also implementing planned structural measures.

Table 7. Results from evaluation of risk reduction measures.

Measure	Structural measures (Scenario 1)	Local Action Plan (Scenario 2)	Local Action Plan + Structural measures (Scenario 3)
Discount rate (%)	5	5	5
Life span (years)	50	5	50
Implementation cost (EUR)	43,000,000	10,000	43,000,000
Maintenance cost (EUR/yr)	10,000	2,500	10,000
Annualized cost (EUR/yr)	2,253,238	4,700	2,253,238
Annualized cost	2.25	0.00	2.25
ACSLS (MEUR/life) [compared with current situation]	-6.27	-6.69	NA
ACSLS (MEUR/life) [compared with situation after implementing Local Action Plan]	NA	NA	-5.94

Note: ACSLS=Adjusted Cost per Statistical Life Saved, NA=Not Applicable.

4. SENSITIVITY ANALYSIS

The effect on societal and economic risk of several factors has been assessed in this study. Input data for the risk model has been modified and risk estimations obtained for each case.

4.1 Effect of selected flood protection level

In general, a flood protection level represents how well protected any given area is against flood damage. For example, a 10-yr flood protection system protects an area against anything equal to or smaller than a 10-yr flood.

Risk analysis for the current situation has been performed by assuming that flood damage is zero for a 1-yr flood event. In this section, the effect of such assumption is analyzed.

As an example, results from Aqueduct Global Analyzer Database at regional scale are available for different protection levels. Model setup, results and limitations of available estimations in this database can be found in (Ward et al., 2013a; Winsemius et al., 2013). Table 8 shows the results for the Valencian region from this database, accounting that there is a region-wide average protection level of 2-, 5-, and 10-yr, respectively.

Risk estimations for the current situation have been obtained for three different protection levels (i.e. assuming that flood damage is zero for 2-, 5-, and 10-yr flood events) and are also summarized in Table 8.

Results show that societal risk in terms of AEAP would change from 2,370 to 1,557 inhabitants/yr if a 10-yr protection level is assumed. Since there is no information on system response for flood events with low return periods (hydraulic modeling was conducted from 25 up to 500-yr flood events), it is noted that risk estimated for the current situation might be overestimated for this case study. Further research on system response for high-frequency flood events would be of paramount interest.

Table 8. Effect of the selection of flood protection level.

	Oliva (Scenario 0: CS)		**Valencia (region)**		**Comparison Local/Region**	
Flood protection level (yr)	Societal risk (AEAP) [inhabitants/yr]	Economic risk (AED) [MEUR/yr]	Societal risk (AEAP) [inhabitants/yr]	Economic risk (AED) [MEUR/yr]	%AEAP	%AED
1	2370	6.11	No data	No data	-	-
2	2279	5.88	47600	746.24	4.8%	0.8%
5	1991	5.16	29000	537.94	6.7%	0.9%
10	1557	4.07	15800	348.04	9.8%	1.2%

Note: CS=current situation; AEAP=annual expected affected population; AED=annual expected damage costs.

We highlight that societal risk for the city of Oliva represents a significant percentage of total flood risk at regional scale if results are compared with those presented by Aqueduct Global Analyzer Database. Despite it accounts for 1% of resident population at regional level, societal risk ranges from 5% to 10%, depending on the protection level, as shown in Table 8.

Results from local flood risk analyzes, as described in this paper, can be used to validate/update available information in global databases.

4.2 Effect of including seasonal population variability on societal risk

The impact of occupancy rates in hotels and campsites on societal risk has been assessed. Two situations are considered:

- Occupation rates set to zero. Only census data and people in dispersed housing are used for estimating population at risk.
- Occupation rates set to maximum plausible values (50% in winter and 100% in summer).

Incorporating the above input data on consequence estimation into the risk model, societal risk results for these two scenarios show that values would range from 1,940 affected population/yr and 0.38 lives/yr (low occupancy) to 2,529 affected population/yr and 0.63 lives/yr (high occupancy). Results show that affected population increases in 450 inhabitants/yr when comparing zero occupancy's and the current situation's results.

These results show the importance of analyzing not only census data but considering potential population in hotels and campsites. This population group is of high relevance in touristic cities, as it is the case in the Mediterranean coast of Spain.

4.3 Effect of population trends on societal risk

Flood risk in the future can be influenced by either climate change, which may increase or decrease the frequency and severity of flooding; or by socio-economic changes, such as ageing population (or decline) and economic growth.

In this section, socio-economic change is considered. The database of Shared Socioeconomic Pathways (SSPs) developed by IIASA (International Institute for Applied Systems Analysis) is used for defining population trends in Oliva, based on national population trends for Spain in 2030 and 2050 (Nakicenovic et al., 2013). This database has been also used in recent local flood risk assessments (Ward et al., 2013b) in Europe.

For the current situation, resident and seasonal population is increased by a factor of 1.06 and 1.13 in 2030 and 2050, respectively. Estimating societal risk for these two scenarios, risk would range from 2,370 affected population/yr and 0.56 lives/yr (current situation) to 2,616 affected population/yr and 0.61 lives/yr in 2050.

Results show that attention should be paid on future population trends and urban developments to update vulnerability assessments.

4.4 Effect of selection of depth-damage curves and asset values on economic risk

The stage damage function used for this case study is the curve proposed in PATRICOVA (Generalitat Valenciana, 2015) for meso-scale flood risk analysis in the Valencian region, denoted as CS-curve. This curve has been compared to other relative (in percentage of damage) depth-damage functions. These curves are shown in Fig.8 and include:

- MAGRAMA: Stage damage function proposed by MAGRAMA for flood risk analysis and mapping at river basin scale (MAGRAMA, 2013).
- EGM: Stage damage function proposed by USACE, based on empirical data from flood events from 1995 to 1997, developed for nation-wide applicability in flood damage reduction studies (USACE, 2000).
- HYDROTEC: Simple curve used for some flood action plans in Germany (Merz and Thieken, 2009).

These generalized functions represent some of the existent depth damage curves for assessing urban flood damage. From results shown in Fig.8 and compared with other depth-damage functions in the literature, it is noted that CS and MAGRAMA curves may tend to overestimate costs. However, both curves include content damage in reference costs to be multiplied by damage percentages thus no additional costs to content should be considered.

Depth-damage functions should ideally be developed for specific characteristics of local building types. Some examples of site-specific stage damage functions in Spain can be found (Velasco et al., 2015). However, the development of synthetic curves for each urban area requires an exhaustive field work, data gathering and later analysis, not feasible in many cases.

Defining regional specific stage damage functions for most relevant land use types would be desirable and useful for comparison among cities. In addition, detailed local data on building types (not available for this study) would be of interest to estimate direct flood damages in future analyses.

Reference values per land use type used for this case study correspond with rates proposed in PATRICOVA (Generalitat Valenciana, 2015). Direct costs for cleanup expenses, emergency prevention actions, and other related costs are not included. Table 9 shows reference values per land use type proposed by MAGRAMA for river basin flood risk analysis and mapping. These rates include replacement costs for infrastructure, content and vehicles. Therefore, reference values differ from those proposed in PATRICOVA (Generalitat Valenciana, 2015).

By matching land use categories defined by both sources (Generalitat Valenciana, 2015; MAGRAMA, 2013), risk is estimated for the current situation by adopting new reference costs and the stage damage function shown in Fig. 8.

It is noted that economic risk outcomes are highly sensitive to the stage damage function and reference values adopted, since economic risk would increase from 6.11 M€/yr (for the current situation) to 180.4 M€/yr (for the current situation, but using proposed values by MAGRAMA). These results show the need for standardized stage damage functions and reference asset values in Spain.

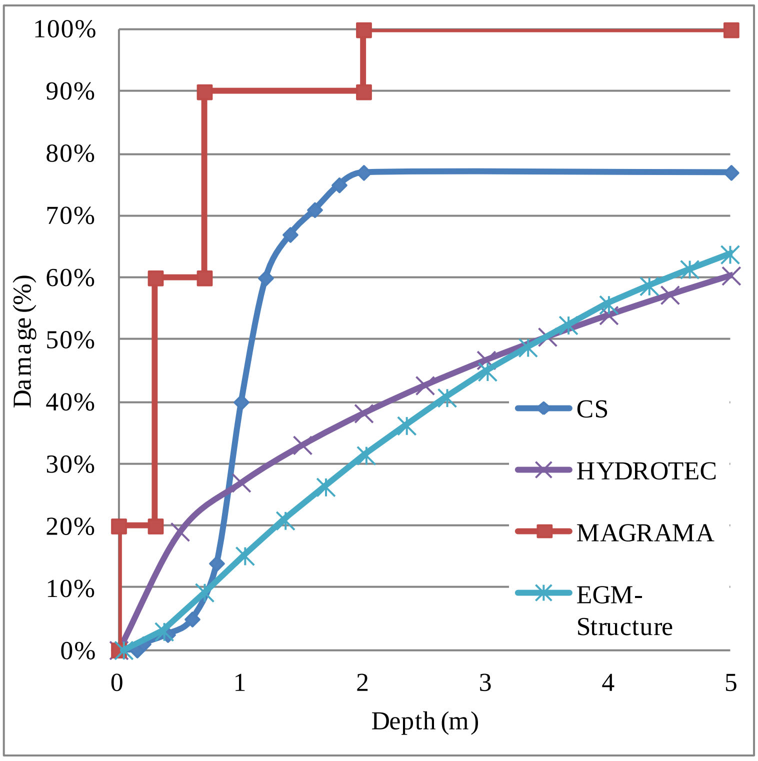

Figure 8: Examples of depth-damage functions compared to function used for the case study analysis (CS).

Table 9. Reference costs in EUR/m² in urban areas: GVA (2015) and MAGRAMA (2013).

Land use type	GVA	MAGRAMA
Warehouse	11.25	150
Commercial	34.55	380
Cultural	34.55	200
Industrial	11.25	450
Office	34.55	380
Households	68.7	350
Health services	34.55	200
Agricultural	0.8	5

5. DISCUSSION

The proposed framework and its application to a real case study in Spain shows how risk analyses provide information to gain knowledge about the system, the potential flood events that can happen and their consequences. Hence, risk analyses, as presented in this article, inform decision-makers, however may not capture all aspects of risk and uncertainties that may be important for making effective decisions.

Therefore, in this section, limitations of the proposed framework and implications of flood risk analysis outcomes to local action planning are described, along with recommendations for improved flood risk analysis.

5.1 Limitations

The analysis framework used in this study is relatively straightforward, but it does allow to analyze risk and to assess the impact of different scenarios. It is proposed as a framework for enhancing local flood risk analysis at regional and national scale, potentially transferable to other local applications in Europe.

However, the following remarks are made:

- Type of flooding. In this paper, we analyzed river flooding but integrating multiple hazards would be of high interest in future upgrades (e.g. to analyze the influence of sea water levels in boundary conditions).
- Flood hazard. It is recognized that over-estimations of annual risk between 33% and 100% have been reported in other studies when only three return periods are used (Ward et al., 2011). Therefore, results suggest that results for the case study could benefit from paying more attention to the potential damage caused by high-probability flood events. As shown in Sect. 4.1, high-probability flood event analysis would help to better adjust existing protection levels and would be of interest for future upgrades (e.g. return periods of 5-yr, 10-yr).
- Economic consequence estimation. A generic relative stage damage function is used for the case study, based on methods used for regional planning. In addition, due to the lack of statistical information on building-specific asset values, available rates by land use type have been used in this analysis, although more suitable for macro-scale flood damage evaluations. As shown in Sect.4.4, information on building typology at micro-scale would be of interest for future upgrades.
- Life-loss estimation. Sources of uncertainty include lack of data on detailed building typology (to better estimate area vulnerability), human behaviour, effectiveness of warning systems, among other factors. Sensitivity analyses indicate that societal risk for this case study is dominated by population concentrated in high vulnerable areas and seasonal variability. As shown in Sect. 4.2, societal risk may range from 1,940 affected population/yr (low occupancy) to 2,529 affected population/yr (high occupancy), then requiring good knowledge of population variations during the year.
- Vulnerability. Other factors influence flood damage such as flow velocity, contamination, building materials and quality, etc., but are not considered in this analysis, since there is no available information on detailed building typology nor site-specific vulnerability functions to incorporate the impact of flow velocity or debris flow. In future upgrades, it would be of interest to analyze vulnerability including such factors, as analyzed for other cases in Europe (Quan-Luna et al., 2011; Totschnig and Fuchs, 2013) .

5.2 Recommendations for flood risk analysis

Based on results from this analysis, we recommend that quantitative risk analyses become the basis for developing local flood risk management plans. Specific recommendations include:

- Upgrading hydraulic modeling to a broad set of flood events for hazard mapping, and analyzing not only river flooding but also pluvial or coastal flooding. As shown in Sect. 4.1, flood hazard mapping should be performed for high-probability flood events.
- Improved data gathering on population characteristics and distribution at local scale. As shown in Sect. 4.2, detailed information on population distribution and variability is required to better analyse risk, including daily and seasonal variations.
- Improved land use data gathering at local scale for better analyze life-loss and economic consequences from flooding. As shown in Sect. 4.4, obtaining detailed data on building and asset characteristics would enable economic consequence analysis at micro-scale then improving the definition of asset values and better estimating economic risks.
- Defining standardized relative stage damage functions and reference costs at national scale. As shown in Sect. 4.4, both local and river basin flood risk analysis should consider the same method for economic consequence estimation to allow comparative analysis, to upgrade current and future flood risk plans and to develop cost-benefit analysis for prioritizing flood risk reduction measures.
- Characterizing risk awareness and better analyzing effectiveness of evacuation procedures in case of emergency by incorporating outcomes from social research (as, for example, described in (Escuder-Bueno et al., 2012)) towards a multi-disciplinary paradigm (including technical, policy and social aspects).

Authors acknowledge the fact that micro-scale quantitative flood risk analysis may require advanced know-how and expertise on risk analysis. However, the development and application of methods such the presented work in this paper will help local authorities to guide future analysis. In most cases, resources have already been allocated for conducting flood hazard analysis, then just requiring updating or further upgrading based on aforementioned recommendations and their combination with consequence estimation analysis.

5.3 Local action planning implications

Results from the case study demonstrate its applicability and usefulness to support decision making for local action planning. As described in Sect. 3.10, implementation costs are lower than benefits in terms of economic risk reduction (ACSLS values are negative).

The application of the proposed framework for quantifying local flood risk for the city of Oliva represents a novel analysis in Spain.

The following recommendations were made to local authorities for defining strategies for local action planning, derived from outcomes of conducted flood risk analysis:

- Definition of specific public education campaigns for resident and seasonal population, with emphasis in high vulnerable groups (e.g. the elderly, schools and campsites): As described in Sect.3.6, lower vulnerable rates are assumed for Scenarios 2 and 3. This assumption should be supported by better public education and warning schemes.
- Definition of a procedure to formally reporting flood events, damages and effect of communication and evacuations procedure: required for future updates of hazard and vulnerability analysis. This would enable to validate assumptions concerning the impact on flood consequences (lower area vulnerability and damages) of implementing the local action plan.
- Verification of established communication schemes between regional and local authorities, and with emergency and civil protection services: needed to ensure effectiveness of non-structural measures for flood risk reduction (reduced damages bases on available warning times).
- Identification of potential locations for assembly points and helicopter landing sites have been set based on population clusters, hazard maps, and available evacuation routes: developed risk maps (examples are included in supplementary material) were used to identify potential locations. These sites should be verified and reviewed in future updates.
- Data gathering on additional urban characteristics (e.g. building typology, daily variability of population in industrial and commercial areas, etc.): to upgrade risk analyses and provide improved outcomes for decision making. As shown in Sect. 4.2., societal risk is highly influenced by seasonal variability.
- Impact of future flood risk mitigation measures: As shown in Sect. 3.10, new risk reduction measures might be planned and evaluated in accordance with the ACSLS indicator (e.g. aiming at reducing annual expected affected population). The proposed framework for flood risk analysis will allow updating in future reviews of the local action plan.

Up to now, risk reduction actions were focused on reducing flood hazard and exposure. All the aforementioned recommendations are provided to enhance flood risk management from a broader perspective towards smart flood risk governance (including hazard, exposure and vulnerability analysis, as part of a risk-informed and collaborative decision-making process for local flood risk management).

6. CONCLUSIONS AND THE WAY FORWARD

Quantification of societal and economic flood risk is not required by current legislation in Spain and is relatively novel in local flood risk management as a result of a lack of guidance, standardized methods or tools for local flood risk analysis. Examples can be found in other countries such as in England and Wales (Hall et al., 2003), but are still scarcely applied in Spain.

The main scope of this study was to propose a common framework for quantitative flood risk analysis at local scale and to analyze urban flood risk for the city of Oliva.

Local authorities are currently developing the local action plan against flooding for Oliva, as required by regional legislation. Results from the flood risk analysis described in this paper have informed local authorities to define strategies and to make decisions on upcoming public education campaigns and training activities. In addition, assembly and monitoring points have been identified based on conducted flood risk analyses and identified hazard levels.

Results show that societal and economic risks, while considerably reduced from planned structural measures (a dam is now under construction), are still significant, but they can be further reduced through local action planning.

The results of this study show that improved communications schemes and verified warning systems could significantly decrease flood risk. These results can be used to support risk communication and increase risk awareness.

Sensitivity of existent flood risk to vulnerability estimations has been addressed and future scenarios have been compared with the current situation.

Existent hazard maps have been used for identifying affected areas. A broad range of hydraulic simulations, covering 5 to 7 return periods would be desirable (Ward et al., 2011). In addition, further research to analyse dam failure scenarios and the impact of climate change on system response is recommended.

A more comprehensive risk analysis can be carried out to include other sources of flood hazards such as pluvial or coastal flooding. The combination of multiple flood hazards should be taken into account in future risk analyses. Cities affected by multiple hazards may benefit from the application of structured frameworks for flood risk analysis as the approach presented in this paper (and available examples for other hazard types), towards a comprehensive and multi-hazard flood risk analysis.

Further research on the impact on risk of mitigation measures (including data gathering through workshops or surveys) could inform local actors on the definition of incentives for flood risk mitigation.

The presented approach can be potentially applied by other cities to perform similar flood risk analysis. There is still a long way to go in the development and implementation of local action plans against flooding. The study described in this paper aims to become a reference example for other cities towards improved flood risk management.

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CODE AVAILABILITY

iPresas UrbanSimp is available for download at www.ipresas.com

DATA AVAILABILITY

Flood hazard maps and the local action plan are available to the public at www.oliva.es [In Spanish]. GIS-based local data is not publicly accessible due to its protection level (owned by local authorities).

AUTHOR CONTRIBUTION

J.T. Castillo-Rodríguez and I. Escuder-Bueno proposed the method and tools for flood risk analysis. J.T. Castillo-Rodríguez performed analyses and prepared the manuscript, in close collaboration with all co-authors (discussion of methods and tools, results and conclusions). S. Perales-Momparler has developed the Local Action Plan (PAMRI) for the city of Oliva including outcomes from this study, following a risk-informed approach, with contributions of all co-authors in a joint science-policy effort. J.R. Porta-Sancho has contributed to the acquisition, analysis of data, and interpretation of results, and supervised all activities concerning the development and approval of the Local Action Plan (PAMRI).

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ANNEX 3: A combined risk analysis approach for complex dam-levee systems

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TITLE

A combined risk analysis approach for complex dam-levee systems

ABSTRACT

In many areas of the world, dams and levees are built to reduce the likelihood of flooding. However, if they fail, the result can be catastrophic flooding beyond what would happen if they did not exist. Therefore, understanding the risk reduced by the dam or levee, as well as any risk imposed by these flood defences is of high importance when determining the appropriate risk reduction investment strategy. This paper describes an approach for quantifying and analysing risk for complex dam-levee systems, and its application to a real case study. The basis behind such approach rely on the potential of event tree modelling to analyse risk from multiple combinations of "load-system response-consequence" events, tested by the authors for a real case study. The combined approach shows how the contribution to system risk of each sub-system can be assessed. It also describes how decisions on risk mitigation measures, at the individual asset scale, can and should be informed in terms of how they impact the overall system risk.

KEYWORDS

dams; levees; safety; system risk; risk analysis; flood risk management

1. INTRODUCTION

Based on data from the CRED EM-DAT database, 90 million people were affected by coastal or river flooding worldwide over the 1980–2010 period (Ligtvoet et al., 2014). By 2050, 15% of the global population will live in flood-prone areas.

Dams and levees reduce the likelihood that people and property will get flooded. They also provide other benefits, such as water storage, recreation, and hydropower production. The role of these structural measures on flood risk reduction is unquestionable. However, their potential failure or mission disruption may lead to high consequences. The response of these structures to potential hazards (floods, earthquakes, droughts, etc.) should be analysed and risk to downstream areas should be quantified so that decision-makers can ensure the benefits gained from these structures are appropriate given the risks.

The purpose of the research here presented is to describe a proposed approach for combined dam-levee risk analysis in order to inform flood risk management in complex systems. Addressing and analysing such *complexity* is one of the identified main concerns in the field of critical infrastructure governance (Escuder-Bueno and Halpin, 2016) where complexity refers (Renn, 2008) to the difficulty of identifying and quantifying causal links between multiple potential and specific adverse events. In this field, it is recognised the need to extend modelling in order to cope with the increasing complexity of systems.

1.1. Current challenges on flood risk reduction

Flood risk reduction is a global challenge. As an example, it is considered one of the specific Blueprint objectives at EU water policy level. The EU Directive 2007/60/EC (European Parliament, 2007) on the assessment and management of flood risks requires all EU Member States to approach flood risk management in a three-stage process: (i) preliminary flood risk assessment, (ii) flood hazard maps and flood risk maps, and, (iii) flood risk management plans. These plans should include measures to reduce the probability of flooding and its potential consequences. The EU Floods Directive applies to different flood sources (river flooding, flash floods, coastal floods, storm surges and tsunamis), including potential failure of flood defense infrastructures.

However, few tools are available that can assess complex systems using a multi-hazard integrated approach.

In addition, there is an opportunity for increased coordination in international research, development and innovation (RDI) activities in the area of complex system risk analysis. Many countries are attempting to tackle this challenge, and sharing of lessons learned will help all involved in the effort.

As an example, the United States is a worldwide reference in dam and levee safety management. Current programs in the United States aim to manage risk from a collaborative perspective, focusing on unifying criteria for dam and levee safety risk analysis. In addition, non-structural risk reduction measures, such as emergency preparedness and recovery, are playing a more relevant role than they did in the past when risk reduction was achieved primarily through the construction of flood defense infrastructures.

1.2. The role of dams and levees on flood risk reduction

Based on ICOLD Register of Dams, 48% of the 58,266 large dams worldwide (> 15 m high) provide flood protection. In the U.S., there are more than 9,000 dams and floodplains are lined by up to 161,000 km of levees (U.S. National Committee on Levee Safety, 2009). In Europe, 6,100 large dams (12% of total number of large dams worldwide) create a reservoir capacity of about 410 km^3.

Any dam or levee is constructed to provide protection up to a given flood magnitude (the design of dam spillway capacity or levee height are based on a “design flood”).

In the U.S., that level of protection varies widely (5-yr to 10,000-yr), depending on the regulations in place when the levee was designed. There is no set National standard for flood risk protection, but State or local standards are becoming more common. For example, California requires 200-yr level of protection for urban communities (Department of Water Resources, 2012). If a local community seeks to cost share construction of levees with the Federal government, those levees are formulated to maximize net benefits (flood risk reduced minus cost of construction) rather than to a specific standard.

Other countries also apply criteria for flood risk protection with levels up to 10,000-yr (Kind, 2014).

1.3. Methods and tools for dam and levee safety risk analysis

Different methods and tools for flood risk characterization, analysis and assessment have been developed and applied in the last decades (de Bruijn et al., 2014; DEFRA, 2006; Graham, 1999; Jonkman et al., 2008; Merz et al., 2010; Penning-Rowsell et al., 2005; Zhang et al., 2016). Existing methods in the literature vary on level of detail (e.g., screening, advanced), type of analysis, estimation of risk components (e.g., probability estimation, consequence estimation or both), and treatment of uncertainty (Apel et al., 2004). Consequently, there exist a wide range of available tools and methods for risk-based flood risk analysis.

Potential failure or mission disruption of flood defences may occur from natural hazards or manmade threats. Physical failure of a part of a dam or levee system may have high structural, social, environmental, economic and political consequences.

Particularly, several risk-based methodologies for dam safety analysis can be found (Harrald et al., 2006). Among them, event tree analysis is quite common, and can assess a wide range of potential combinations of plausible events that may lead to failure or mission disruption (Bowles and Chauhan, 2003; Castillo-

Rodríguez et al., 2014; Rosqvist et al., 2013). Event trees can be represented in a compact form through influence diagrams.

The level of detail of a risk analysis will depend on information available and how it is incorporated into the risk model. The risk model may integrate results from a wide range of techniques for dam and levee failure analysis (de Bruijn et al., 2014; Olsson et al., 2003; Vrouwenvelder et al., 2010).

This paper presents an integrated framework for flood risk analysis, which aims to estimate flood risk from dam and levee failure through the use of event tree modeling.

1.4. Towards risk-informed dam and levee safety governance

In this context, the application of risk analysis techniques has emerged as a paradigm shift, enhancing dam safety and flood risk assessment and management.

Regarding dam safety, following the journey initiated by the United States Bureau of Reclamation (USBR) in the nineties, the United States Army Corps of Engineers (USACE) and the Federal Emergency Regulatory Commission (FERC) have implemented risk-based dam safety management processes in the last decades (USACE, 2014). At the European level, France enacted specific regulation in 2008 to develop the process at national level and Spain has recently published technical guidelines to apply risk analysis techniques for dam safety management (SPANCOLD, 2012).

The state-of-the-practice worldwide recognizes the benefits of applying risk analysis as a tool for supporting decision-making on dam safety management.

Concerning levee safety, trends are shifting worldwide from hazard analyses to more complex risk approaches (de Bruijn et al., 2014; Jonkman et al., 2011; Pinter et al., 2016; Voortman et al., 2003) .

As an example, the Levee Safety Program established by the USACE started in 2007 with the creation of the National Committee on Levee Safety (NCLS). In 2009, the NCLS Report to Congress provided recommendations for a National Levee Safety Program (U.S. National Committee on Levee Safety, 2009). These recommendations were focused on promoting “an involved public and reliable levee systems working as part of an integrated approach to protect people and property from floods”. As part of this Program, an inventory and screening-level risk assessment has been conducted for levees that fall within the Federal program. In 2014, the Water Resources Reform and Development Act of 2014 (WRRDA) authorized USACE to stand up the National Levee Safety Program, to include all levees in the Nation, not just those in the Federal program, in consultation with the Federal Emergency Management Agency (FEMA).

The NCLS committee recommended that rather than focusing on a single event, risk from the full range of possible flood events should be considered. In recent years, USACE has performed a screening level risk assessment and resulting risk characterization for more than 2,000 levee segments, based on the Levee Screening Tool (LST) methodology (Margo et al., 2009).The screening process incorporates review of operation and maintenance, field inspections, stage-frequency, structural, geotechnical, and component evaluation, and estimation of potential life loss. This method uses engineering assessment ratings (acceptable, minimally acceptable and unacceptable descriptors for assessing performance indicators) to infer the probability of levee breach. Baseline rates for reference performance modes, likelihood ratios for performance indicators and the method proposed by (Hill et al., 2003) for adjusting individual performance indexes are used. Levee failure is considered for scenarios with breach prior to overtopping and with overtopping. Results of the analysis are used to characterize levees into various categories, from 'Very High Risk' to 'Low Risk', which then informs further investment decisions for the portfolio. This screening levee assessment is the first stage of an on-going transition towards risk-informed levee safety management at national scale in the U.S.

2. PROPOSED METHODOLOGY

This paper describes a combined approach for flood risk analysis including failure of different flood protection defenses (i.e. dams and levees). This integration is conceptually and technically feasible and performed through a generic dam-levee risk model architecture herein proposed.

2.1. Concepts and overall analysis framework

For the purpose of this paper, the following terms are used:

- *Overtopping probability.* It is obtained by analysing all combinations of events that result in water elevations that exceed dam or levee crest levels.
- *Failure probability.* It is obtained as the likelihood of failure occurrence in any given year, by analysing all combinations of events that may lead to failure, including different load conditions and potential failure modes, taking into account potential breach with and without overtopping.
- *Societal risk.* It is obtained by combining flood event probabilities and the potential consequences suffered by the population, generally expressed in terms of affected population or loss of life. Societal risk is commonly represented through FN-curves on a double log scale that depict the relation between life-loss and cumulative annual exceedance probabilities (Jonkman et al., 2011). The area under the FN-curve is equivalent to the expected annualized number of fatalities (EAF).
- *Economic risk.* It is obtained by combining flood event probabilities and the potential economic consequences (Merz et al., 2010), expressed in monetary units. Similarly to societal risk, the area under an FD-curve is equivalent to the expected annualized economic damage (EAD).
- *Total risk.* It is obtained by analysing flooding due to all potential flood events resulting from both failure and non-failure scenarios.

- *Incremental risk.* It is obtained by analysing consequences from failure, over and above any consequences which might have occurred for the same flood event or conditions, had the flood defense not failed (Morales-Torres et al., 2016; Serrano-Lombillo et al., 2011). Incremental risk is generally considered to evaluate dam risk results (ANCOLD, 2003).

The risk analysis procedure proposed in (Castillo-Rodríguez et al., 2014) is considered, summarized in the following steps:

- Phase I: definition of the scope and aim of the study
- Phase II: review of available data
- Phase III: definition of the current situation
- Phase IV: risk model architecture
- Phase V: input data
- Phase VI: risk calculation
- Phase VII: risk representation
- Phase VIII: sensitivity and uncertainty analyses
- Phase IX: risk evaluation
- Phase X: risk reduction measures
- Phase XI: risk management and governance

The proposed approach is based on the aforementioned steps but not limited to their application. In this paper, a combined risk model architecture for complex dam-levee systems is presented to be applied in Phase IV.

2.2 Proposed risk model architecture for complex dam-levee systems

A generic influence diagram for risk analysis of complex dam-levee systems is presented in this paper and shown in Fig.1. The proposed risk model architecture provides an innovative model for analysing risk from complex dam-levee systems in an integrative and quantitative risk model, not yet considered in practice.

There are three general categories of input data for the risk model:

- *Loads.* These nodes include information from hydrological studies, water pool levels at reservoirs, annual exceedance probabilities of water elevations, reliability of water control structures (e.g. outlet works), flood routing studies, etc.
- *System response.* These nodes include information from system response analysis (including failure mode identification, breach development, peak discharges for failure and non-failure scenarios), structural models, hydraulic models (e.g. wave arrival times, flood depths, etc. at flooded areas), etc.
- *Consequences.* These nodes include information from life-loss estimation, economic consequence estimations (including rebuilding costs of flood defence infrastructures), and other potential consequences in quantitative terms.

It is assumed that the system is composed by a dam (or system of dams) located upstream an area protected by one or more levee structures.

Information required (numbers denote node location in Fig.1) for the risk model may include, but it is not limited to:

1) Rainfall-runoff transfer information based on hydrological studies, rainfall-runoff methods, etc. to characterize inflow floods at reservoirs or peak discharge in river courses.
2) Historical data or simulations of water pool levels at reservoir.
3) Reliability analysis of outlet works, gates, spillways, etc. that control water levels at river courses or reservoirs. Estimations may be based on historical data, fault tree analysis or expert judgement.
4) Flood routing results from inflow hydrographs, previous water levels and reliability of water control structures. Loading scenarios are characterized by maximum water pool levels.
5) Estimation of failure probabilities based on failure mode identification, numerical modelling, Monte Carlo simulations, fault tree analysis, expert judgement, etc.
6) Outflow discharges and hydrographs, depending on maximum water pool levels and failure modes (e.g. type of breach, breach development, etc.).
7) Results from flood routing analyses based on outflow hydrographs.
8) Flood characteristics in downstream areas (flood depth, velocity, rise-rate, wave arrival times, flooded areas, etc.), obtained from hydraulic models.
9) Flood characteristics along the river course obtained from dam-breach models.
10) Estimated potential fatalities and economic damages at the study area.
11) Flood characteristics at the study site from hydraulic modelling of levee failure scenarios.
12) Estimated potential fatalities and economic damages at the study area, including reconstructions costs.

Common cause adjustment is proposed for system response analysis when failure modes are not mutually exclusive (Hill et al., 2003; SPANCOLD, 2012). Conditional probabilities for identified failure modes that are not mutually exclusive can be adjusted for common cause occurrence by using the uni-modal bounds theorem. In Sect.3, results for the case study from using different bounds are included.

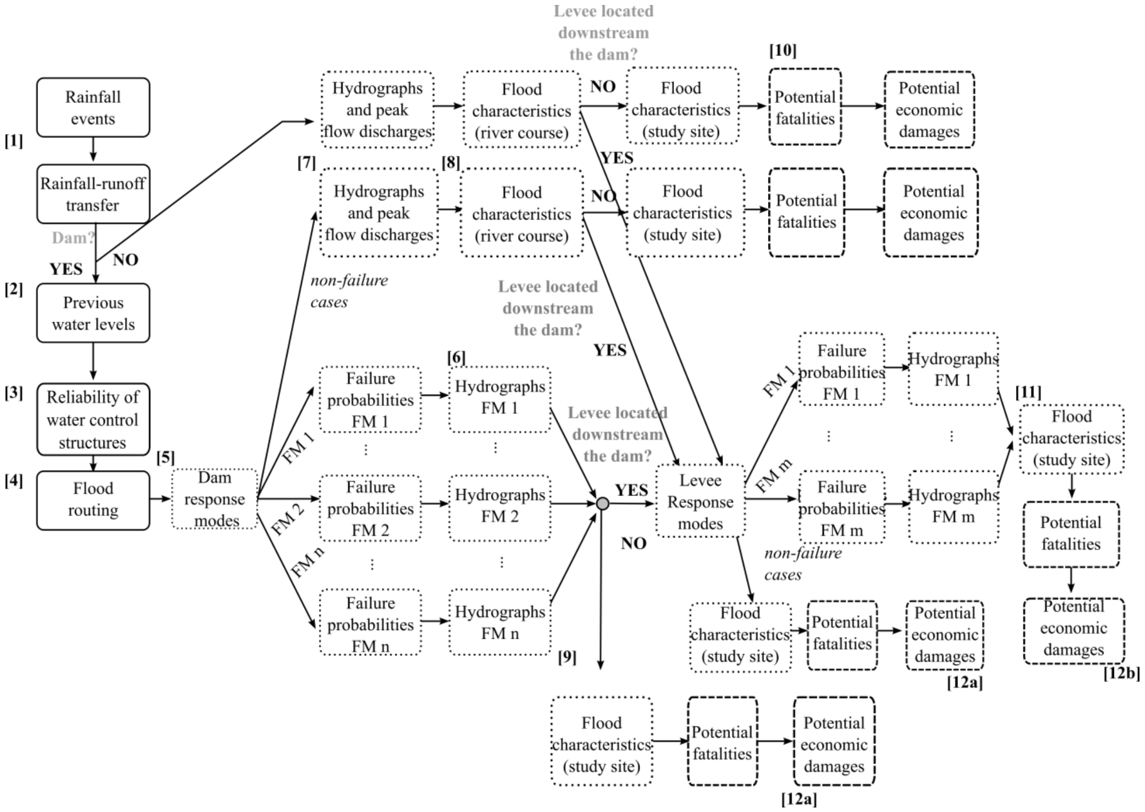

Figure 1. Generic combined risk model scheme. Nodes outlined with solid, dotted and dashed lines refer to loads, system response and consequences, respectively.

2.3 Consistency and utility of the outcomes from the combined risk analysis

The use of event tree modelling has proven to be a robust and consistent method for risk calculation (Castillo-Rodríguez et al., 2014; Morales-Torres et al., 2016). The proposed method for combined dam-levee risk modelling can be used to estimate risk at system scale, incorporating loads, system response and consequences from scenarios that take into account both types of flood defense infrastructures.

Results from the combined analysis can be used to inform decisions on how to allocate risk reduction measures from a system-scale perspective rather than asset-specific.

3. CASE STUDY ANALYSIS

A case study, representing a real system in U.S., was analysed following the proposed method and risk model architecture in Sect.2.

The system is composed by a 3-mile long earthen flood control dam and levees located in downstream river courses. The dam protects a population at risk of approximately 1.25 million people since areas both up- and downstream are highly urbanized. Two river courses (named A and B) are regulated by the dam with control structures on each river. The dam is normally dry with low water levels at the reservoir.

The primary concerns in this system were internal erosion during the normal, unusual, and extreme hydrologic loading conditions; performance of the spillway and outlet works under significant seismic loadings (the dam is located in a seismically active area); and overtopping during an extreme flood event. Therefore, a dam risk analysis was conducted in 2011 (USACE, 2011). However, a risk analysis from a combined perspective including both dam and levee response is still required.

The analysis described in this paper has been performed to provide answers to the need for assessing existing risk in a complex system composed by multiple structures. Previous studies have focused on single structures (dam risk analyses or levee performance assessments) but not providing risk outcomes from a comprehensive approach. Because of its high potential consequences in case of failure, this case study analysis aims at assisting dam and levee owners to assess the current situation and develop future risk-informed flood management strategies.

3.1 Phase I: definition of the scope and aim of the study

The dam includes two gated outlet structures (named A and B, with discharge into river courses A and B, respectively), providing water storage and flood control. Both courses are lined by levee structures, divided into 3 and 5 levee segments, respectively. A simplified scheme of the dam-levee system is depicted in Figure 2. Results from this case study will contribute to the discussion on how to assess risk in complex systems and how risk outcomes may support decision-making on flood risk management.

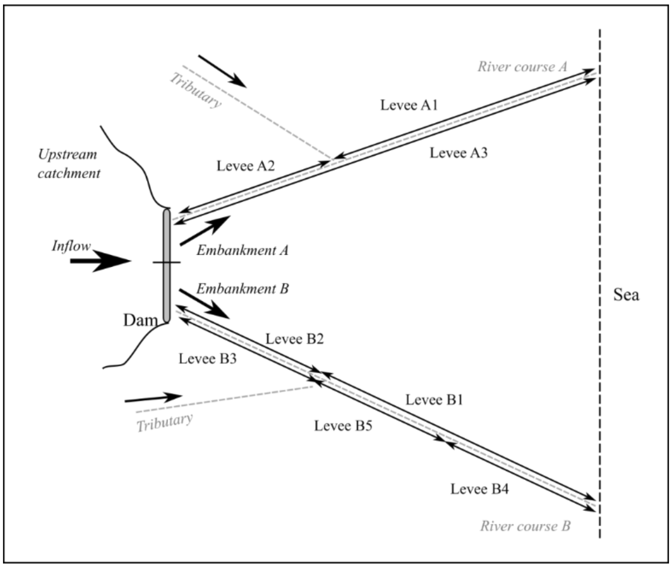

Figure 2. Simplified scheme representing analysed dam-levee system. (B1 and B2 are segmented because levee breach along one segment would not lead to flooding in the other).

3.2 Phase II: review of available data

Two main information sources are available: a dam risk analysis conducted in 2011 (USACE, 2011), including dam failure probabilities for six identified potential failure modes for hydrologic scenario and three in case of seismic scenario. In addition results from applying the LST method (Margo et al., 2009) to all downstream levee segments are also available.

3.3 Phase III: definition of the current situation

The baseline scenario refers to the current situation of the system, including current dam operating rules during flood events.

3.4 Phase IV: risk model architecture

A combined dam-levee risk model is performed in this study. In addition, individual risk models for the dam and each levee segment were performed to compute risk for all sub-systems.

The risk model architecture depicted in Fig. 3(a) is used for computing incremental dam risk, including hydrologic and seismic scenarios (abbreviations in are provided in Table 1 and Table 3). Nodes in Fig. 3(a) include input data on loads, system response and consequences to estimate risk from hydrologic and seismic scenarios. The first node, *Scenario*, is used for defining analysed loading scenarios (hydrologic and seismic). The second node, *Day/night*, is used for defining probabilities for fractioning time exposure scenarios to incorporate daily variation on consequences. The third node, *Flood*, is used to divide the event tree into several branches, obtaining annual exceedance probability (AEP) as a function of the return period of the flood event. Logarithmic interpolation was performed to obtain intermediate AEP values. Each AEP value is then related to a resulting water level at the reservoir, in node *WPL*, and peak outflow discharges, in node *Qout*, in case of failure and non-failure. Node *FM* includes six failure branches for the hydrologic scenario and all downstream nodes include consequence data for the breach and non-breach scenarios. Linear interpolation was performed to obtain intermediate consequences. The economic consequences were assumed to be the same for both day and night exposures. Failure modes with similar breach characteristics and hence consequences were grouped (e.g. FM1 and FM2). Non-failure consequences were a function of peak outflow, while failure consequences were a function of peak pool elevation.

For the seismic scenario, annual exceedance probabilities are obtained as a function of the peak ground acceleration (PGA) in node *PGA* and concomitant water levels at the reservoir in node *WPL seismic*.

Similarly, the risk model architecture shown in Fig. 3(b) is used for computing total risk from both dam failure and non-failure cases, including hydrologic and seismic scenarios. Node names used in both dam risk models are defined in Table 3. In this influence diagram, a non-failure branch is included to compute total risk.

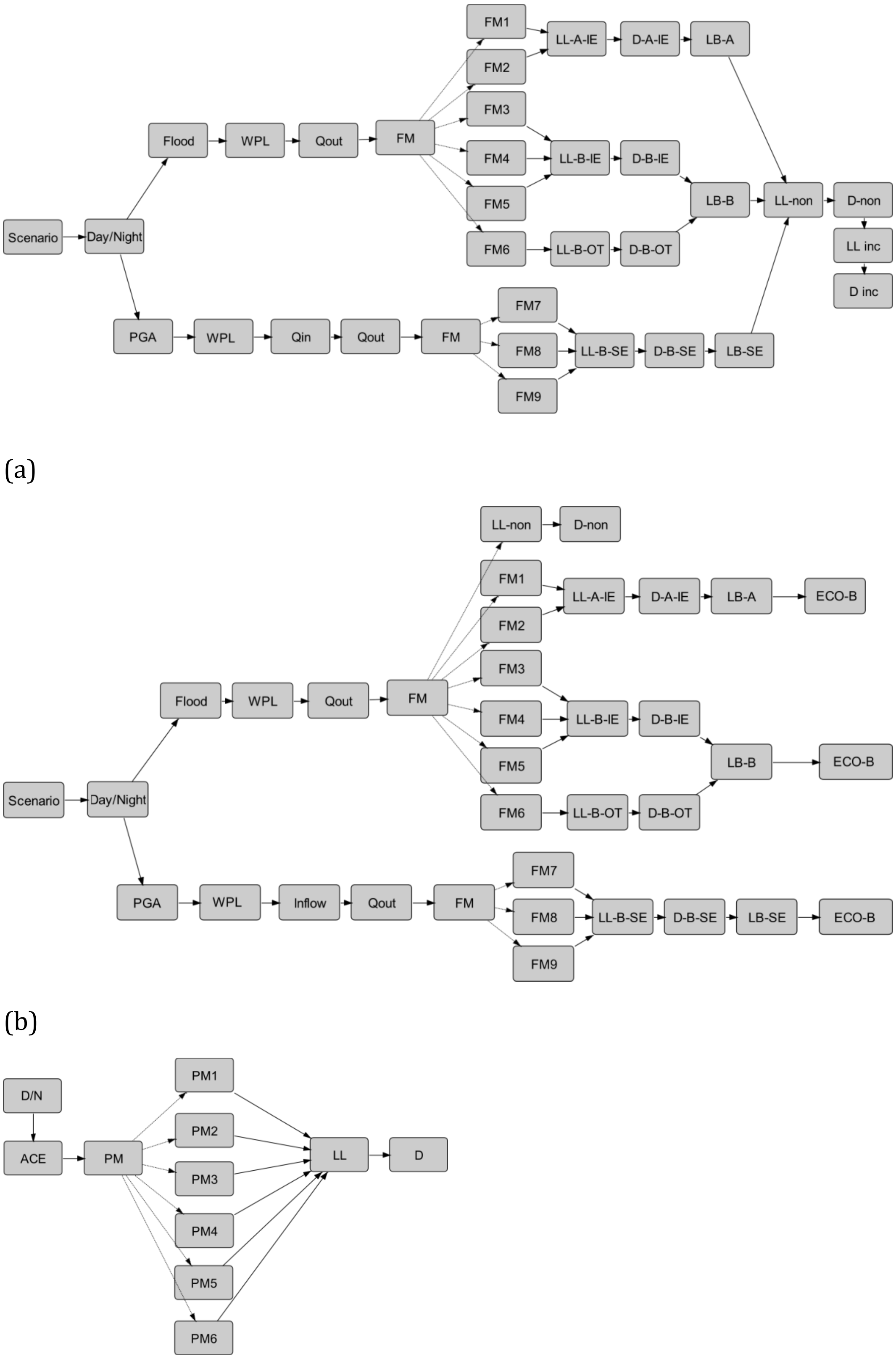

Figure 3. Risk model architecture schemes for the case study: (a) dam risk model (incremental risk); (b) dam risk model (total risk); (c) levee risk model

Table 1. Abbreviations used in risk model architectures for the case study.

Abbreviation	Description
A	Embankment A
ACE	Annual chance of exceedance
B	Embankment B
D	Damage
Day/Night	Moment of the day
Flood	Flood event
ECO	Economic consequences
FM	Failure mode
IE	Internal erosion
INC	Incremental
LB	Loss of benefit
LL	Loss of life
non	Non-failure
OT	Overtopping
PGA	Peak ground acceleration
PM	Levee performance mode
Qin	Inflow discharge
Qout	Outflow discharge
Scenario	Hydrologic or seismic scenario
WL	Water level at levee segment
WPL	Water level at reservoir

Table 2. System response combinations.

Dam	Levee subsystem A	Levee subsystem B	Consequences
Failure from seismic scenario	No	No	Life-loss and economic damages from flooding due to dam failure (levee failures do not provide appreciable additional consequences).
Failure from hydrologic scenario	No	No	Life-loss and economic damages from flooding due to dam failure (levee failures do not provide appreciable additional consequences).
No failure	Yes	No	Life-loss and economic damages from levee failure in protected area A and from flooding due to dam releases in B.
	Yes	Yes	Life-loss and economic damages from levee failure in protected areas A and B.
	No	Yes	Life-loss and economic damages from levee failure in protected area B and from flooding due to dam releases in A.
	No	No	Life-loss and economic damages in areas A and B from dam releases.

Table 3. Description of nodes used in dam risk models

Node	Description
Scenario	This node is used to allow risk calculations for two analysed scenarios: hydrologic and seismic (diverts the event tree in two branches: one per scenario).
Day/night	Probabilities of being during the day or at night when the initiating event (flood or earthquake) occurs.
Flood	Annual exceedance probabilities of flood events.
WPL	Probabilities of being at different water levels at the reservoir when the flood arrives, based on dam operation.
Qout	Outflow rates through outlet works and spillways based on flood routing.
FM	Node for conducting common cause adjustment for dam failure computation.
FM1-FM9	Failure probabilities per dam failure modes based on water elevation levels at the reservoir.
LL-X-YY	Life-loss estimates in case of failure in river course X (A or B) and failure mode YY (denoted as OT for overtopping failure mechanisms, IE for internal erosion and SE for seepage).
D-X-YY	Economic damage estimates in case of failure in river course X (A or B) and failure mode YY (denoted as OT for overtopping failure mechanisms, IE for internal erosion and SE for seismic loading).
LB-X-YY	Loss of benefit estimates in case of failure in river course X (A or B) and failure mode YY (denoted as OT for overtopping failure mechanisms, IE for internal erosion and SE for seismic loading).
LL-non, D-non	Life-loss and economic damage estimates for non-failure cases (flood routing).
LL-inc, D-inc	Incremental life-loss and economic damage estimates based on failure and non-failure cases.
D ECO-LB	Economic damages and loss of benefit to compute both categories of economic costs from dam failure.
PGA	Probabilities for different seismic events based on peak ground acceleration rates.
Qin	Inflow rates into the reservoir, concomitant with the analysed seismic event
WPL seismic	Water levels at the reservoir, concomitant with the analysed seismic event

The risk model architecture shown in Fig. 3(c) is used for computing flood risk from levee breach prior to overtopping and flooding due to overtopping (breach and non-breach cases) for each levee segment. Node names are defined in Table 4. The first node, D/, is used for defining probabilities for fractioning time exposure scenarios to incorporate daily variation on consequences. The second node, ACE, is used to relate annual exceedance probabilities (AEP) to each resulting water elevation at the levee segment. Node PM includes six failure branches to include the six potential performance modes. Nodes LL and D incorporate consequences in terms of life-loss and economic costs.

Table 4. Description of nodes for levee risk models.

Node	Description
Day/night	Probabilities of being during the day or at night when the flood occurs.
ACE	Annual exceedance probabilities of flood events.
PM	Node for conducting common cause adjustment for levee performance modes.
PM1-PM6	Failure probabilities per levee performance mode based on water elevation levels.
LL	Life-loss estimates in case of failure for different water elevation levels.
D	Economic damage estimates in case of failure for different water elevation levels.

Based on the generic risk model proposed in Sect.2 and individual risk models depicted in Fig.3, the combined risk model architecture used for this case study was defined and it is shown in Fig. 4. This model is an ad-hoc influence diagram developed for the case study, connecting both dam and levee individual risk models, and differs from the generic structure due to the following specific conditions:

- Levee segments are divided into two subsystems, that is, distributed along two different river courses. Two distributions of outflow discharges for dam scenarios from flood routing are used.
- It is assumed that for each levee subsystem, multiple levee breaches do not occur.
- Common cause adjustment is applied over all failure modes for each levee subsystem.

3.5 Phase V: input data

3.5.1. Loads

Estimates of the probabilities of occurrence of analysed loading conditions are included into the risk model.

Dam. Two loading scenarios are considered for the dam (hydrologic and seismic scenarios). Inflow floods include events with return periods from 1-yr to 17,522-yr. This range is divided into 20 branches in node Floods (Fig.3) of the dam risk model. Resulting water levels at the reservoir given the load event are included in node WPL (Fig.3).

Levee. The loading function is represented by two discrete flood loading conditions that are based on the likelihood of the levee being loaded at any flood level between the toe and top. Annual chance exceedance (ACE) values for water surface elevations at the toe and top of all levees are used (ranging from 0.001 to 0.5). The range of analysed loading conditions at levees segments is also divided into 20 event tree branches in node ACE (Figs. 3 and 4).

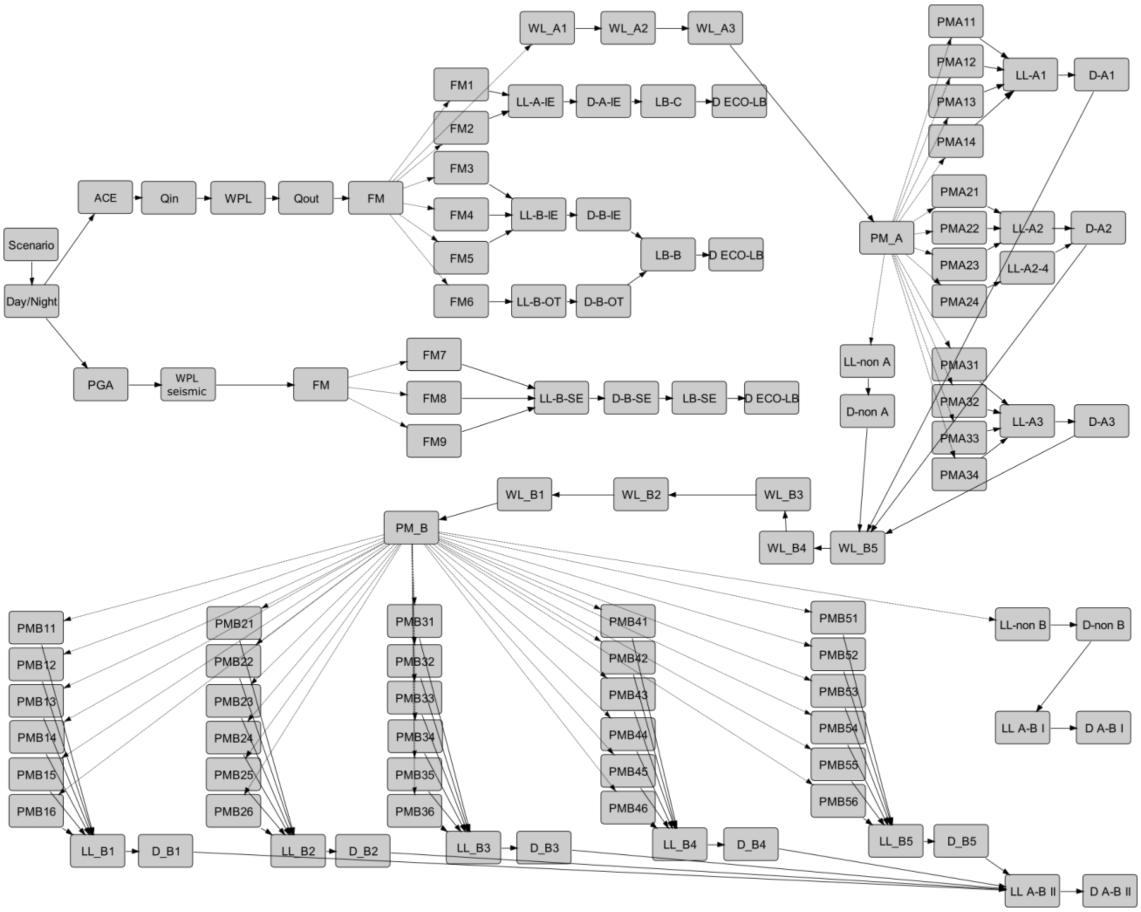

Figure 4. Combined dam-levee system risk model.

3.5.2. System response

Dam response. A total of 32 potential dam failure modes were identified in 2011 consisting of both hydrologic (flood) and seismic loading conditions. Among them, 9 failure modes are considered to be incorporated into the dam risk model. Results from the failure mode identification and elicitation process are included into the risk model, relating water level at the reservoir (loading event) and dam failure probabilities.

In addition, both the regulated and breach outflow hydrographs are included, results from a hydraulic model using HEC-RAS are used. As an example, Figure 5 shows outflow rates in case of dam failure. Figures 6 and 7 show an extract of conditional failure probabilities for considered dam failure modes (hydrologic and seismic scenarios).

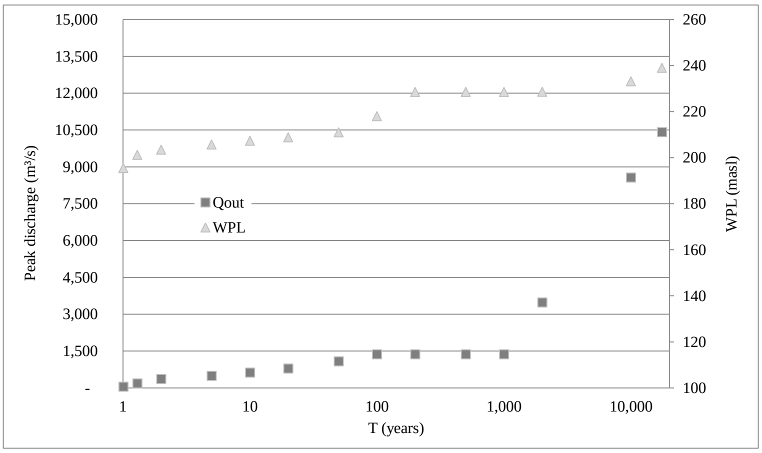

Figure 5. Outflow peak discharges (Q_{out}) in case of dam failure and water levels at reservoir (WPL) per return period of inflow flood event.

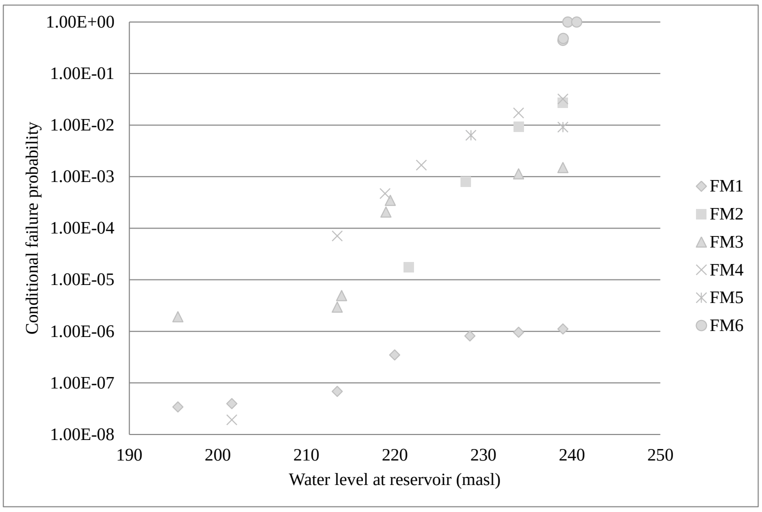

Figure 6. Conditional failure probabilities per dam failure mode: hydrologic scenario.

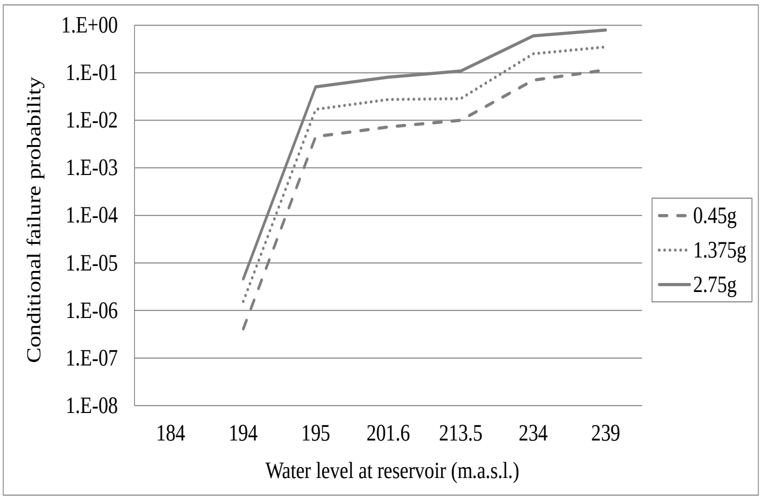

Figure 7. Extract of dam fragility curves for seismic scenario (peak ground acceleration 0.45g, 1.375g and 2.75g).

Figure 6 depicts input data probabilities per dam failure mode (FM) for the hydrologic scenario: scour in a poorly compacted layer in the embankment adjacent to a gallery at B-side (FM1), scour of the embankment at A-side (FM2), backward erosion piping in foundation of central dam body (FM3), backward erosion piping in foundation at A-side (FM4), dam overtopping (FM5), and erosion into the collapsed toe drain at the B-side embankment (FM6). Three failure modes are considered for the seismic scenario (Fig.3): failure of outlet works walls during an earthquake (FM7), seismic deformation of embankment leading to overtopping (FM8) and internal erosion in embankment due to transverse cracking due to earthquake (FM9).

Levee response. Similarly, failure probabilities for loads up to top of levee were derived from the LST assessment (Margo et al., 2009) for the 6 potential performance modes (PMs): embankment and foundation seepage and piping (PM1), embankment stability (PM2), embankment erosion (PM3), floodwall underseepage and piping (PM4), floodwall stability (PM5), and closure systems (PM6). For overtopping events, a failure probability equal to 1 is assumed for water elevations 0.5m [1.64 ft] above top of levee (instead of applying p_f=1 at top). It is considered that failure will occur for elevations above that level. Consequently, the curve shown in Figure 8 is applied for estimating levee performance probabilities based on loading conditions. In this figure, the distribution used for failure probability estimations in nodes FM is shown based on water elevations at toe (EL_{TOE}) and top of levee (EL_{TOP}). As an example, levee failure probabilities for water elevations at levee crest are shown in Figure 9 for levee segments A1, A2 and A3, including results for performance modes from PM1 to PM4.

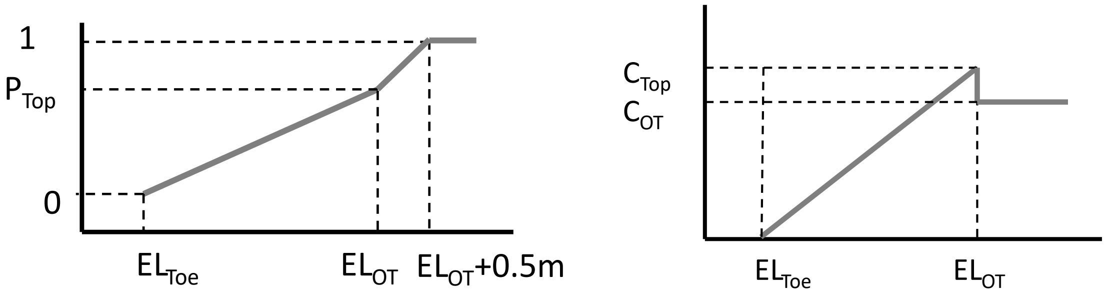

Figure 8. Failure probability (left) and consequence distribution (right) for levee segments based on water elevations (EL).

3.5.3. Consequences

Estimation of consequences, including life loss and economic impacts for both failure and non-failure scenarios, is critical to a successful risk assessment. Consequences are available by an estimate of potential fatalities and economic damages for the following scenarios:

a) dam failure with no levee breaches;
b) dam non-failure with levee breach prior to overtopping of levee;
c) dam non-failure with levee breach due to an overtopping flood event, and,

d) dam non-failure with no levee breaches.

HEC-RAS and FLO-2D models were developed for the study in 2011 to simulate dam failure and non-failure scenarios over a range of possible hydrologic loading conditions. The HEC-LifeSim method (Bowles and Aboelata, 2005) was used for life-loss estimations and results have been incorporated into the risk model. The HEC-LifeSim method uses arrival times and hydraulic conditions in downstream areas to estimate fatality rates based on flood depths, velocities, and combined depth-velocity ratios. For levees, life-loss estimations were conducted based on the LST method, applying fatality rates proposed by Jonkman et al. (Jonkman et al., 2008). The curve shown in Figure 8 is applied for estimating life-loss based on levee response conditions. The distribution is modified for each levee segment based on outputs from the LST method for water elevations at toe (EL_{TOE}) and top of levee (EL_{TOP}).

Economic impacts due to dam failure were evaluated in 2011, including physical damage to structures, contents, and vehicles; the value of project benefits that would be foregone; and estimates to repair the dam. Other damages such as those to crops and infrastructure were not included. Damage to structures, contents, and vehicles were estimated with HEC-FIA modeling. Damage is based on peak flood depths for the evaluated flood events and estimated using HAZUS depth-damage curves for structures, contents, and vehicles (Scawthorn et al., 2006). In addition, the total project flood damage reduction, recreation and water supply benefits lost due to dam failure are considered. However, indirect costs were not considered. Results were incorporated into the risk model. The method used for estimating economic consequences for levee failure is also based on the use of depth-damage curves and can be found in the description of the LST (Margo et al., 2009).

In the dam risk analysis, it was assumed that levees located downstream do not fail when considering dam performance. Hydraulic simulations of dam response scenarios assumed the levees were in place with no potential for breach.

Assuming no levee breaches, flood consequences for dam non-failure scenarios range from 0 to 10 fatalities and 18,026 $M in damages (peak discharge up to 7,800 m^3/s). For dam failure scenarios, flood consequences reach 214 fatalities and 42,076 $M in damages (peak discharge up to 10,410 m^3/s). For levee failure scenarios, the maximum values belong to levee segment B2 (20 m high), up to 300 fatalities and 13,383 $M in damages.

As an example, Figures 10 and 11 show an extract of input data on economic and life-loss consequences due to dam failure (internal erosion failure modes) and failure of levee segment A2, respectively.

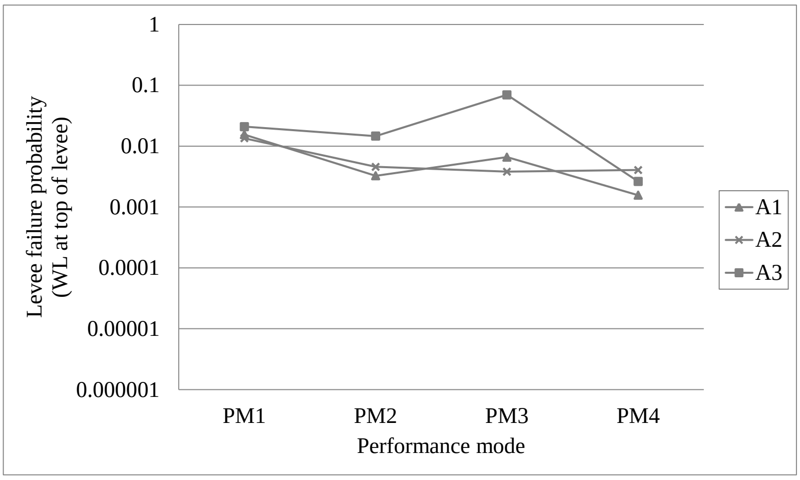

Figure 9. Levee failure probabilities per performance mode for water elevation at top of levee crest (levee segments A1, A2 and A3).

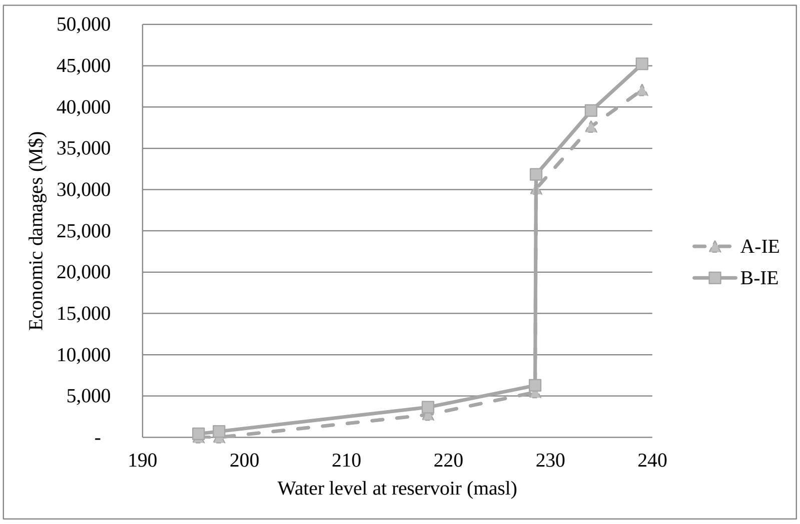

Figure 10. Economic consequences from dam failure (internal erosion failure modes: embankments A and B).

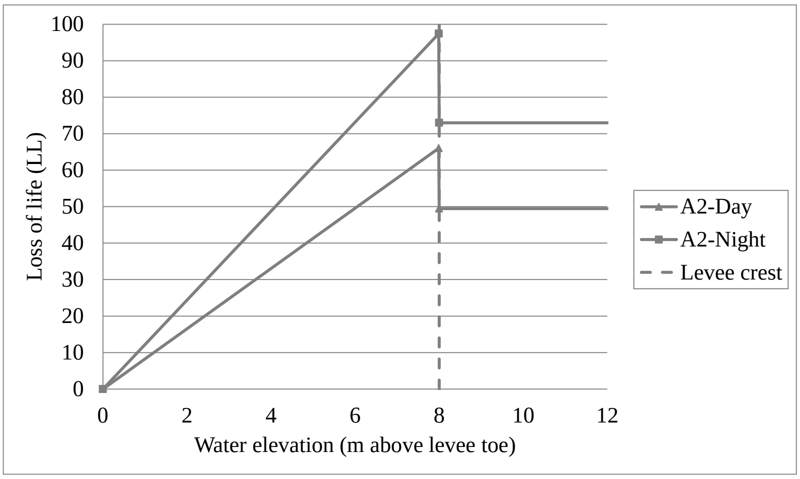

Figure 11. Life-loss consequences from levee failure for levee segment A2.

3.6 Phase VI: risk calculation

The software tool iPresas Calc, developed by iPresas Risk Analysis, is used to perform risk calculations (iPresas Risk Analysis, 2014). Separate event trees were considered to compute incremental and total risk for the dam, risk for each levee segment and a combined dam-levee model to obtain the total flood risk estimate. A common cause adjustment was applied to all non-mutually exclusive dam failure modes and levee performance modes.

Results from the separate dam risk model (not including risk associated with potential breach of levees) are shown in Table 5. The estimated incremental societal risk is 0.01 lives per year and dam failure probability is about $1.34 \cdot 10^{-4}$.

Results from levee models are included in Table 6 and are shown in Figure 12. Incremental risk results range from 0.001 up to 4.5 lives per year. Annual levee failure probabilities are generally greater than 10^{-4} and annualized societal incremental risk above 0.01 lives per year.

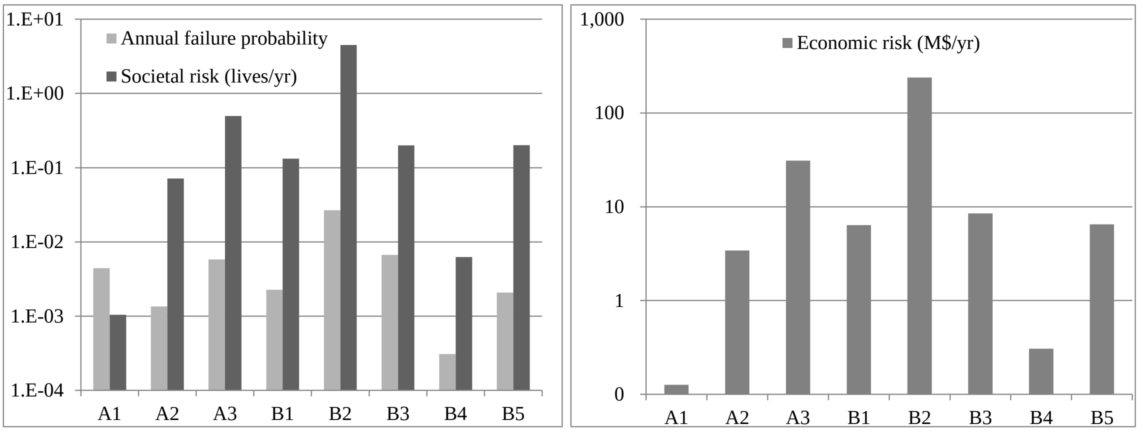

Figure 12. Failure probability, societal and economic risk per levee segment based on risk outcomes from separate risk models.

3.7 Phase VII: risk representation

Figure 13 shows the fN pairs for the dam and each levee segment. Results show that levee segments in subsystem B present, in general, higher values.

Finally, results from the combined model are included in Table 7. Estimated ssocietal risk is approx. 5.5 lives per year and economic risk is about $M 292 per year.

Figure 14 depicts FN-curves for both dam risk model (total risk terms) and the combined dam-levee model.

Table 5. Results from dam risk model (incremental *vs* total risks).

Risk model	Dam (incremental)			Dam (total)		
Scenario	Hydrologic	Seismic	Global	Hydrologic	Seismic	Global
Failure probability (1/yr)	1.34E-04	1.55E-06	1.35E-04	-	-	-
Economic risk ($/yr)	1,045,961	2,368	1,048,328	17,518,841	4,922	17,523,763
Societal risk (fatalities/yr)	0.0104	0.000012	0.0104	0.0131	0.000012	0.0131

Table 6. Results from separate levee risk models.

Levee Segment	Failure probability	Economic risk ($/yr)	Societal risk (lives/yr)
A1	4.44E-03	126,500	1.05E-03
A2	1.35E-03	3,425,148	7.17E-02
A3	5.81E-03	31,032,335	4.96E-01
B1	2.26E-03	6,392,352	1.32E-01
B2	2.68E-02	238,628,175	4.50E+00
B3	6.69E-03	8,490,563	2.00E-01
B4	3.09E-04	307,445	6.27E-03
B5	2.08E-03	6,505,021	2.02E-01

Table 7. Results from combined dam-levee model.

Scenario	Hydrologic	Seismic	Global
Economic risk ($/yr)	291,628,124	4,922	291,628,124
Societal risk (fatalities/yr)	5.55	1.24E-05	5.55

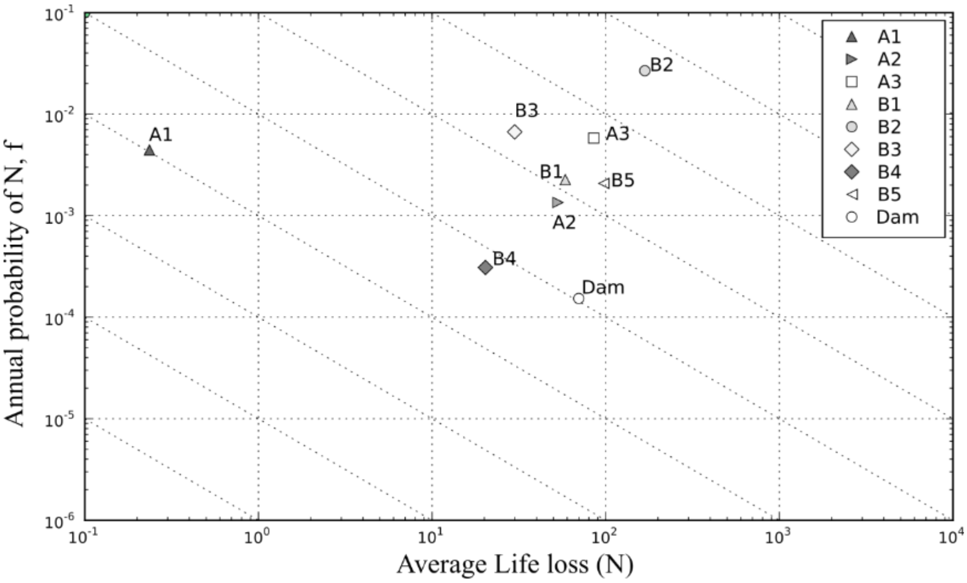

Figure 13. fN graphs from separate risk models.

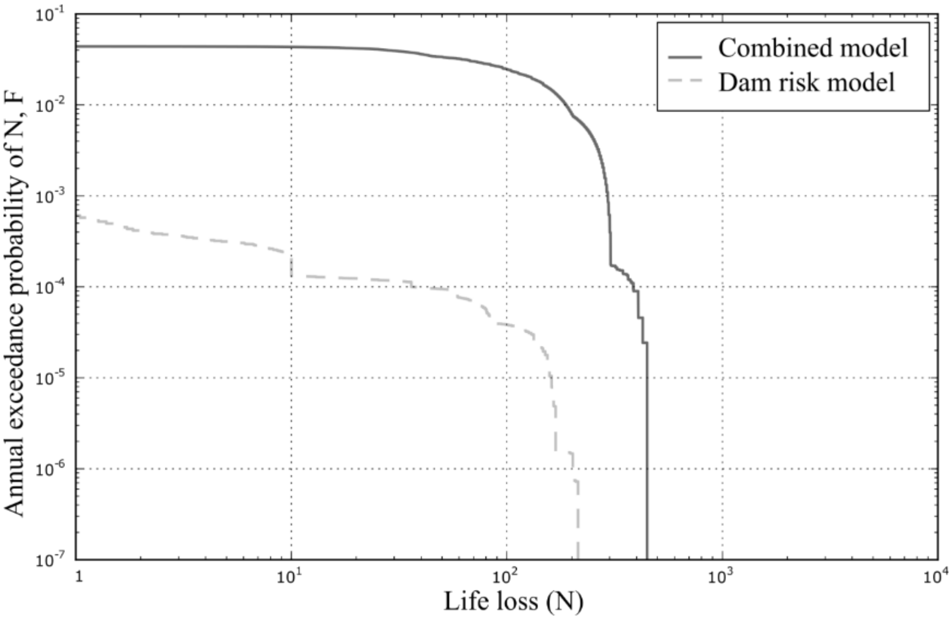

Figure 14. FN curves from dam risk model vs. combined dam-levee risk model.

3.8 Phase VIII: sensitivity analyses

Different bounds for common cause adjustment (CCA) were applied to evaluate the impact on risk results of selected options. Figure 15 shows FN-curves for two situations applying upper (base case) and lower bounds. Societal risk for the case study applying the lower bound for CCA is estimated to be 3.42 lives per year (about 61% of societal risk obtained from applying upper bounds for CCA, as proposed in the LST). If no adjustment for common cause of dam and levee failure is made, the estimate of societal risk increases to 5.7 lives per year.

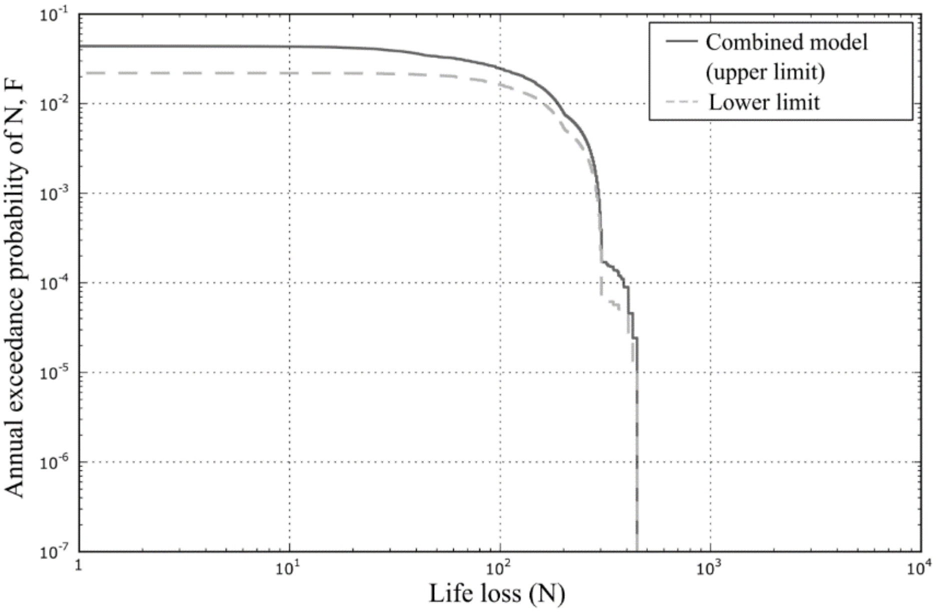

Figure 15. FN curves from combined model (upper and lower limit from CCA).

4. DISCUSSION

Results from combined risk analysis of complex systems can inform decisions on selecting actions for flood risk reduction, based on the contribution of each element of the system.

Focusing only on risk analysis of the dam (Table 5), results show both the incremental societal risk and probability of failure are above tolerability recommendations for dams used by many agencies (Munger et al., 2009). As such, measures to reduce incremental risk associated with the dam should be investigated. Typically, remediation measures should include a wide range of options, including those that reduce frequency and magnitude of loading, those that reduce probability of breach given loads, and those that reduce consequence in the case of flooding.

In total risk terms, societal risk is estimated at about 0.013 lives per year. Based on those estimates, 77% of total risk is due to incremental risk. Therefore, decreasing incremental risk by lower the probability of failure or associated consequences would also have a significant impact on total risks.

For the presented case study, the potential life loss is relatively high. Much of this is due to the fact that people are located directly downstream from the dam, meaning they do not have very much time to receive warning and evacuate if something goes wrong at the dam. Therefore, one potential risk reduction alternative could be installation of warning sirens directly downstream from the dam. Additional analysis with those sirens in place shows that life loss could be reduced by approximately 30% if the dam was to breach (due to larger warning times). While installation of sirens would not reduce the probability of failure (therefore not addressing that portion of the tolerability criteria), they will reduce the overall incremental and total risk for a relatively small financial investment.

Results from the levee analysis (no dam failure) show the risk is orders of magnitude higher than the risk associated with dam failure. This is not surprising, at least in the U.S., as the typical large dam has a spillway that allows for it to safely pass very rare hydrologic events (1 in 10,000 chance per year or less frequent) without breaching, while the typical levee is designed to pass much lower frequency events, and is not designed to withstand overtopping.

Results for the case study show the overall risk for the community downstream of the dam is mainly driven by levee segment B2. Therefore, investing in remediation activities at this segment would impact on societal risk from a system perspective. For example, reducing the probability of failure for the driving failure modes (embankment seepage and floodwall stability) by an order of magnitude could reduce risk from an estimated 5.55 lives and $M 292 per year to 1.94 lives and $M 100 per year. However, additional considerations should be taken into account when analysing efficiency of risk reduction measures, such as budget limitations, cost- benefit analysis for both economic and life safety perspectives.

5. CONCLUSIONS

This paper presents an approach for analysing risk in complex systems by combining information from multiple structures. The basis behind such approach rely on the potential of event tree modelling to analyse risk from multiple combinations of load-system response-consequence event, tested by the authors for a real case study.

Several points are herein summarized.

- The procedure described in this paper, based on event tree modeling and risk analysis techniques, illustrates quantitative risk information can be combined to provide risk estimations for all elements within the system.
- For this study, the aim was to provide a framework for combined risk modeling that may benefit from advances in dam and levee safety risk characterization. This risk modeling approach may evolve in line with further research on input data estimations for dam and levee safety risk analysis.
- In practice, each dam or levee operator may choose different methods for input data estimations (e.g. loading conditions, life-loss estimations, etc.). The risk model architecture here presented can be used to estimate risk by integrating information from different sources of information in nature and level of detail. However, it is noted that the analyses of complex dam-levee systems requires the use of homogenous methods for characterizing inputs from both dam and levees. Hence, dam and safety risk analyses would benefit from standardization concerning loads, system response and consequence estimation methods.
- In this paper, the presented approach has been applied to a real case study (location and details are kept confidential) to analyse risk at system scale.
- Regarding levee performance, probabilities for levee breach prior to overtopping based on the LST were used, adapted to incorporate non-failure scenarios for overtopping events up to +0.5 m from top of levee. Other generic levee failure probability functions are available (Pinter et al., 2016) and could be used, but site-specific conditions were considered during levee screening assessments to evaluate performance at each levee segment thus obtaining performance rates for this particular example. In addition, the adopted levee failure probability distribution function considers +0.5m as a reference level for all segments. It is recognised that this overtopping height could be adapted based on levee height in further studies.
- As shown in the case study, correlation among failure modes might condition results depending on the adopted hypothesis for CCA. Further research will be focused on analysing the impact of system interdependencies on risk outcomes. In addition, it is assumed that multiple levee breaches do not occur within the same subsystem. Recent studies have focused on providing new methods for analysing multi-component systems and the impact of correlation between components on overall risk

(Roscoe et al., 2015). Further research will focus on how to couple advanced reliability techniques into event tree modeling for combined dam-levee systems.

From a general perspective on how this approach will impact on safety management of flood defense infrastructures, some remarks are here included.

- The proposed approach can be adapted to other dam and levee systems. The presented risk model architecture is generic and can be adapted to site-specific characteristics as shown in its application to a case study.
- The procedure described in this paper allows obtaining risk outcomes for complex systems that are valuable to a wide variety of actors (e.g. local, river basin and national authorities, water boards and emergency agencies). Within this context, the level of detail of the analysis should match the needs of decision makers. Therefore, the presented approach allows to estimate risk for systems including several infrastructures. Having an overall picture of quantitative flood risk for the whole system, able to capture the contribution of each element, will help decision-makers to better understand risks and define actions for risk reduction.

Finally, a major challenge to be addressed when evaluating risk in complex systems is the application of tolerability recommendations at system scale. Although recent efforts have been allocated on defining tolerability guidelines for levee safety (in line with current dam safety practices), there is still a need for defining criteria to evaluate risk at larger scales (e.g. district, region scale). Examples can be found in the literature for regional flood risk studies (Jonkman et al., 2011; Voortman et al., 2003). However, the acceptable level of flood risk in a given study area may differ among regions and countries since economic, societal and environmental criteria considered for defining tolerability limits may be different (depending on existing risk aversion, risk component to be considered or risk dimension, e.g. incremental or total terms). Outcomes from combined risk modelling as presented in this paper provide input for such discussion.

ACKNOWLEDGEMENTS

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Environment (MAGRAMA), promoting collaboration in efforts involving Dam Safety and Risk Management of hydraulic infrastructures.

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ANNEX 4: Screening procedure for analysing the impact of manmade threats in dam risk management

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TITLE

Screening procedure for analysing the impact of manmade threats in dam risk management

ABSTRACT

In recent years, different institutions and organizations have developed methods and tools to analyze the impact of natural and manmade risks to critical infrastructures. Most of these methods are based on the definition of risk from the triplet 'threat-vulnerability-consequence'. The analysis of manmade threats has encountered a number of additional challenges, such as the estimation of the probability of an attack performed by goal-oriented and intelligent adversaries and the relation between manmade threats (security) and natural hazards (safety). In this paper, after reviewing the literature on asset and portfolio risk analysis, and discussing more specifically the strengths and limitations of existing methodologies for dam security risk analysis, a screening procedure for analyzing the impact of manmade threats in dam risk management is proposed. Dam operation and emergency management requires risk-informed decisions on how to prioritize actions for risk reduction. This procedure has two main advantages: it allows the combination of results from natural and manmade threats, providing a new perspective on the relationship between safety and security, and it may offer valuable information prior to the estimation of the probability of an attack, then allowing an holistic risk analysis aiming at reducing societal and economic risk in case of dam failure. An example on how the procedure can be used by dam owners and operators is shown for a portfolio of four dams, including final remarks and future research needs.

KEYWORDS

Dam risk analysis, natural hazards, manmade threats, societal risk, critical infrastructure management.

1. INTRODUCTION ON DAM SAFETY AND SECURITY RISK MANAGEMENT

Dams are vital infrastructures that provide social, economic and environmental benefits, including hydroelectric power generation, river navigation, urban water supply, irrigation, flood control, and recreation. Many of them are considered critical infrastructures as they are essential for the functioning of the society and economy. Consequently, dam failure or mission disruption may result in adverse consequences. Dam operation may be affected by natural hazards (e.g. floods, earthquakes, wildfires, etc.) or manmade threats (e.g. vandalism, terrorism or sabotage).

Commonly, *dam safety* refers to the protection of the society and the environment from dam failure or (un)controlled releases due to natural, technological and any other unintentional hazards. *Dam security* refers to manmade threats attributed to agents or adversaries, presenting intent and capability to harm dam operation, human life, property or the environment. Considering both sources of hazard (natural and manmade) is relevant to analyze risk and to inform decision-making processes on dam risk management from a joint perspective.

According to many experts (in an engineering context), a risk analysis would consist of getting answers to the following three questions (Kaplan and Garrick, 1981):

- what can happen?;
- how likely is it that an event will happen?, and,
- what are the consequences of such event?

Risk has been traditionally defined as the result of the triplet '*threat-vulnerability-consequences*', where *vulnerability* is often viewed as an intrinsic characteristic of the system at risk, although many analysts acknowledge that vulnerability depends on a hazard, e.g. with respect to its frequency and severity (e.g. when referring to the conditional dam failure probability for a given load scenario), hence it is useless to discuss vulnerability independently of its hazard context (Birkmann, 2007). The concept of vulnerability has been continuously broadened towards a more comprehensive approach encompassing susceptibility, exposure, coping and adaptive capacity, as well as different vulnerability types such as physical, social, economic, environmental and institutional (Birkmann, 2007; Gouldby and Samuels, 2009).

Dam safety risk analysis should consider all potential adverse events, paying close attention not only to 'low probability-high impact' events (Merz et al., 2009) but to all the range of plausible events. Incremental risk is usually employed in dam safety management for analyzing risk that can only be attributable to dam failure. This risk is computed using incremental consequences which dam failure might inflict on downstream areas (loss of life or economic damages), or at the dam itself, over and above any losses which might have occurred for the same natural event or conditions, had the dam not failed (ANCOLD, 2003). Moreover, the terms *societal risk* and *economic risk* are used depending on consequence characterization (estimation of potential loss of life and economic damages, respectively). When risk outcomes from dam safety risk analysis are expressed quantitatively, they are typically given in annualized terms. Existing tolerability criteria (ANCOLD, 2003; USACE, 2014) are formulated in terms of individual and societal incremental risk (expressed in lives·yr^{-1} units).

Dam safety quantitative risk analysis approaches require of both probability and consequence estimation methods, which have been used and are in continuous evolution since early eighties of last century (ICOLD, 2005). Due to the uncertainty on estimating risk components (Hartford and Baecher, 2004), quantitative risk estimates do not provide precise numerical results, but conclusions from risk assessments may be used to inform decisions. For example, the United States Army Corps of Engineers, USACE, currently applies a Risk-Informed Dam Safety Programme to develop balanced and informed safety assessments and to evaluate, prioritize and justify dam safety decisions (USACE, 2014). At the European level, a framework for risk-informed dam safety management has also been published by the Spanish National Committee on Large Dams (SPANCOLD, 2012).

Moving to the field of security risk, since the 9/11 attacks (IEP, 2012), the United States has become a reference for other countries concerning homeland security policies and actions. In 2003, the U.S. Homeland Security Presidential Directive 7 (HSPD–7) outlined the requirements for protecting critical infrastructures. One of the research and development priorities, stated as ‘Advance Risk Modeling, Simulation, and Analysis for Decision Support’, aimed at ‘creating models and algorithms accessible to owners and operators of critical infrastructures, standardizing vulnerability and risk analysis, developing the foundations for quantitative and economics based security and risk assessment and conducting quantitative risk assessments to better quantify terrorism risks to critical infrastructure sectors’. Among the 11 defined critical infrastructure sectors, HSPD–7 established Dams as a specific key asset. In addition to HSPD–7, the U.S. Strategy for the Physical Protection of Critical Infrastructures and Key Assets (2003) also enhanced the need for developing risk assessment methodologies for dams and a nationwide security program for dams.

Following the U.S. practices, or in parallel, other countries have developed their own security programs. In the European context, Directive 2008/114/EC (EC, 2008) was the first step to identify and designate European critical infrastructures (including dams). In addition, the European Commission established the ‘Prevention, Preparedness and Consequence Management of Terrorism and other Security-related Risks Programme’ in the period 2007–2013 (EC, 2007). This program aimed at promoting and developing measures based on comprehensive risk assessments, and at preventing or reducing security risks. Other international examples are the Canadian National Strategy for Critical Infrastructure (GC, 2009) and the Australian Critical Infrastructure Resilience Strategy (CA, 2010).

However, integrated safety and security risk management is a major challenge for the dam community. While the application of quantitative risk analysis techniques for informing decision-making on dam safety management is increasingly widespread among owners and operators, security stands behind and safety and security assessments remain disconnected when making decisions.

In this paper, a procedure for screening the relative importance of dam security threats, when compared to safety risk, is proposed.

2. OVERVIEW OF SECURITY RISK ANALYSIS METHODS

In line with policies and programs, different security risk analysis methods have arisen, typically focused in analyzing system vulnerability against a given manmade threat. These methods have mainly been developed in the last two decades, many of them created and applied in the United States.

As an example, in response to Presidential Decision Directives 62, Combating Terrorism, and 63, Critical Infrastructure Protection (CIP), the Interagency Forum for Infrastructure Protection (IFIP) was chartered in 1997 to exchange security and protection system information among dam owners and operators. Members of this group included the USACE, the United States Bureau of Reclamation, the Tennessee Valley Authority, and Sandia National Laboratories, among others. The latter developed the Risk Assessment Methodology for Dams, RAM-D, for evaluating security risks associated with potential attacks, and for providing information to support dam management in making decisions (Matalucci, 2002). This methodology was applied at several federal dams.

During the early formation of the U.S. Department of Homeland Security (DHS), an initial contract with the American Society of Mechanical Engineers - Innovative Technologies Institute (ASME–ITI) called for the development of the Risk Analysis and Management for Critical Asset Protection, RAMCAP, process (ASME, 2006). More recently, the DHS has developed a tool named the Dams Sector Analysis Tool (DSAT), intended to provide Dams Sector agents with secure access to a series of modules and applications. Created in collaboration with the USACE, the DSAT serves as a web-based tool to integrate available information on dam critical infrastructure facilities. Among DSAT tools, the Common Risk Model for Dams (CRM–D), developed by the Institute for Defense Analyses (IDA), assists in quantifying vulnerabilities based on standard security configuration attributes and pre-selected attack vectors (Kirpichevsky et al., 2013).

At the European level, the 'Prevention, Preparedness and Consequence Management of Terrorism and other Security related Risks Programme' funded transnational and national projects for contributing to the development of CIP programs in Europe (EC, 2006). As an example, the DAMSE project developed a European Methodology for the Security Assessment of Dams (Escuder et al., 2009) in the period 2006-2007. This methodology describes how to identify and qualitatively estimate risks associated with a set of adversarial attack scenarios on dams.

In this section, six key discussion points are considered, classified in four categories as shown in Table 1. These categories are *Completeness, Risk outcome, Independency,* and, *Scope.*

- Regarding the first category (completeness), the capability of existing security risk analysis methods to estimate all risk components has been considered. Estimation of all risk components is required to compare safety and security risk analysis outcomes.
- Concerning the second category (risk outcome), two sub-categories have been considered: first, the capability of the security risk analysis methods in obtaining quantitative risk estimates, and, second, the typology of the

risk outcome, to analyze whether existing security risk analysis methods will obtain risk outcomes in annualized terms as in dam safety risk analysis.

- Independency among risk components is also considered. For this third discussion category, security risk analysis methods are evaluated to identify how they do incorporate interdependencies among risk components.
- Finally, the scope of the analysis is also considered and two aspects are taken into account: first, the capability of existing methods for analyzing risk at the portfolio level (several dams), and, second, their applicability for prioritizing risk mitigation measures.

A set of security risk methods has been reviewed based on these categories (within the dam sector and outside it).

Table 1. Points for review and discussion.

Category	Sub-category	Key discussion point for review
Completeness	-	Are existing (dam) security analysis methods able to estimate all risk components?
Risk outcome	Quantitative risk estimates	Are existing (dam) security analysis methods able to estimate all risk components in quantitative terms?
	Annualized risk estimates	Do current (dam) security analysis methods estimate threat probabilities in annualized terms?
Independency	-	How do current (dam) security analysis methods incorporate correlations among risk components?
Scope	Scale	Are existing (dam) security analysis methods able to compare risks at the portfolio level?
	Prioritization of risk mitigation measures	Are existing (dam) security analysis methods able to prioritize among risk mitigation measures?

Methods for security risk analysis that propose useful concepts and tools for hydraulic infrastructures include the Vulnerability Assessment Methodology (Hart, 2004), the Systematic Analysis of Vulnerability Intrusion (Winblad, 1987), the Analytic System and Software for Evaluating Safeguards and Security (Al-Ayat, 1990), the Anti-terrorism Risk-based Decision Aid 'ARDA' model (Dillon et al., 2009), the Critical Asset and Portfolio Risk Analysis 'CAPRA' methodology (Ayyub et al., 2007), the Dam Assessment Matrix for Security and Vulnerability Risk 'DAMSVR' method (Foos et al., 2003), the Dynamic Event Tree Generation Method 'DETGM' (Toubaline et al., 2012), the Mission-oriented risk and design analysis 'MORDA' (Buckshaw et al., 2005), the Risk Assessment Method Property Analysis and Ranking Tool 'RAMPART' (Pohl, 2013), the Probabilistic modeling of terrorist threats for Military Operations Method '2SM' (Paté-Cornell and Guikema, 2002), and the Three Sided Model for analyzing basic scenarios of terrorist attacks at hydropower engineering facilities '3SM' (Makhutov et al., 2012).

Table 2 includes a list of reviewed methods. Key discussion points included in Table 1 were analyzed and main aspects concerning method characteristics, strengths and limitations regarding combined safety and security analysis and dam quantitative risk analysis (QRA) are summarized in Table 3.

Table 2. Reviewed security risk analysis methods.

Name	Stands for	Type of Tool	Infrastructure	Developed in/by	Used by
ARDA	Anti-terrorism Risk-based Decision Aid	Decision-making approach for prioritizing anti-terrorism measures	Navy facilities	2009; Georgetown University and Innovative Decisions Inc	U.S. Navy
CAPRA	Critical Asset and Portfolio Risk Analysis	Quantitative all-hazards framework	All critical infrastructures	2006; University of Maryland	Maryland Emergency Management Agency
CRM-D	Common Risk Model for Dams	Systematic approach for evaluating and comparing risks from terrorist attacks	Dams and navigation locks	2011; Institute for Defense Analyses (IDA), USACE and Department of Homeland Security (DHS)	USACE and DHS
DAMSE	European Methodology for the Security Assessment of Dams	Risk analysis and assessment	Dams	2008	Dam owners of the DAMSE consortium (Spain, Italy and Austria)
DAMSVR	Dams Assessment Matrix for Security and Vulnerability Risk	Qualitative risk assessment	Dams	2003	Federal Energy Regulatory Commission (FERC)
DETGM	Dynamic Event Tree Generation Method	Risk analysis	Infrastructures	2012	NA
MORDA	Mission-oriented risk and design analysis	Quantitative risk assessment model	Information systems	2005; U.S. Department of Defense	Department of Defense (US)
RAM-D^{SM}	Risk Assessment Methodology -Dams	Dam security risk assessment software	Dams	2001; Sandia National Laboratories and Interagency Forum for Infrastructure Protection (IFIP)	IFIP and USACE
RAM-PS	Risk Assessment Methodology for Physical Security	Semi-quantitative risk assessment	Infrastructures	2000; Sandia National Laboratories	Department of Defense (US)
RAMCAP	Risk Analysis and Management for Critical Asset Protection	Risk Analysis and Management framework	All critical infrastructures	2006	Department of Homeland Security (DHS)

Table 2. Reviewed security risk analysis methods (continued).

Name	Stands for	Type of Tool	Infrastructure	Developed in/by	Used by
RAMPART	Risk Assessment Method Property Analysis and Ranking Tool	Risk analysis software tool	Buildings	2002; Sandia National Laboratories	General Services Administration (GSA)
2SM	Probabilistic modeling of terrorist threats for Military Operations	Rational decision analysis model	Military facilities	2002; Stanford University	U.S. Military Service
3SM	Three sided model for analyzing basic scenarios of terrorist attacks at HEF	HEF security risk assessment approach	Hydropower Engineering Facilities (HEF)	2011	Not known

Table 3. Summary of main aspects of reviewed methods.

Name	Characteristics	Strengths	Limitations regarding combined safety-security analysis and QRA
ARDA	Multi-attribute utility theory. Consequence assessment includes mission, personnel and economic impact. Concept of susceptibility. DAWDR approach (Detect, Assess, Warn, Defend, Recover).	Decision maker risk matrix. Use of risk utility function.	Use of risk scores for likelihoods and consequences. Use of risk scoring not generally recommended for prioritzing mitigation measures.
CAPRA	Expected loss as a function of hazard intensity attributed to a hazard scenario. Probability of adversary success as a function of hazard intensity for a specified attack profile.	Use of target susceptibility matrix. Attack profile matrix. Use of utility functions. Expected loss for every attack scenario.	Prioritization based on benefit-cost ratio. Use of site-specific baseline rates
CRM-D	A general model of how adversaries make their targeting. Tools used are qualitative research, probability theory, statistical analysis, game theory and Monte Carlo simulation.	Attack probability estimation from utility functions. Expected losses for every attack scenario. Attack probability for an attack scenario as a function of consequences and system vulnerability. No additional input from expert elicitations is required for new attack scenarios. Basis for a portfolio-wide prioritization of critical dams.	Attack probabilities are not annualized values as usually obtained in safety analysis. Terrorist decision model based on expert elicitation of 18 different sets of 4 hypothetical attack alternatives.
DAMSE	For screening analysis of conditional security risk. Proposes generic fault trees to evaluate system vulnerability against malevolent threats.	Consequence, system vulnerability and threat assessment. Baseline for future development of a quantitative framework for dam risk analysis.- It can be used for preliminary analysis for allocating resources for risk mitigation.	Attack probabilities are not assessed. Use of qualitative risk estimates.
DAMSVR	Adaptation of the CARVER method (Criticality, Accesibility, Recuperability, Vulnerability, Effect and Recognition factors)	Consequence, vulnerability, system effectiveness and threat analyses. Attractiveness of the critical asset is considered (ease of access, simplicity of destruction.) Definition of asset security risk value: ASR factor = {Consequences x (Vulnerability + Probability of Loss + Threat) / Security effectiveness}/300	"Consequences" refers to impact in downstream areas and "vulnerability" refers to asset characteristics. Threat analysis only for assets with "probable" priority ratings. Use of rating scores and factors (ASR ranges from 0.001 to 1). ASR is weighted more heavily on the "Consequences" than the other variables. Prioritization based on qualitative risk-scoring.

Table 3. Summary of main aspects of reviewed methods (continued).

Name	Characteristics	Strengths	Limitations regarding combined safety-security analysis and QRA
DETGM	Network modeling for system analysis. Dynamic event tree generation. Use of truncation rules to limit the tree size. Compact representation of event trees.	Dynamic behavior of the system.	Specified types of attack.
MORDA	Multiple Objective Decision Analysis. Measures the adversary's attack preferences instead of the adversary's probabilities of attack.	Assess interdependencies between countermeasures and attacks. Portfolio assessment.	Data requirements for characterizing adversary attacks (high-detailed studies).
RAM-DSM	Generic dam fault trees. Dam layout sketches. Adversary sequence diagrams (ASD). Project-specific check sheets.	Use of generic fault tree for system effectiveness analysis. Framework for supporting decision-making on risk mitigation measures.	Probability of occurrence of terrorism, sabotage is assumed as a constant value when data is not available. Use of risk scores.
RAM-PS	Risk assessment framework based on the risk triplet (consequences, vulnerability and threat).	Event tree analysis for estimating probability of attack. Basis for more specific methodologies.	Use of qualitative estimates of likelihood of an attack.
RAMCAP	Two approaches: Qualitative (semi-quantitative) or Quantitative (semi-qualitative).	Consequence and vulnerability scores. Event tree analysis for estimating probability of attack.	Use of a conditional risk matrix. It cannot be used to adjust for correlations among risk components. Risk matrices assign the same score to different pairs of consequences-vulnerability scores.
RAMPART	Software tool for non-analysts.	Risk assessment framework based on the risk triplet. Combines database from expert knowledge with information from the user (infrastructure manager).	Use of qualitative risk scoring. Designed for buildings not for dams
2SM	Rational decision analysis model: Descriptive mode on the terrorist side / Prescriptive mode on the defender side.	Influence diagrams and utilities to assess probabilities.	It can be used for single-period assessment Requires high knowledge of adversary preferences
3SM	Three sided model for analyzing basic scenarios of terrorist attacks.	The method obtains attack probability estimates.	Varying level of uncertainty of specific elements depending on attacker or defender perspective. Developed for Hydropower engineering facilities, although it could be modified to be applied in dams.

After an in-depth review of all aforementioned methods, what they stand for, type of tool (e.g. if it was developed for screening, in-depth analysis, risk analysis, risk assessment, etc.), the type of infrastructure for which it was developed, year of publication/release and authors, main users (e.g. organizations or institutions that have applied the method), and main references associated, the following conclusions are drawn:

- Several existing methods provide a first approach towards quantitative security risk analysis. However, there is still a need for further research to provide quantitative estimates for all risk components, including attack probabilities.
- Annualized risk estimates are obtained by the CAPRA (Ayyub *et al.* 2007) using a baseline approach that cannot be easily assessed for each system if information on security incidents is not available.
- Interdependencies among risk components have only been assessed by CRM–D (Kirpichevsky et al., 2013) by means utility functions, still lacking of validation for their applicability at different scales and contexts.
- CRM–D can be applied to quantitative security risk analysis of dams, though only in terms of conditional security risk outcomes (given that a successful attack has occurred). This implies the need for identifying potential attack scenarios and estimating attack probabilities.

As an overall conclusion, in today's practice only conditional security risk outcomes from previously defined attack scenarios are available to direct application on dams. Consequently, advanced dam risk governance practices treat safety and security risk in a totally disconnected manner. As a matter of fact, Chapter 23 of USACE's policies and procedures (USACE, 2014) states that 'security postures will vary from project to project' and that 'the determination of the recommended steady-state security posture for USACE dams will be based on the completion of a security risk assessment'. With regard to these security assessments, the methodology developed and endorsed by USACE relies on the CRM–D model outcomes to support risk–informed decisions and to implement physical security risk mitigation measures. However, work on characterizing the threat event is still required.

3. SCREENING PROCEDURE FOR ANALYZING THE IMPACT OF MANMADE THREATS

The procedure for screening of the impact of manmade threats on the overall risk management of a dam herein proposed is based on the comparison of annualized incremental safety risk analysis outcomes and conditional security risk estimates. Figure 1 shows a flow diagram and the connections between safety and security risk analyses outcomes and how are related as proposed in this paper. The procedure includes a 3-step process including:

- Step 1 "Dam safety risk analysis": obtaining annualized incremental safety risk as the main outcome.
- Step 2 "Dam security risk analysis": obtaining conditional security risk.
- Step 3 "Comparative analysis": obtaining the equivalent annualized probability of attack and compared with a reference threshold value.

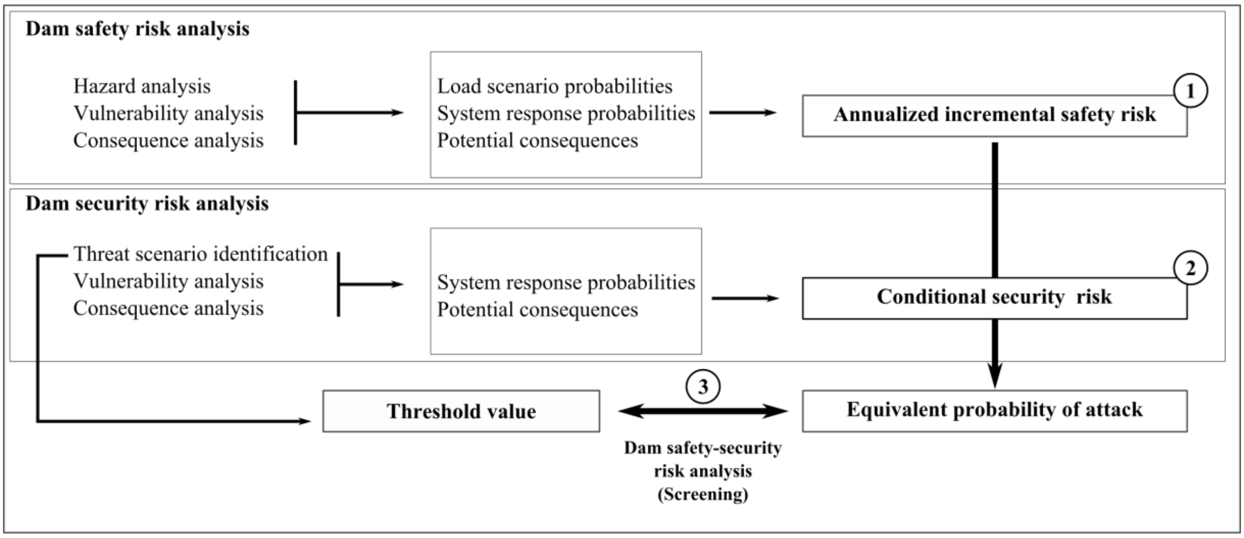

Figure 1. Screening procedure for analyzing the impact of manmade threats in dam risk analysis.

The three steps are described in Table 4.

Table 4. Steps of the screening procedure for analyzing the impact of manmade threats in dam risk management.

Step	Name	Description	Main outcome
1	Dam safety risk analysis	Analysis of natural hazards, system response and consequences, including: Probability estimations of load events and system response. Estimation of incremental consequences in case of dam failure or mission disruption.	Annualized incremental safety risk.
2	Dam security risk analysis	Analysis of manmade threats, system response and consequences, including: Analysis of past incidents and context. Attack scenario identification. Probability estimations of system response. Consequence estimation in case of dam failure or mission disruption.	Conditional security risk. Threshold value.
3	Comparative analysis	Estimation of the equivalent annualized probability of attack, based on outcomes from Steps 1 and 2. Comparative analysis of threshold value and equivalent probability of attack, based on outcomes from Steps 2 and 3.	Equivalent annualized probability of attack.

In Step 3, an indicator is proposed for the comparative analysis to assess the impact of manmade threats. This indicator named *equivalent annualized probability of attack*, it is denoted as $\lambda_{eq,i}$, reveals the potential attack probability that would result in similar risk estimates for both natural hazards and manmade threats.

The equivalent annualized probability of attack is defined as the ratio between annualized incremental safety risk, r_N, and conditional security risk, hereafter denoted as $r_c(A_i)$:

$$\lambda_{eq,i} = \frac{r_N}{r_c(A_i)} \quad (1)$$

where $\lambda_{eq,i}$ is the equivalent annualized probability of attack; r_N is the annualized incremental safety risk, $r_c(A_i)$ is the conditional security risk and A_i is each identified attack scenario.

This ratio has units of yr^{-1} and it represents the attack probability that equals risk from natural hazard analysis and the given attack scenario.

An attack scenario with an actual probability of occurrence greater than λ_{eq} would result in a security risk level higher than the existing risk from natural hazards. If the resulting value is not plausible, then safety risk can be understood as the 'main' source of risk. On the contrary, plausible values indicate that security risk levels may be significant when compared to existing safety risk.

At asset (dam) level, this indicator can be used for screening analysis to identify if manmade threats are driving the current risk climate; thus plausible attack scenarios may lead to security risk levels that are higher than existing safety risk levels.

Following the proposed procedure, results obtained for the equivalent annualized probability of attack inform on the relative impact of manmade threats when compared to safety risk levels.

An additional indicator, $\lambda_{eq,th}$, named *threshold probability of attack*, is proposed to represent a threshold value for analyzing the equivalent attack probability, $\lambda_{eq,i}$. Estimation of the threshold probability of attack requires information on past incidents, context characterization and the consideration of site-specific conditions.

The following ranges are defined for assessing the impact of manmade threats into dam risk management, based on the resulting equivalent annualized probability of attack and the asset-specific threshold probability of attack:

- $\lambda_{eq.i} > 1$: dams in which safety risk is significantly higher compared to risk from manmade threats. Consequently, such cases require the attack probabilities to be so high that, in order to make both safety and security risks somewhat equal, would require attack scenarios that may be virtually not credible.
- $\lambda_{eq,th} \leq \lambda_{eq} \leq 1$: dams in which required attack probabilities to equal both safety and security risks are relatively high (with probabilities of occurrence ranging from $\lambda_{eq,i}$ to 1).
- $\lambda_{eq,i} < \lambda_{eq,th}$: dams with high conditional security risk for the identified attack scenario when compared to existing safety risk.

Estimation of the threshold probability of attack based on information from intelligence communities would be desirable. If the equivalent annualized probability of attack might be contrasted with this information, dam owners and operators would be able to assess how credible it is that security risk becomes the major risk driver for a particular dam. However, in practice, it is not possible to access to such level of information. Data on reported past incidents against dams, or similar infrastructures, may be used if available.

4. CASE STUDY

The aim of this case example is to show how results from risk analysis for natural hazards and manmade threats can be compared to provide information for an integrated dam risk management.

The example provided in this section to show how the screening procedure can be used by dam owners and operators to analyze risk on dams. A set of four concrete gravity dams is considered, which represents part of the portfolio managed by a dam owner. All dams include spillway gates.

Outcomes from safety risk analysis are available and shown in Figure 2a, representing fN pairs that relate annual dam failure probabilities and incremental average consequences. Results are compared with international tolerability recommendations as proposed by ANCOLD and USACE (SPANCOLD, 2012).

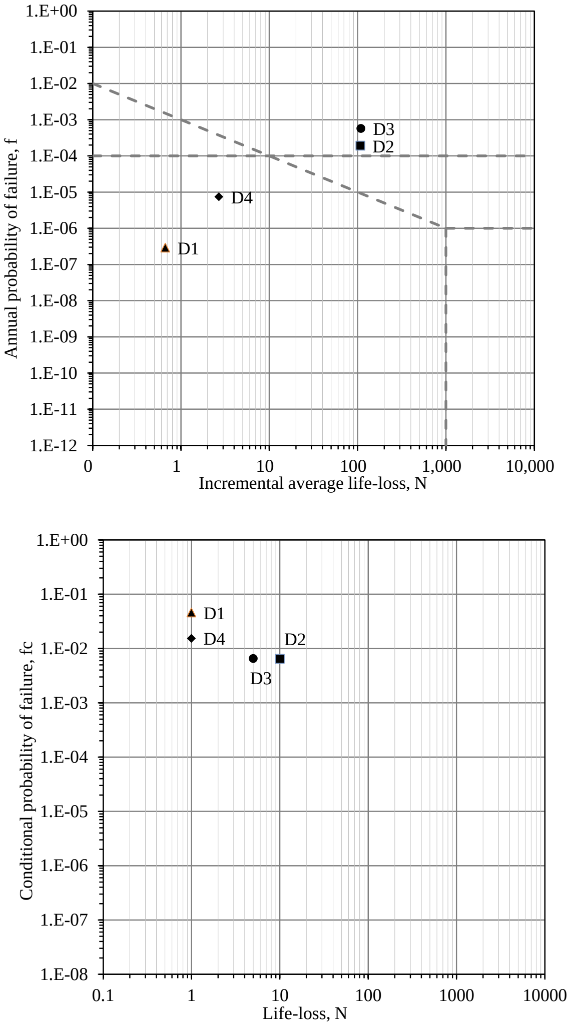

Figure 2. fN graph obtained for the case study example showing (a) safety and (b) security risk outcomes.

As observed in Fig.2a, dams D1 and D4 show risk estimates in line with recommendations for existing dams, with societal risk estimates below $1{\cdot}10^{-3}$ lives·yr^{-1}. Although it is common practice in the dam engineering community to use these recommendations, they should be considered as part of a comprehensive risk evaluation process, not considering minimum requirements to meet such criteria but reducing risk through prioritization based on efficiency and equity principles (Morales-Torres et al., 2016).

After a preliminary identification process of potential attack scenarios, the attack scenario that presents the highest conditional security risk estimate, in terms of societal risk, is chosen. For this scenario, the spillway is the targeted element. A sequential and progressive failure of spillway gates is considered for each dam (5-10 minutes in total).

System vulnerability has been estimated based on the presence of physical barriers, access to control panels, gate structure, main and supplementary energy supply, etc. It is assumed that potential attackers are terrorist groups with the capability of utilizing man-portable explosive devices and small vehicles. Their objective would be to access the gate chamber, activate control commands to open spillway gates and later block/damage them to avoid gate closure. It is considered that the water level at the reservoir is at Normal Operating Level (NOL) when the attack occurs (NOL is set at the top of the spillway gates for all dams).

Outcomes from security risk analysis for the given attack scenario are shown in Figure 2b, representing fN pairs that relate conditional system failure probabilities and estimated consequences in case of a successful attack. Risk acceptance criteria are not included in this case since there is no consensus on tolerability recommendations. Although it is out of the scope of this paper, the ALARP principle might be considered for evaluating the impact on security risk of mitigation actions, based on risk reduction up to a level that is as low as reasonably practicable in terms of cost against the benefits obtained.

As observed, dams D2 and D3 show consequence estimates lower than the average life-loss resulting from dam failure due to natural hazards. However, this graph does not include the risk component related to the threat probability then it cannot be fully compared against safety outcomes.

Therefore, the proposed screening procedure has been applied and results are included in Table 5, where outcomes from both safety and conditional security risk analysis are included. Results from step 1 include dam failure probability, annualized incremental societal safety risk and incremental average life-loss (obtained by dividing annualized risk and dam failure probability). Results from step 2 include conditional dam failure probabilities, estimated life-loss for the given attack scenario and conditional security risk (obtained by multiplying the first two outcomes). Results from step 3 include the estimation of the equivalent probability of attack for each dam.

Table 5. Summary of risk outcomes from safety and security analyses for the case study example.

	Step 1			**Step 2**			**Step 3**
Dam	Dam failure probability, $f_{p,j}$ [yr^{-1}]	Incremental average life-loss, N_j [lives]	Annualized incremental societal safety risk, $r_{N,j}$ [$lives \cdot yr^{-1}$]	Conditional failure probability, $f_{c,j}$	Life-loss for scenario $A_{0,j}$, $N_{A0,j}$ [lives]	Conditional security risk, r_c ($A_{0,j}$)[lives]	Equivalent probability of attack, $\lambda_{eq,j}$ [yr^{-1}]
D1	$3 \cdot 10^{-7}$	$7 \cdot 10^{-1}$	$2 \cdot 10^{-7}$	$5 \cdot 10^{-2}$	1	$5 \cdot 10^{-2}$	$4 \cdot 10^{-6}$
D2	$2 \cdot 10^{-4}$	$1 \cdot 10^{2}$	$2 \cdot 10^{-2}$	$6 \cdot 10^{-3}$	10	$6 \cdot 10^{-2}$	$3 \cdot 10^{-1}$
D3	$6 \cdot 10^{-4}$	$1 \cdot 10^{2}$	$6 \cdot 10^{-2}$	$7 \cdot 10^{-3}$	5	$3 \cdot 10^{-2}$	2
D4	$7 \cdot 10^{-6}$	3	$2 \cdot 10^{-5}$	$2 \cdot 10^{-2}$	1	$2 \cdot 10^{-2}$	$1 \cdot 10^{-3}$

Note: Estimates and units of columns 2 to 7 are those currently being used by dam owners in terms of risk governance.

For the sake of simplicity, it is assumed that the attack scenario with the highest conditional risk for each dam, $A_{0,j}$, is the only relevant to account for (where j denotes the dam at study).

A value for the threshold probability of attack equal to $1 \cdot 10^{-5}$ [yr^{-1}] is considered in this example. This value has been obtained based on reported past incidents against dams worldwide. According to the DHS report on 'Worlwide Attacks against Dams' (DHS, 2012), in the period 2001-2011, 25 attacks were conducted against dams: four in Afghanistan and Burma, three in Iraq, two in Russia, India, Nepal and Philippines, and one in Indonesia, Thailand, and in the U.S, respectively. Explosive devices, standoff weapons, and incendiary devices were used by assault teams. Based on the number of large dams (>15m high) in each country, a simplified estimate of $1 \cdot 10^{-5}$ [yr^{-1}] for the probability that an individual large dam may be attacked was obtained for the U.S. (probabilities are higher in areas of ongoing armed conflicts). Despite the limitations of available data (low number of reported incidents, different scenarios and adversary goals, changing contexts, etc.), the resulting value is used for the purpose of this example.

Combining results from both safety and security analyses (Table 2), Dam 1 shows an equivalent probability of attack lower than the threshold value. For this dam, plausible probability values for the given attack scenario result in higher security risk levels if compared to existing safety risk from natural hazards ($2 \cdot 10^{-7}$ $lives \cdot yr^{-1}$). Consequently, security risk mitigation measures along with safety risk reduction actions might be considered for this asset to conduct a balanced operation in terms of dam risk management.

However, results for Dams 2, 3 and 4 show values of the equivalent probability of attack larger than the threshold value, thus current security risk levels for the given attack scenario are low when compared to existing safety risks. It should be noted that safety risk outcomes for dams 2 and 3 are $2 \cdot 10^{-2}$ $lives \cdot yr^{-1}$ and $6 \cdot 10^{-2}$ $lives \cdot yr^{-1}$, respectively. Consequently, safety risk would in principle stand for the main concern for the current situation. After implementing safety risk reduction measures, an updated combined safety-security analysis would be required to analyze the need for security risk reduction measures.

5. DISCUSSION AND FINAL CONCLUSIONS

The reliability and validity of existing risk analysis techniques have been objects of discussion particularly on the applicability of probabilistic (quantitative) risk analysis approaches, developed in principle for safety risks, to terrorism risk (Aven and Heide, 2009; Aven and Renn, 2009; Brown and Cox, 2011; Ezell et al., 2010), though examples of such approaches to model security risks can be found. However, uncertainty associated to risk from manmade threats should be adequately assessed when conducting detailed quantitative risk analysis approaches.

The reviewed methods in this paper focus on current practices applied within the critical infrastructure community for security risk assessment. The analysis of the state-of-the-art has shown that the majority of these approaches cover mainly two of the three risk components in a quantitative manner. Some authors (Cox, 2008) argue indeed the failure of existing approaches to adjust correlations among risk components or to incorporate the adaptive nature of potential attackers.

Therefore, threat assessment is nowadays the major challenge when analyzing manmade threats. Methods such as decision tree analysis, hierarchical optimization models, scenario-generating approaches, or game-theoretic approaches, appear as alternative methods for modeling terrorism risks to the classic quantitative risk assessments (mainly based on the use of expected values). We acknowledge the limitations of assessing terrorism risks quantitatively, and we have seen that owners using them are aware of that and are using the outcomes with precaution.

The review of existing methods has revealed the need for improving and upgrading risk analysis tools in general and dam security risk analysis tools in particular, if they want to play in the same field as dam safety risk assessment existing tools.

Therefore, this paper presents a procedure for screening of the impact of manmade threats on dam risk, integrating state of the art outcomes of dam safety and conditional security risk analyses by using a combined indicator, named equivalent annualized probability of attack. It allows to compare safety and security risk levels and to inform decisions at the asset scale. We are convinced that this approach it will help dam owners and operators to meet the challenging task of addressing both safety and security issues. The proposed procedure takes advantage of state-of-the-art QRA practices in dam safety management (with proved robustness and consistency, applied to real cases worldwide) to improve current security risk analysis.

Historical data on reported dam incidents for providing a first estimate of the threshold value for the equivalent annualized probability of attack have been used in the given example, but this only provides a guide for future analyses. New developments on dam facilities (monitoring, control and security systems, gate operability, etc.) may result in specific and more sophisticated attacks (e.g. cyber-security attacks aiming at interrupting services provided by the dam), focused on affecting dam operation rather than structural reliability. In addition, a larger threshold value for the probability of attack might be used in conflict areas where attack events are expected to become more common (e.g. iconic targets or areas of armed conflicts). We recognized the uncertainty related to the prediction of malevolent threats, highly dependent on the socio-political context.

The goal of current (and future) work of intelligence communities, analysts, and experts should include the development of comprehensive methods for human-induced threat identification, aiming at reducing subjectivity and uncertainty. Therefore, a more intensive exchange of knowledge and expertise between the dam community and intelligence services would be desirable.

Potential users of the screening procedure presented in this paper are dam owners, operators, regulators, and decision makers. All are required to prioritize and allocate investments for dam risk reduction, especially in terms of risk reduction in downstream areas. The main purpose of this approach is to provide them with a screening tool, a step forward towards a more integrative dam risk management.

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ANNEX 5: Towards an integrated flood risk management in urban areas: pluvial and river flooding including structural collapse

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Title

Towards an integrated flood risk management in urban areas: pluvial and river flooding including structural collapse

Abstract

The concept of Integrated Flood Risk Management (IFRM) promotes an integrated and holistic approach to flood management and aims at combining the efficient use of flood plains and the reduction of potential consequences due to flooding. Thus, it requires a combination of policy, regulatory, financial and physical measures.

Current methodologies for flood risk assessment have been generally developed in qualitative or semi-quantitative terms. In addition, these methodologies have been applied to site-specific cases (examples may be found in research projects of the 1st and 2nd CRUE ERA-Net funding initiative). Consequently, a general applicable methodology for quantitative flood risk assessment in urban areas is still required.

This paper presents the basis for such approach, incorporating different hazards (pluvial flooding, river flooding and structural collapse of flood defence infrastructures such as dams, levees or dikes), evaluating economic and societal consequences, and providing a framework to inform decision making towards an IFRM.

1. INTRODUCTION

1.1. Overview

Floods may result from a wide combination of meteorological and hydrological extremes (WMO and Global Water Partnership, 2008). In most cases, floods are additionally influenced by human factors. Urban areas may basically be affected by local floods, river floods, flash floods or coastal floods and they may present high flood risk levels due to their population density rates, multiple economic activities, infrastructures and property values (Pelling, 2003). Furthermore, present requirements of residential and industrial areas have resulted in new urban developments in flood-prone areas, increasing risk to people and inducing significant economic costs.

An analysis of global statistics (Jonkman, 2005) showed that inland floods (including drainage floods, river floods and flash floods) caused 175,000 fatalities and affected more than 2.2 billion people worldwide from 1975 to 2002. An example of these events is the disastrous flood in the Elbe River basin in August 2002 (Engel, 2004). Coastal floods were not included in these statistics, but they may cause even more catastrophic floods in terms of loss of life as the flooding caused by hurricane Katrina in 2005 (Jonkman et al., 2009).

In this paper, drainage floods (pluvial flooding), river floods and flooding from structural collapse of flood defence infrastructures (e.g. dams, levees, dikes, etc.) are considered.

As a result of past and recent flood events and their consequences, social demand for higher levels of safety has become a major challenge for the governments of European countries. In the European context, two Directives have been approved in recent years to establish the basis for present and future actions in flood risk assessment and management:

- Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 (European Parliament, 2000) established a framework for Community action in the field of water policy. This Directive requires the development of river basin management plans for each river basin district in order to achieve good ecological and chemical status, mitigating the effects of floods. However, reducing flood risk was not one of the main objectives of that Directive, nor did it take into account the future changes on risk as a result of climate change.

- Directive 2007/60/EC of the European Parliament and of the Council of 23 October 2007, also called EU (European Union) Floods Directive (European Parliament, 2007), established a framework for the assessment and management of flood risks, aiming at the reduction of adverse consequences for human health, the environment, cultural heritage and economic activity.

After the EU Floods Directive, all EU Member States must undertake the necessary actions to provide an assessment of potential risks including preliminary flood risk assessments, flood hazard maps, flood risk maps and flood risk management plans for each river basin district.

In Spain, this Directive was transposed into national legislation in July 2010 by the decree RD 903/2010 (Spanish Ministry of the Presidency, 2010). This decree contains all actions to be undertaken and the corresponding deadlines.

Before the EU Floods Directive, several initiatives emerged to improve coordination of flooding research across Europe. As an example, the CRUE network, created in late 2004, was funded as a European Research Area Network (ERA-Net) under the 6th EU Framework Programme. The vision for the CRUE network was to provide coordinated and comprehensive transnational evidence based on flood risk management. For that purpose, two CRUE funding initiatives were carried out from 2007 to 2011: the first, based on risk assessment and management and, the second, on flood resilient communities and managing the consequences of flooding.

Fourteen research projects were conducted in the period 2007-2011, focusing on the development of improved methodologies and strategies for an effective flood risk management, taking into account sustainability, public participation, risk awareness and risk communication (Thieken and Beurton, 2012). Results, key findings and recommendations for policymakers have been published and presented in different forums (e.g. Graz, Austria (Escuder-Bueno et al., 2011); Valencia, Spain (Escuder-Bueno et al., 2012c)).

In accordance with the objectives of the EU Floods Directive, flood risk management plans shall take into account relevant aspects such as cost-benefit analyses, environmental objectives, spatial planning, land use, etc. These plans should focus on prevention, protection and preparedness, including flood forecasting and warning. In addition, authorities have to make these plans available to the public and encourage active involvement in their production, review and updating. These plans have to be effectively communicated to target groups such as decision makers, urban planners, emergency services and the public (De Bruijn et al., 2015; Meyer et al., 2011).

With that purpose, new tools are now being developed to provide the required analyses and results to carry out these plans and their implementation, from national to local scale.

The ongoing efforts on flood risk research aim to develop methodologies to assess the existing flood risk in urban areas by integrating different sources of hazard. These methodologies should provide tools to compare and analyze measures for flood risk reduction.

In this context, this article presents a comprehensive methodology for urban flood risk analysis, integrating pluvial and river flooding including structural collapse of flood defence infrastructures such as dams or dikes, which allows to analyze the impact of different risk reduction measures in comparison with the current situation, providing a tool to inform authorities, support decision making and improve risk awareness towards an integrated flood risk management.

This article describes such methodology and its application to a case study where outcomes of flood risk analysis have been used to inform local authorities for developing a municipal action plan against flood risk.

1.2. Towards an integrated flood risk management

1.2.1. The concept of flood risk

A wide range of definitions for the term *risk* can be found in the literature (Gouldby and Samuels, 2005). However, attempts to develop common understanding on risk management concepts and terms among organizations are relatively new (Gouldby and Samuels, 2005; IEC, 2009) or in process. The term risk may present multiple dimensions relating to safety and security, as well as economic, environmental and social issues. These different meanings are the result of its extensive use in multiple disciplines thus there is no unique definition for risk.

In the context of flood risk analysis, *flood risk* may be defined as the product of the probability of potential flood events and their consequences (Equation 1), or, alternatively, as the product of flood hazard and society's vulnerability to floods (Klijn et al., 2008).

$$risk = probability\ x\ consequences \qquad (1)$$

In general, potential adverse consequences of flooding can be classified in consequences for human health, for cultural heritage and economic activity, and for the environment. According to these three dimensions, flood risk may be assessed in terms of societal, economic or ecological risk (Kubal et al., 2009).

Despite the fact that there are examples of multi-criteria flood risk assessment and mapping approaches that cover the three dimensions of risk (Meyer et al., 2011), in practice, each of the three dimensions is generally obtained separately (e.g. different flood risk maps, risk calculations, etc.). In most cases, ecological risk is not evaluated due to a lack of applications of quantitative risk assessment in these terms. In this article, ecological risk is not considered for the description of the methodology and its application. However, the overall process herein described can be applied to assess any dimension of flood risk.

1.2.2. From flood risk analysis to integrated flood risk management

Flood risk management includes a global concept and includes the application of logical and systematic methods for communicating flood risk, establishing the context for identifying, analysing, evaluating, and treating flood risk and the required risk reduction measures for risk mitigation and control (IEC, 2009).

Flood risk assessment is that part of flood risk management which provides a structured process that identifies and analyses flood risk in terms of consequences and their probabilities.

Based on the guidelines published by ANCOLD in 2003 (ANCOLD, 2003), the methodological framework of flood risk assessment can be divided into the following steps:

- Risk identification;
- Risk analysis or risk estimation;
- Risk evaluation, and,
- Risk assessment.

In general, flood risk assessment attempts to answer the following fundamental questions (International Organization for Standardization (ISO), 2009):

- what can happen and why? (by risk identification and characterization of potential flood events)
- what are the consequences of flooding? (by risk analysis)
- what is the probability of their future occurrence? (by risk analysis)
- are there any factors that mitigate flood consequences or that reduce the probability of the flood event? (by risk analysis)
- is the existing level of risk tolerable or acceptable and does it require further risk reduction measures? (by risk evaluation)

Consequently, flood risk assessment deals with the overall process of risk identification, risk analysis and risk evaluation, as shown in Figure 1.

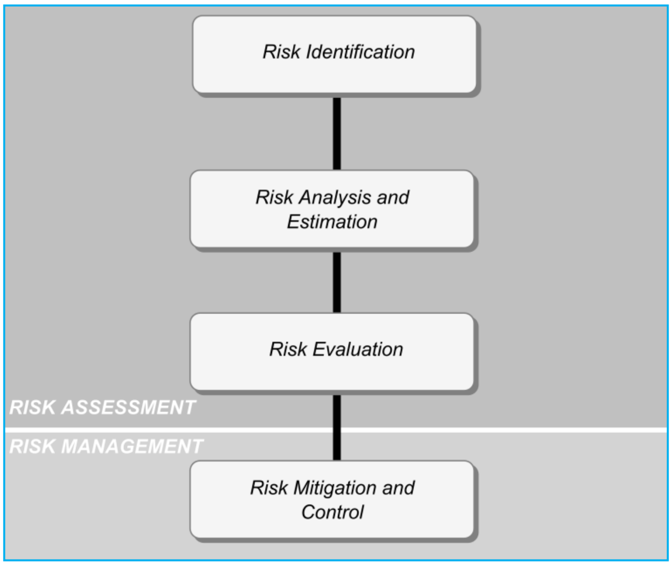

Figure 1: Flood risk assessment and management.

First, risk identification includes the process of finding, recognizing and describing risks. It involves also the identification of risk sources, their causes and their potential consequences, including the use of historical data, theoretical analysis, informed and expert opinions, and including stakeholder's needs. Second, risk analysis includes the process to comprehend the nature of risk and to establish the level of risk, including risk estimation. Finally, risk evaluation consists of comparing the results of risk analysis with risk criteria or tolerability standards to establish whether the risk is acceptable or tolerable and what kind of measures can be applied, if needed, for flood risk reduction.

In general, a risk reduction measure may be considered as an action that is taken to reduce either the probability of flooding or the consequences (or both risk components). These measures can be divided into two groups: structural and non-structural measures. Structural measures refer to any physical construction to reduce or avoid possible impact of floods, which include engineering measures and construction of hazard-resistant and protective infrastructures. Non-structural measures include measures such as policies, awareness, knowledge development, public commitment, methods and operating practices (Escuder-Bueno et al., 2012a).

However, risk cannot be entirely eliminated since structural measures handle the consequences of a specific severe event, typically called design event, and there is always a residual risk, even in the case of perfect behavior of the flood defense infrastructure. Although non-structural measures may reduce part of this risk, residual risk relates to the consequences that cannot be prevented by the combination of existing structural and non-structural measures.

Therefore, risk analysis and assessment should focus on obtaining the existent/residual risk and evaluate the effect of risk reduction measures.

In practice, different analyses have been conducted from transnational to local levels, but there is still a lack of tools to face the problem from different levels of detail. For that reason, analyses have generally required the development of *ad hoc* models depending on the case study.

In this article, the use of F-N curves and risk models is proposed for flood risk analysis as it provides a comprehensive and robust method to represent quantitatively societal and economic risk. Outcomes of flood risk analysis will inform local authorities and involved actors on flood emergency management to develop improved flood emergency plans and to define and implement risk reduction measures.

2. METHODOLOGY

2.1. Basic concepts

As it has been introduced above, the use of F-N curves and risk models is proposed in this methodology for flood risk analysis as it provides a comprehensive and robust method to represent societal and economic risk in quantitative terms.

The basis of the use of F-N curves for urban flood risk analysis was first presented in the *SUFRI Methodology for pluvial and river flooding risk analysis in urban areas to inform decision making*, developed within the SUFRI project in the period 2009-2011, 2nd CRUE ERA-Net funding initiative (Escuder-Bueno et al., 2011).

F-N curves provide a representation of both risk components, probability and consequences, in quantitative terms, as shown in Figure 2. When analyzing societal risk, F-N curves represent the annual cumulative probability of exceedance (F) of a certain level of potential fatalities (N). In case of economic risk, these curves are called F-D curves and represent the annual cumulative probability of exceedance of each level of potential economic damages (D). The area under the curve represents total societal or economic risk, respectively.

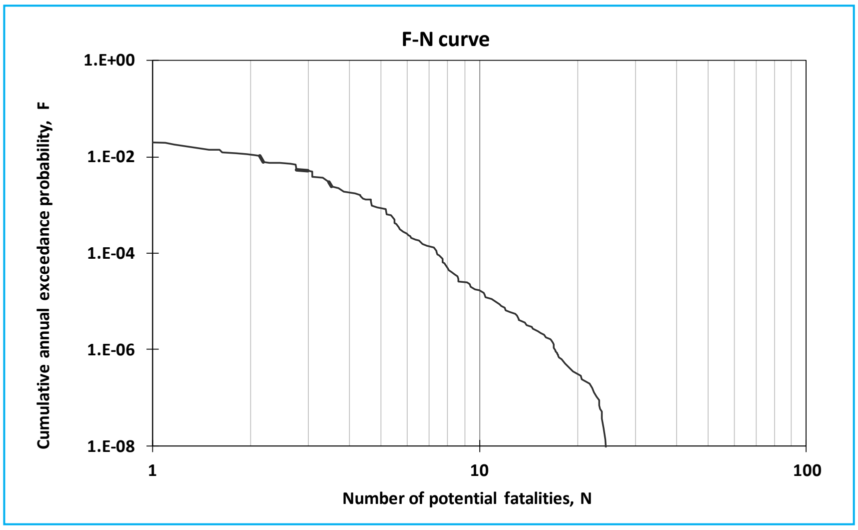

Figure 2: Example of a F-N curve-

F-N and F-D curves are used to represent outcomes of flood risk identification, characterization and estimation and they allow the comparison of different scenarios, e.g. existing risk vs. risk after implementing new measures for flood risk reduction. Therefore, these curves may capture the impact of risk reduction measures in the probability of the flood event (i.e. the curve shifts downwards in case of a reduction of such probability) and/or in flood consequences (i.e. the curve shifts to the left to the extent of such reduction on potential flood consequences due to the risk reduction measure).

F-N and F-D curves can be obtained from outcomes of risk estimation. There exist different techniques for risk analysis and estimation. In this article, we propose the use of event trees and influence diagrams. An event tree is an exhaustive representation of all events and possibilities that can lead to, for example, the failure of a flood defence infrastructure. It is commonly used as a tool for carrying out the calculation of a failure probability or the risk associated to it (Serrano-Lombillo et al., 2009). Each branch of the event tree comprises a possible flood event with related conditional probabilities and potential consequences, as shown in a simplified example in Figure 3.

Within the event tree framework, risk models are proposed to perform the analysis by using a simplified scheme or influence diagram that includes all necessary information to develop the event tree and characterize flood risk.

Influence diagrams are a compact conceptual representation of the logic of a system, e.g. a system of dams or an urban area protected by flood defenses. In its most generic form, an influence diagram can be any graphic representation which includes the relationships between possible events (loads), state and response of the system and consequences. An influence diagram offers a visual representation of the risk model, in which each variable is represented by a node and each relationship by an arc (a simplified example is shown in Fig. 4).

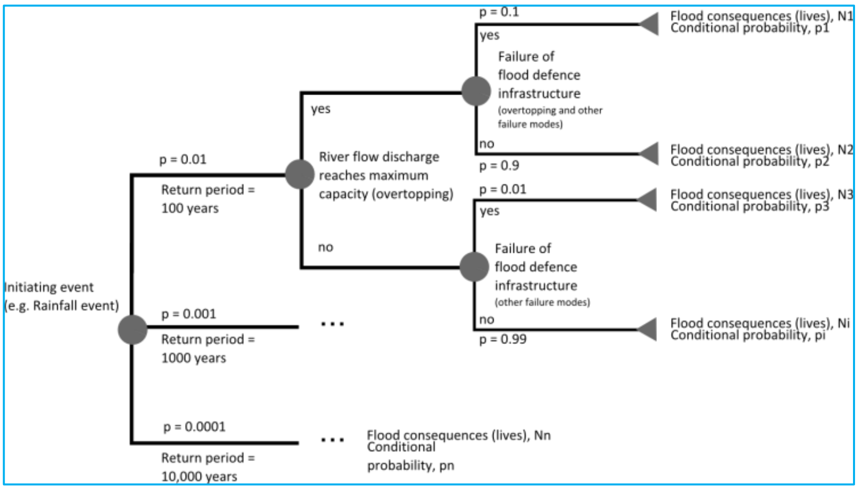

Figure 3: Example of an event tree

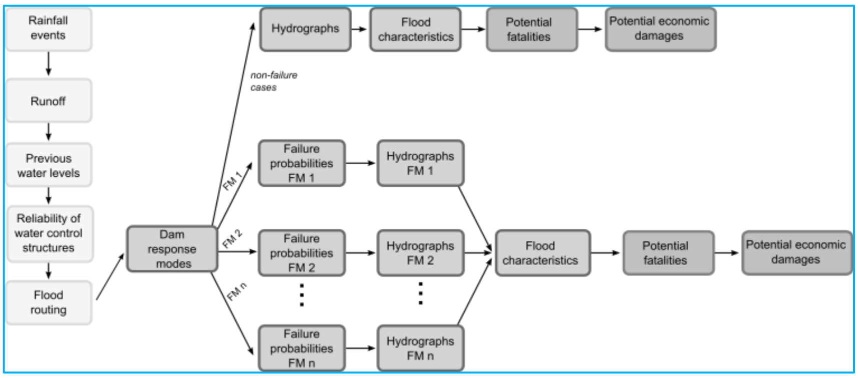

Figure 4: Example of an influence diagram

2.2. Description

The proposed methodology establishes ten phases for the risk analysis process, following the scheme developed in the SUFRI project as shown in Figure 5 and Table 1.

First, Phases I and II focus on the definition of the scope of the study and level of detail of the analysis based on review of available information. Next, Phase III includes the definition of the Base Case, that is, the characterization of the ‘system’ and the definition of the necessary assumptions to analyze the current situation. Later, in Phase IV, a series of possible flood events is defined to estimate the corresponding system response and potential consequences. In Phase V, the risk model architecture for the Base Case is established and it will be the reference model for analyzing other situations such as the impact of risk reduction measures. Consequently, Phase VI includes all necessary estimations to provide the risk model with input data on loads, system response and consequences. Then, results from risk calculations can be represented in F-N and F-D curves, allowing flood risk evaluation when possible (depending on the existence of standards or tolerability criteria). Finally, the analysis of the impact of risk reduction measures (e.g. non-structural measures) is developed in Phase X by comparing new outcomes with results from the Base Case.

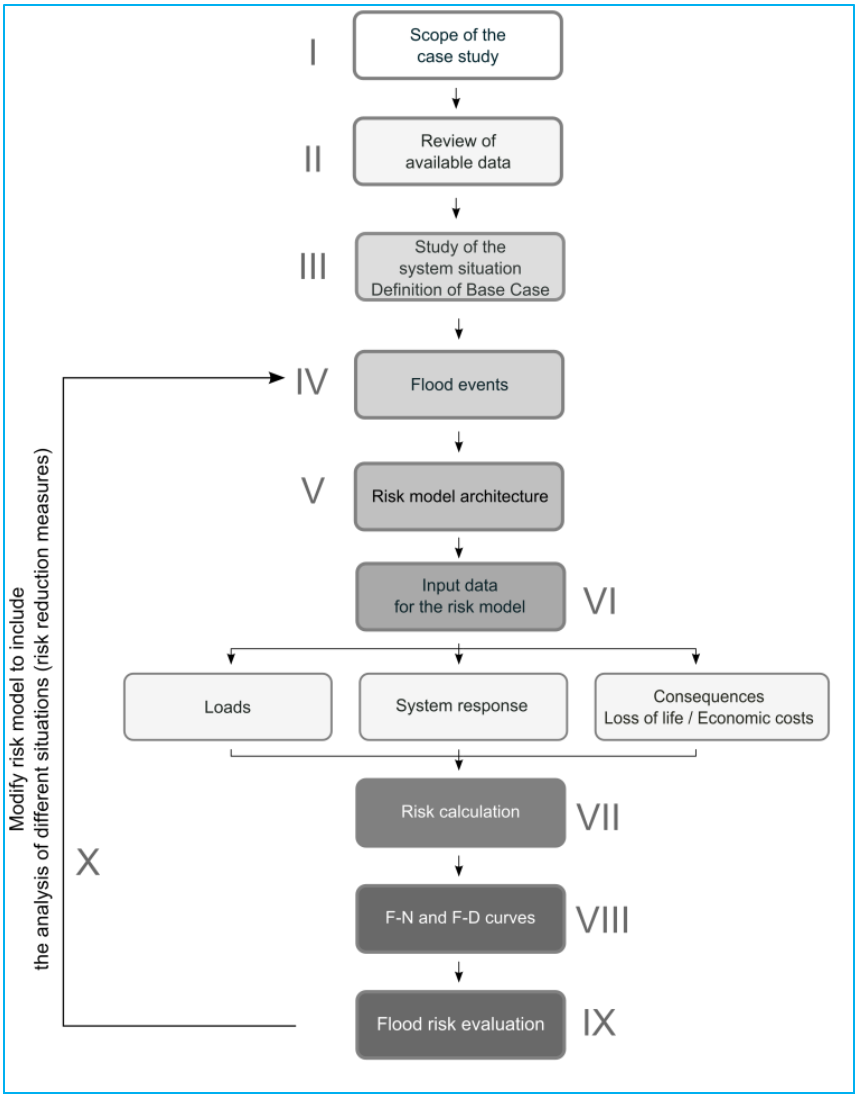

Figure 5: Phases of the methodology for flood risk analysis and assessment.

Table 1: Phases of the methodology

Phase	Definition
Phase I	Definition of the scope and aim of the study
Phase II	Review of available data
Phase III	Study of the current situation: Definition of the Base Case
Phase IV	Definition of flood events
Phase V	Definition of the risk model architecture
Phase VI	Estimation of input data for the risk model
Phase VII	Risk calculation
Phase VIII	Representation of F-N and F-D curves
Phase IX	Flood risk evaluation
Phase X	Analysis of different situations and comparison with the Base Case

3. APPLICATION TO A CASE STUDY

3.1. Introduction

The methodology has been applied to the urban area of Benaguasil (Valencia, Spain). Benaguasil is a town located in the east of Spain (Figure 6), 20 km inland the city of Valencia. Benaguasil is a traditional agricultural village, with a population of about 11,000 inhabitants and a surface of 25.6 km^2. The case study of Benaguasil is suitable for the analysis since it is situated in the left bank of the Turia river (Figure 6). The municipal term is located in the catchment areas of the Turia river, managed by the Jucar River Authority, and two tributary rivers: Castellana and Escarihuela brooks (Figure 6).

The urban area is also affected by the existence of another brook, Benaguasil brook, which is located at the eastern part of the city.

Benaguasil is located 40 km downstream Loriguilla dam. The dam is 78.67 high and the maximum volume reservoir is 73 Hm^3. Dam construction works were finished in 1965 and its Emergency Action Plan (EAP) was formally written in 2004 (but it has not been implemented yet). A first risk analysis of Loriguilla dam was carried out in 2007 (Gómez de Membrillera-Ortuño, 2007) as part of a PhD dissertation at Universitat Politècnica de València. Information from this analysis has been used to incorporate input data into the risk model of the case study concerning flood routing, failure modes and reliability of water control structures. The EAP of Loriguilla dam provides information of flooding areas, peak discharges, arrival wave times, maximum flood depths, etc. in several locations along the Turia river course. The municipal term of Benaguasil is affected by the flood but no damages are identified in the urban area.

Regarding pluvial flooding, Benaguasil experiences frequent flooding from rainfall events which result in high runoff rates due to the existence of high slopes at the urban area and three nearby hills located at the eastern part of the city (*el Picador, la Mina* and *Montiel*).

Figure 6: Location of the case study: a) at national scale; b) Municipal term of Benaguasil (in red)

During the SUFRI project [11], local authorities exposed their willingness to collaborate in the application of the methodology for flood risk analysis to improve local flood emergency planning.

3.2. Analysis

The analysis of pluvial flooding in the city of Benaguasil was first carried out within the SUFRI project [11] as a pilot case. In this article, which is based on findings of such project, the work goes one step further by considering river flooding (from Turia river and Castellana and Benaguasil brooks) and the structural collapse of Loriguilla dam.

Two situations are analyzed for this case study:

- the current situation, denoted as Base Case;
- a hypothetic situation with non-structural measures, denoted as NonSt-Case, which includes measures to cope with residual risk, including public education and warning, along with the implementation of the EAP of Loriguilla dam.

Pluvial flooding, river flooding from Castellana and Benaguasil brooks and river flooding from Turia river including structural collapse of Loriguilla dam have been analyzed for each of these two situations.

Concerning estimation of flood consequences, potential loss of life and economic damages have been obtained for residential, industrial and tertiary areas (e.g. sports centres). Neither potential consequences in rural areas nor to infrastructures are considered. Potential consequences due to pluvial flooding are only estimated within the urban area of Benaguasil not at the whole municipal term. However, potential consequences in case of river flooding or structural collapse include affected households and industrial activities (e.g. quarries) within the municipal term.

The analysis followed the ten phases shown in Table 1 and it is here summarized. The analysis has considered all flood events which result from rainfall events at the urban and river catchment areas for return periods up to 500 years. The structural collapse of Loriguilla dam is analyzed based on inflow rates at the reservoir for return periods up to 10,000 years.

Three risk models have been developed for analyzing this case study, under the hypothesis of independence of pluvial flooding, river flooding from Castellana and Benaguasil brooks, and river flooding from Turia river including structural collapse of Loriguilla dam. This hypothesis is a simplification of a very complex reality. However, climate and topographic conditions of Benaguasil make it a reasonable assumption. These three models are shown in Figure 7.

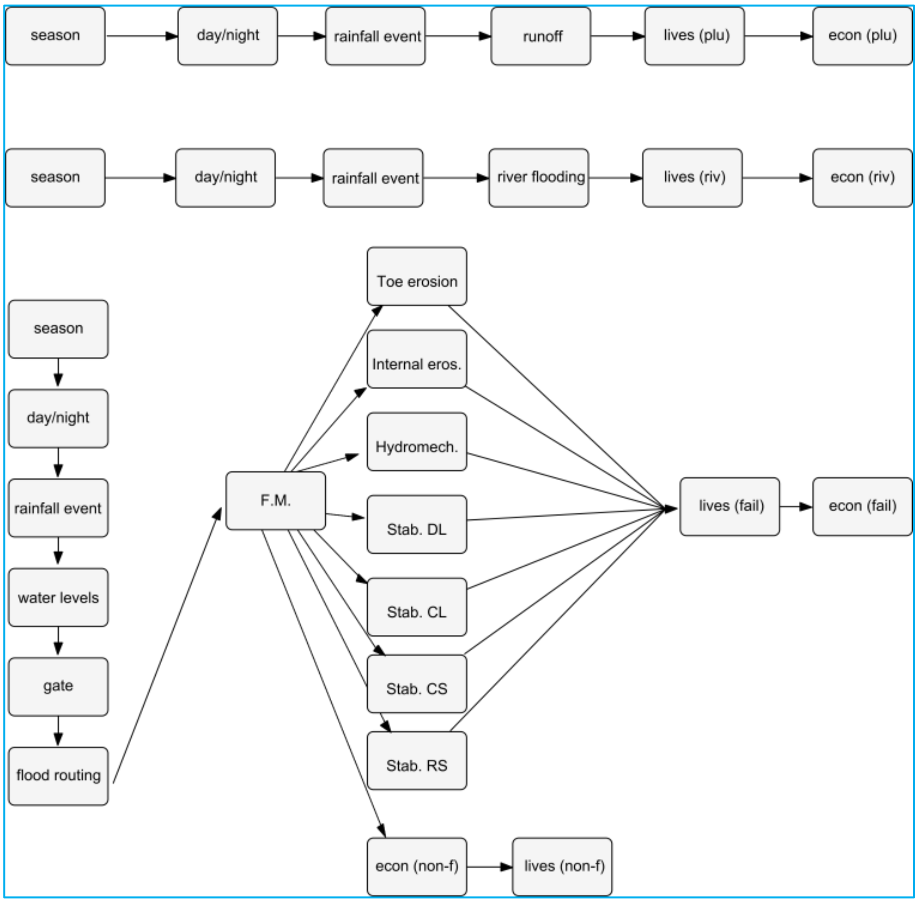

Figure 7: Risk models used for the analysis of the case study. a) Pluvial flooding; b) River flooding from Castellana and Escarihuela brooks; c) River flooding from Turia river, including Loriguilla dam structural collapse

Input data on loads, system response and consequences for the three models were obtained for the two situations, Base Case and NonSt-Case.

Four different zones within the municipal term of Benaguasil were identified for estimating potential consequences depending on the source of flood hazard (denoted as Zones A, B, C and D). These zones are: first, Zone A included potentially affected areas by river flooding from Castellana brook in the proximity of the Turia river course; second, Zone B included potentially affected areas by river flooding from Benaguasil brook; next, Zone C referred to the entire urban area of Benaguasil and it has been considered for estimating flood risk due to pluvial flooding, and, Zone D included areas where the EAP of Loriguilla dam identifies elements potentially affected by structural collapse (mainly auxiliary households and industrial activities).

Table 2 summarizes the two analysed situations and the three different risk models used for calculations.

Table 2: Summary of the proposed analysis for the case study of Benaguasil.

	Source of hazard		
Situation	Pluvial flooding (Model 1)	River flooding Castellana and Benaguasil brooks (Model 2)	Turia river and structural collapse (Model 3)
Base Case Current situation	Affected area: Zone C Current potential loss of life and economic damages	Affected area: Zones A and B Current potential loss of life and economic damages	Affected area: Zone D Current potential loss of life and economic damages
NonSt-Case Non-structural measures of public education and warning +EAP Loriguilla dam	Affected area: Zone C Potential loss of life and economic damages for higher flood severity understanding and warning systems	Affected area: Zones A and B Potential loss of life and economic damages for higher flood severity understanding and warning systems	Affected area: Zone D Potential loss of life and economic damages with EAP

Results of the aforementioned risk models in terms of F-N and F-D pairs were used to combine all possible flood events, and the corresponding conditional probabilities, from pluvial flooding, river flooding from Castellana and Benaguasil brooks and Turia river flooding along with structural collapse to obtain total flood risk. Potential consequences are estimated combining inputs from the three types of flood events, adapting input data to avoid double counting in areas affected by several sources of hazard.

3.3. Results

Results for the two analysed situations, integrating pluvial flooding, river flooding and structural collapse of Loriguilla dam, are represented in Figures 8 and 9.

In terms of societal risk (Figure 8), the Base Case shows a cumulative annual exceedance probability of $1 \cdot 10^{-2}$ of 10 potential fatalities or more. However, the situation with non-structural measures shows that this value decreases up to 3 potential fatalities, approx., for the same probability. This reduction demonstrates the impact of the considered non-structural measures of public education and warning on flood risk reduction.

These curves show a small increase to the right for a cumulative annual exceedance probability of $5 \cdot 10^{-6}$. This increase on flood risk captures the impact of structural collapse of Loriguilla dam. It is noticeable that expected consequences from dam failure contribute a small share to the total flood risk as the main urban area is located far from flooding due to structural collapse.

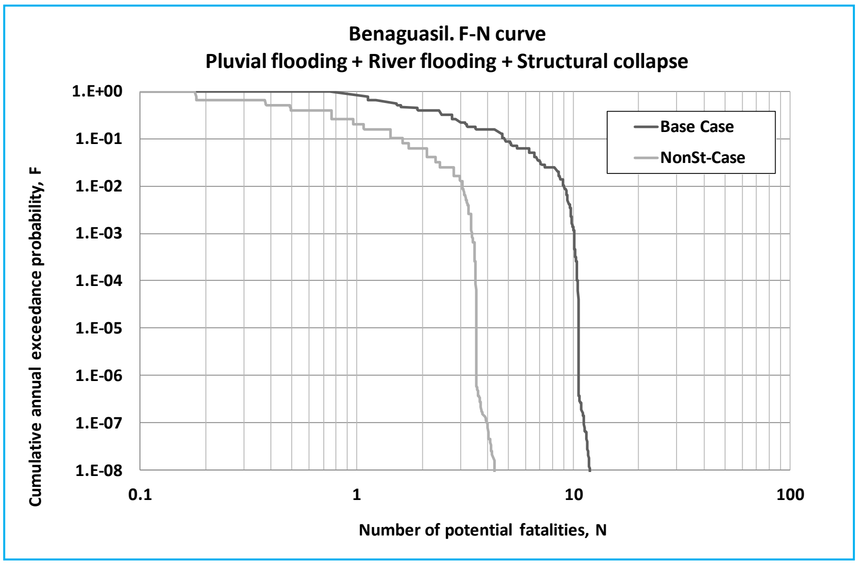

Figure 8: F-N curves integrating pluvial flooding, river flooding and structural collapse. Base Case and NonSt-Case

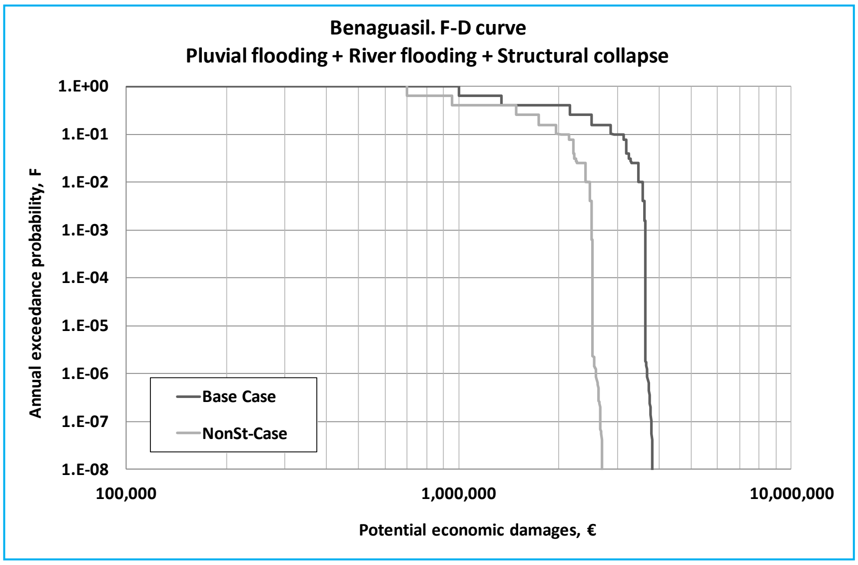

Figure 9: F-D curves integrating pluvial flooding, river flooding and structural collapse. Base Case and NonSt-Case

Economic risk is represented in Figure 9. The Base Case shows a cumulative annual exceedance probability of $1 \cdot 10^{-3}$ of approximately 3,400,000 € of potential economic damages or more. This value decreases for the situation with non-structural measures moving to 2,600,000 €. Both curves show a slight increase to the right, which reflects the small impact of structural collapse of Loriguilla dam on economic risk. However, F-D curves show relatively high potential consequences for high probability values (10^{-1}, 10^{-2}) due to pluvial flooding.

Validation is generally performed by comparing simulations with observed past events. However, specific observations and quantitative data from past events were not available. Despite these limitations, results of the current situation have been validated by local authorities based on experience of recent flood events, mainly based on pluvial flooding.

Representation of results from flood risk analyses into F-N and F-D curves has allowed to communicate existent risk and potential effect of risk reduction measures to local authorities. Based on these outcomes, the local government has decided to develop a Municipal Action Plan against Flood Risk for the city of Benaguasil. The aim of this plan is to define the necessary organizational and operating schemes, procedures and measures before, during and after the flood. Results of flood risk analysis have been used to develop qualitative flood risk maps for emergency services, urban planners and the public. In addition, information campaigns, activities for public education, advice to the public, etc. are also included in this plan to promote public education on flood risk. In addition, communication chains and warning messages are considered to be activated in case of flood. The implementation of this plan will represent a key action towards an improved flood risk management in Benaguasil.

4. CONCLUSIONS

The main aspects on flood risk analysis, assessment and management have been discussed in the first section of this paper, including references to existing methods for estimating flood risk. Existing methods for flood risk analysis do not take into account the integration of several sources of hazard. To help covering this lack, this article presents a comprehensive methodology for urban flood risk analysis integrating the analysis of pluvial and river flooding including structural collapse of flood defense infrastructures.

The methodology is mainly based on the methodological piece developed within the SUFRI project that allows the quantification of flood risk in urban areas, complemented with the analysis of structural collapse of flood defense infrastructures. The goal of the proposed methodology is to analyze flood risk and to support decision making on risk reduction measures. This methodology provides a tool that can be applied to inform authorities, local entities and stakeholders involved on decision making to establish risk mitigation actions.

The methodology here presented is generally applicable. However, flood risk understanding and awareness of population at risk should be addressed for each case study. Hence, integrating social research data may be helpful to characterize consequences (Escuder-Bueno et al., 2012b).

The use of risk models and F-N and F-D curves provides societal and economic risk values in quantitative terms. The relevance of quantitative flood risk analysis in urban areas is supported by results, indicating that F-N and F-D curves are helpful and comprehensive tools to represent flood risk. These curves are helpful in planning and managing mitigation measures. Furthermore, they may be used to compare predicted risks against tolerability criteria or to historical data. Reinforcement of best policies (e.g. urban planning, emergency management, civil protection, etc.) and good governance may be achieved by outcomes of flood risk analysis. In addition, the uncertainty of the results will depend on the available data, level of detail of hydrologic and hydraulic calculations, estimation of system response and potential consequences.

The proposed methodology has been applied to a case study with the aim of developing a municipal action plan against flood risk based on outcomes of flood risk analysis. The results of the case study showed that the impact of non-structural measures on flood risk can be captured by the presented approach.

The results of the analysis of non-structural measures revealed that current risk is sensitive to warning times and public education would reduce considerably societal and economic risk.

Based on the existent flood risk and the potential of non-structural measures on risk reduction, it is confirmed that the implementation of a municipal action plan against flood risk would reduce potential consequences.

Further work needs to be done to estimate the economic cost of the proposed non-structural measures and their efficiency. Flood risk analysis can support decision making by providing information to prioritize risk reduction measures. Hence, it is important to measure not only the impact but also the efficiency of different measures. Further research could be conducted to evaluate efficiency by defining indicators, as those found in the literature for dam safety management (ANCOLD, 2003).

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ANNEX 6: A risk-informed journey towards improved dam safety governance in Spain

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A risk-informed journey towards improved dam safety governance in Spain

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TITLE

A risk-informed journey towards improved dam safety governance in Spain

ABSTRACT

The world has evolved significantly in last decades in the way of understanding floods and dam and other critical infrastructure protection. Modern societies depend on the correct and efficient behavior and operation of these infrastructures. In addition, there is an increasing social demand for higher safety levels, then requiring the integration of design, construction and operation of dams on a risk management framework that allows to mitigate both natural and manmade threats.

In this context, the application of risk analysis techniques has emerged as a paradigm shift, enhancing dam safety and flood risk assessment and management.

The dam safety management context in Spain is evolving as a result of new regulation, guidelines and state-of-the-practice at national and international level. This paper presents an overview of this changing context and how Risk Analysis arises as a tool to guide dam owners towards an integrated dam safety management and governance. Successful pilot cases can be found for which the benefits of applying risk analysis techniques have been proved, supporting prioritization of risk reduction measures and improving dam knowledge, operation and maintenance. These pilot cases represent the first steps of a journey for dam owners, aiming at achieving efficient, transparent and robust dam safety governance.

KEYWORDS

Dam Safety Management, Dam Safety Governance, Risk Analysis

1. INTRODUCTION

The world has evolved significantly in last decades in the way of understanding floods and critical infrastructure protection (including dams). Modern societies depend on the correct and efficient behavior and operation of these infrastructures.

Society demands higher levels of safety and reliability of critical infrastructures, then requiring the integration of design, construction and operation of dams on a risk management framework that allows to mitigate both natural and manmade threats in an efficient and effective way. This concept of integrated risk management has acquired importance in recent years and current dam safety management strategies require incorporating aspects such as sustainability, resilience and public participation.

In this context, the application of risk analysis techniques has emerged as a paradigm shift, enhancing dam safety and flood risk assessment and management. The European Flood Directive 2007 (EC, 2007) and the European Directive on Critical Infrastructure Protection 2008 (EC, 2008) are examples of such change. Both directives remark the need for identifying, characterizing and analyzing risk for establishing strategies for flood risk and critical infrastructure management.

In the United States, following the journey initiated by the United States Bureau of Reclamation in the nineties, the United States Army Corps of Engineers (USACE) and the Federal Emergency Regulatory Commission (FERC) have implemented risk-based dam safety management processes. At the European level, France enacted specific regulation in 2008 to develop the process at national level.

The state-of-the-practice worldwide recognizes the benefits of Risk Analysis as a tool for supporting decision making for critical infrastructure management, encouraging other improvements in operation and maintenance, surveillance or emergency preparedness.

In Spain, national regulation includes since 2008 the need for considering risk management as a key driver for establishing dam safety strategies, following the example of other countries. Therefore, in recent years there has emerged a new perspective for dam safety management which incorporates Risk Analysis, which aims at combining both the traditional (essentially deterministic) and the risk-informed dam safety approach, focusing on all risk components associated with a potential dam failure or uncontrolled release.

In this paper, an overview of the dam safety management framework in Spain is provided (including actors and legislation), emphasizing the paradigm shift that has arisen in recent years with the application of risk analysis techniques to support dam safety management and governance.

2. DAM SAFETY MANAGEMENT IN SPAIN

2.1. Context

Spain is geographically located in the Southwest of Europe, with an area of 505,182 km^2 and a population of roughly 47 million inhabitants. Spain´s total water resources are estimated in 112 km^3 per year, resulting in about 2,700 m^3/per person/year (the average of European Union countries is 3,200 m^3/per person/year) (SPANCOLD, 2006). Nevertheless, these water resources are highly irregular in time and an uneven geographic distribution (Figure 1a).

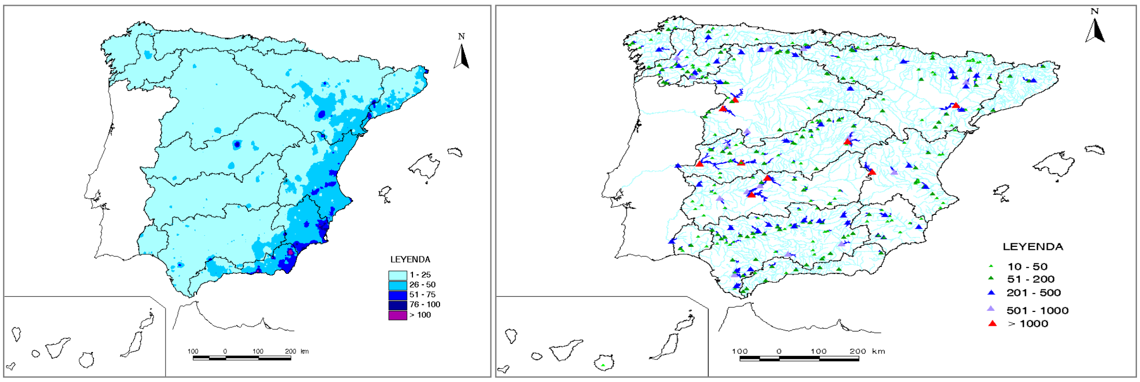

Figure 1: (a) Registered maximum daily rainfall vs. average yearly rainfall; (b) Dams in Spain and storage capacity in hm^3. Source: MAGRAMA, 2015.

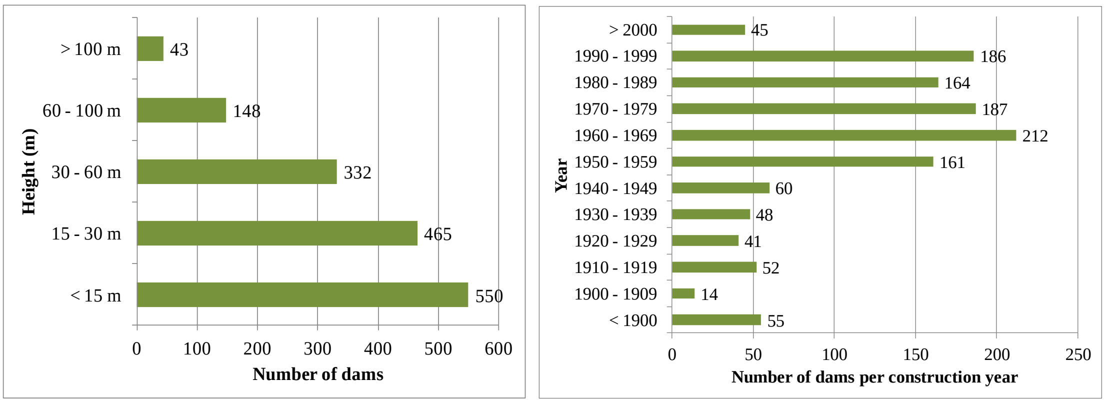

Figure 2: (a) Classification of dams in Spain based on dam height; (b) Number of dams in Spain per year of construction. Source: MAGRAMA, 2015.

Spain has a large tradition on dam construction. According to ICOLD (International Commission on Large Dams), Spain ranks ninth in the world in terms of number of large dams (the ICOLD Register of dams includes dams above 15 m high or ranging from 5 to 15 m high with a storage capacity above 3 hm^3), where the registered numbered of large dams is of 1082.

The total number of dams in Spain rises to 1225 (Figure 2a), most of them built in the last 60 years (Figure 2b).

Dams have played an important role in Spain regarding flood protection, hydroelectric production and water resources management over decades. Dams have been built across the whole country in both upstream and downstream areas of river catchments basins, aiming to cope with highly irregular water inputs, frequent drought events, and floods that usually take place in a short period of time (e.g. ratios between registered maximum daily rainfall and the average yearly rainfall above 100% are found in eastern areas, Figure 1a).

2.2. Actors

Given the aforementioned facts, it is undeniable that there exist a large number of dam owners in Spain, including public and private holders. Around one third of the total Spanish large dams are owned and operated by Spanish Ministry on Food, Agriculture and Environment (MAGRAMA), through the surrogated authorities given to the River Basin Authorities (RBAs) which, in addition, hold the authority to enforce and develop integrated water resources planning and management, flood control and environmental protection, among other activities. In accordance with the Water Framework Directive (WFD), 18 River Basin Districts have been defined in Spain (Figure 3). River Basin Authorities are public entities with autonomy of action and their own legal personality. Two types of them can be distinguished: inter-regional basins (e.g. Jucar River Basin) and intra-regional basins (e.g. Catalonia Intra-regional Basins).

With more than 1400 dams (including also small dams and ponds), functions and responsibilities of dam owners regarding dam safety management have evolved as a result of a changing dam safety regulation framework. The current national dam safety regulation framework is presented in next subsection.

2.3. Legislation and other instruments

Regulation on Water and Flood Risk is strongly connected to Dam Safety Management. Overarching national and European legislation influencing, one way or another, dam safety management, include the Water Act of 1985 (and subsequent upgrades), the National Hydrological Plan Act of 2011 (and subsequent upgrades) and the Water Framework Directive (WFD) of 2000 and its transposition to Spanish Legislation.

More related to Dam Safety Issues are the more recent European Directives on Floods and Critical Infrastructure, as well as their transposition to the Spanish Legislation:

- European Directive 2007/60/EC (EC, 2007) on the assessment and management of flood risks (so-called EU Flood Directive).
- European Directive 2008/114/EC (EC, 2008) on the identification and designation of European critical infrastructures and assessment of the need to improve their safety levels.

Directive 2007/60/CE acknowledges and explicitly requires that risk analysis must be used as a tool for flood risk reduction, through the development of flood risk management plans at river basin level and conducting flood risk analyses including dam failure.

More particularly, the history of dam safety regulation in Spain has been influenced by two dam failure events: the failure of Ribadelago dam (Zamora, Spain) in 1959 and the failure of Tous dam (Valencia, Spain) in 1982. Both failures were landmark events in the national dam safety regulation framework.

The current dam safety regulation context in Spain includes mainly two standards:

- the "Instruction for the Design, Construction and Operation of Large Dams" (*Instrucción para el Proyecto, Construcción y Explotación de Grandes Presas*) published in 1967, and,
- the "Technical Regulation for Dam and Reservoir Safety" (*Reglamento Técnico sobre Seguridad de Presas y Embalses*) published in 1996.

The approval of the 1996 Technical Regulation did not imply the revoke of the 1967 Instruction. This fact has been one of the problems more intensely discussed by the Spanish dam community and both standards remain applicable up to now.

The 1996 Technical Regulation included concepts and dam safety criteria that had evolved significantly since the publication of the Instruction of 1967 and it is applicable to all publicly owned dams and to all private dams constructed after 1996. This Technical Regulation affects more specifically on dam safety issues and has a partial but progressive implementation.

The Technical Regulation was approved one year after the adoption of the Basic Directive of Civil Protection Planning against Flood Risk (1995). Up to this point, dam safety management had focused almost exclusively on the infrastructure; however, the 1995 Civil Protection Directive incorporates the consideration of both flood risk components (probability and consequences). Therefore, the 1995 Civil Protection Directive represents a milestone in the dam safety regulatory framework so far, requiring the implementation of Dam Emergency Action Plans (DEAPs) for those that have previously been classified as Category A or B based on its potential risk (considering the possibility of adverse potential consequences in case of failure or uncontrolled dam release). This classification was defined by the 1996 Technical Regulation.

Table 1 shows the number of dams in Spain classified by potential risk in A, B or C. Considering A and B dams, 301 out of 821 required DEAPs have already been approved (Table 2). Before being approved, DEAPs are evaluated by MAGRAMA and the Spanish Civil Protection Department.

Table 1: Number of dams per category based on potential consequences in case of failure (potential risk). Source: MAGRAMA, 2013.

Category	Number	Owner (public/private)
A	718	400/318
B	103	43/60
C	629	208/421
Total	1450	651/799

Table 2: Number of approved EAPs. Source: MAGRAMA, 2013.

EAP	Number	Owner (public/private)
Approved	301	194/107
In evaluation by MAGRAMA	203	121/82
In evaluation by Civil Protection	42	28/14
Total	546	343/203

The content of a DEAP should include aspects such as dam safety analysis, dam break scenarios, flood mapping and identification of affected areas (usually consisting of a qualitative assessment of potential consequences), emergency procedures, and organizational schemes. The elaboration and implementation of DEAPs has constituted a complex process, requiring the development of guidelines by MAGRAMA to support the process.

The last update of the Spanish Public Water Regulation (16 January 2008) added a new chapter which deals with dam safety, including the need for considering risk management as a key aspect for dam safety, whose main objective is to unify all dam safety criteria to be applied to all dams. Consequently, three Technical Standards were published in 2011, but not approved so far, that will replace both the 1967 Instruction and 1996 Technical Regulation.

In addition to the aforementioned regulatory documents, a set of Technical Guidelines for Dam Safety has been published by the Spanish National Committee on Large Dams (SPANCOLD) of the International Commission on Large Dams (ICOLD).

These guidelines include the state of art in several dam safety aspects and provide recommendations for accomplishing current standards. Published in 2012, the Technical Guide on Dam Safety, Operation of dams and reservoirs, titled "Risk Analysis applied to Dam Safety Management" is a recent milestone in the Spanish context and describes the general process for implementing Risk Analysis in order to inform decision-making and prioritization of risk reduction measures for dam safety management (SPANCOLD, 2012). This guideline can be considered a significant contribution towards integrated risk-informed dam safety management.

2.4. New paradigm: Risk-informed dam safety management

The application of risk analysis techniques to dam safety management has involved a paradigm shift, but dam safety risk analysis is not new. Following the failure of Teton dam in 1976, the U.S. Bureau of Reclamation (USBR) implemented a dam safety program in 1978, in accordance with national dam safety legislation. This program was in line with their mission “to protect, to the extent practicable, people from risks posed by dams.” It represented the first step in a journey toward dam safety risk-informed management.

Risk-based approaches for dam safety analysis were presented by the Australian National Committee on Large Dams (ANCOLD) in 1994, through the Dam Safety Management Guideline (ANCOLD, 2003), which was later revised in 2003. Risk-based approaches were also introduced by the United States Society on Dams (USSD) in 2003, in a White Paper on Dam Safety Risk Assessment (USSD, 2003). In addition, the International Commission on Large Dams (ICOLD) published its Bulletin 130 in 2005 (ICOLD, 2005), including concepts such as the As-Low-As-Reasonably-Practicable (ALARP) criterion and the Cost-Per-Statistical-Life-Saved indicator (CPSLS).

Risk-informed dam safety management requires outcomes from risk analysis and assessment for supporting decisions. Risk analysis allows the dam owner, as well as the public, to understand the system and to document all information regarding contributions made to risk. Different risk analysis methods can be found. These methods may be partial or complete, if they analyze one or both risk components (probability and consequences). In addition, they may be classified as quantitative or qualitative, based on the nature of obtained risk outcomes. Among existing methodologies for dam safety risk analysis (Harrald et al., 2006), several complete and quantitative examples can be found. At the Spanish context, the framework for risk-informed dam safety management published by the Spanish National Committee on Large Dams (SPANCOLD) includes the analysis of all potential combinations of hazard events, system response and potential consequences that may result from dam failure or mission disruption through the application of risk modeling and the use of event tree analysis for risk calculation (SPANCOLD, 2012). Related work on risk assessment methods where event tree analysis has also been applied can be found in the literature (Castillo-Rodríguez et al., 2014; McGill et al., 2007; Serrano-Lombillo et al., 2011).

The publication of the SPANCOLD Technical Guideline emerged from the collaborative effort of several institutions and experts, incorporating results from research projects that had been developed in recent years. These projects resulted, among other outcomes, in tools for risk calculation, analysis and assessment, and prioritization of risk reduction measures (e.g. the software tool iPresas Calc (Serrano-Lombillo et al., 2009) which allows risk calculation by means of event trees and influence diagrams, first developed at the Polytechnic University of Valencia and now being developed and upgraded by Ingeniería de iPresas SL, a UPV Spin-Off Company).

Efforts from a wide sector of the Spanish dam community are now allocated to enhance and promote risk-informed dam safety management through research and development, practical applications, training and communication. The aim is to achieve improved dam safety governance, based on efficiency, transparency, and sustainability principles. Risk-informed decisions may help to allocate funds more efficiently to protect the population downstream and to explain why actions are taken.

Some examples of further steps in this risk-informed journey are the publication of a simplified methodology (Escuder-Bueno and González-Pérez, 2014) for the evaluation of hydrologic risk on dams and prioritization of risk mitigation measures or new advances for the incorporation of man-made threats into dam risk analysis (Castillo-Rodríguez et al., 2016).

3. CASE EXAMPLES AND LESSONS LEARNED

3.1. Pilot cases

Beyond the regulatory context and the aforementioned advances in risk analysis applied to dam safety management, a series of practical conditions have contributed to its application over the last years, including[9]:

- The need for analyzing existing risk due to the inclusion of dam owners' public responsibility in regulation, along with the social demand for higher safety levels and for justification of the use of private and public funds.
- The need for prioritizing corrective actions for risk reduction.
- The need for optimizing water resources management as well as to increase dam regulation capacity.
- The difficulty of building new dams, mainly due to social and environmental reasons, that will predictably make necessary to extend the dam operational phase.
- The ageing of existing dams (most of them are over 30 years old in Spain).

Several pilot cases have been conducted recently in Spain. These examples include dams from public and private owners, such as:

- Iberdrola [Private owner, Water supply and hydropower], 2010.
- Catalan Water Agency [Public owner, Water supply and irrigation], 2010.
- Duero River Authority [Public owner, Portfolio of dams] , 2010-2013.
- Gas Natural Fenosa Engineering [Private owner, Hydropower and irrigation], 2014-2015.
- Canal Isabel II Gestión [Public owner, Water supply], 2014-2015.
- Government of Extremadura [Public owner, Irrigation], 2014-2015.

These pilot cases have included dam risk analyses at small and large scale (e.g. at portfolio level). As an example, the work conducted by the Duero River Authority represents one of the most complete and documented international examples for a portfolio of dams in recent years (Ardiles et al., 2011). The Duero River Authority promoted the analysis of 27 large dams located in the North-West region of Spain, with a broad variety of typologies and physical characteristics. It was the pilot case used by MAGRAMA to test on transition towards risk-informed decision making in dam safety management.

After analyzing risk for all dams and systems of dams within the portfolio, a set of more than 88 risk reduction measures was considered to analyze different scenarios and to establish the optimal strategy for dam safety management. The software tool iPresas Manager was used for analyzing risk outcomes for all dams and different scenarios, obtaining the optimal sequence of actions, taking into account equity and efficiency principles. Figure 3 shows a screenshot of the software tool for one step in the obtained prioritization sequence. In this graph, results for step 5 out of 88 are depicted. This type of risk representation allows to analyze how actions impact on societal risk (vertical axis) at portfolio level in the prioritization sequence (horizontal axis). After implementing the first five actions, societal risk shifts from 0.3 lives/year to 0.06 lives/year with a total cost of 3 M€. Economic risk would be reduced from 1.7 M€/year to 0.25 M€/year. Results from portfolio analysis shown that no risk reduction is provided further than measure 27 (approx. 28 M€), as risk reduction from applying next measures would become very marginal. This would represent one third of the total cost of implementing all measures (approx. 67M€).

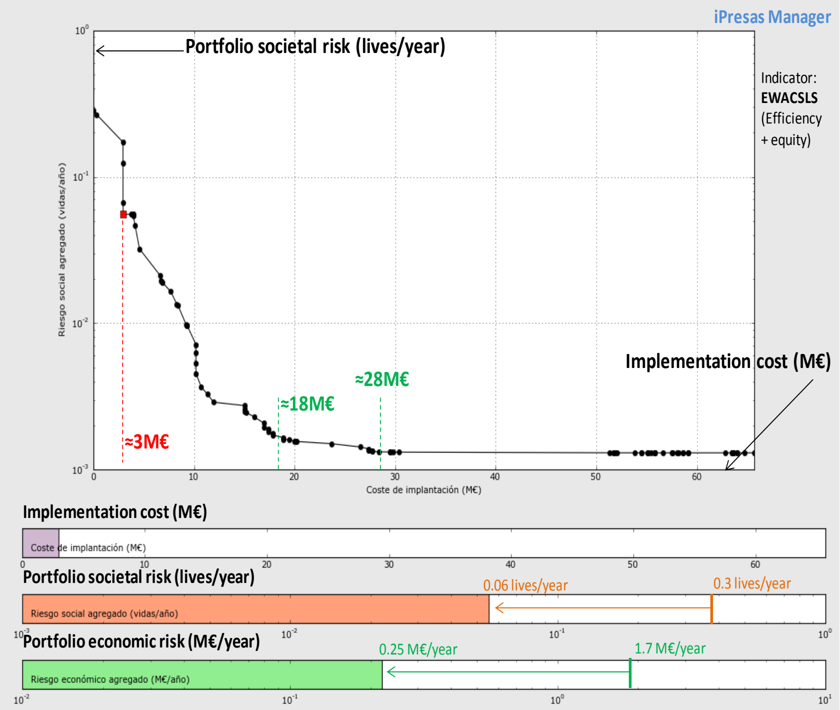

Figure 3: Portfolio societal risk (lives/year) in the prioritization sequence. Source: iPresas Manager.

Lessons learned from pilot cases conducted in Spain have revealed the benefits of incorporating risk analysis techniques to dam safety management. These benefits include, among others:

- Improved understanding of the dam system (deeper knowledge of the dam, identification of knowledge gaps, uncertainty analysis, etc.).
- Improved decisions (prioritization of investments including efficiency and equity principles).
- Improved risk communication (for public education and awareness).
- Improved information for dam operation and maintenance.
- Improved emergency procedures and flood risk management plans.
- Good dam governance (decisions are justified, defensible and transparent).
- Business risks are known, enhancing business sustainability at mid and long term.

3.2. The value of integrating information for dam safety management

The application of risk analysis techniques provides a logical framework for better understanding the dam system itself. The added value of integrating all information regarding the dam system is inherent to any dam risk analysis, even in the case of purely qualitative analyses. Information from inspection and monitoring, operation and maintenance, operational rules, emergency action plans, etc. is reviewed, discussed, updated and, in a quantitative stage, incorporated to the risk model representing the system. Dam owners benefit from this process, gaining a better knowledge of the system.

The benefits of risk analysis and the added value of integrating information through risk analysis techniques go beyond the dam safety management discipline. As proposed in Castillo-Rodríguez et al. (2014), risk analysis techniques allow to integrate also all information from multiple hazards for flood risk analysis and management. In this case, dam failure events and uncontrolled releases represent one of the possible sources of flood hazard.

Similarly to the overall process proposed for dam safety risk analysis by the SPANCOLD Technical Guideline, a generic risk model architecture is provided (Castillo-Rodríguez et al., 2014) for flood risk analysis from multiple hazards, as shown in Figure 4.

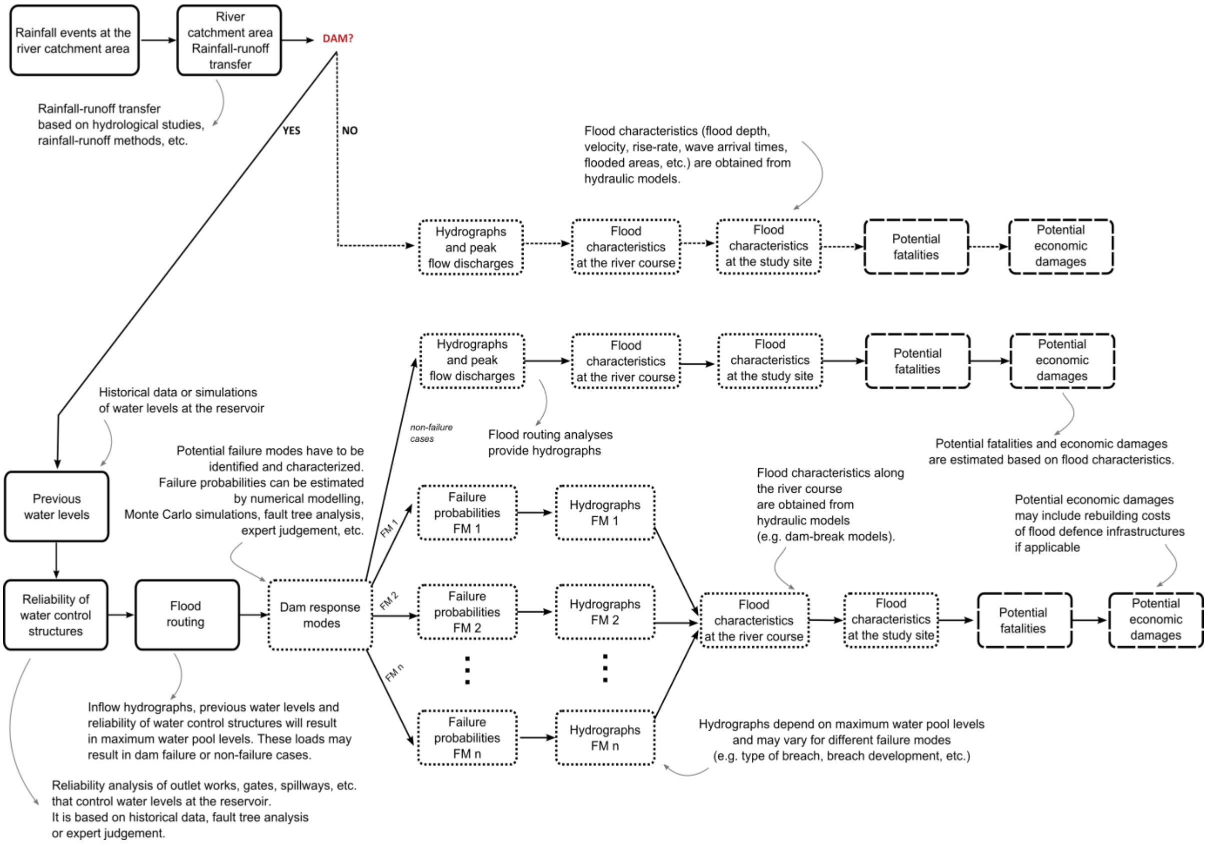

Figure 4: Generic risk model architecture for integrating multiple hazards for flood risk analysis and management. Source:(Castillo-Rodríguez et al., 2014)**.**

This overall scheme integrates the analysis of pluvial flooding, river flooding and flooding from dam failure to provide better and more complete information to decisionmakers on flood risk management.

This integrative approach was applied to a case study in Spain (including flooding from failure a concrete gravity dam upstream the analyzed urban area). Risk outcomes, represented in a FN graph, are shown in Figure 5. Results show cumulative annual exceedance probabilities (vertical axis) for each level of potential consequences by integrating three sources of hazard: pluvial flooding, river flooding and flooding from dam failure. Three scenarios are depicted: the Base Case (current situation), the scenario after implementing the Dam Emergency Action Plan (DEAP) and a third case after implementing non-structural measures of improved emergency management and public risk awareness. A significant impact on flood risk reduction was found for DEAP-case and the scenario with non-structural measures ("high probability" flood events are reduced if compared with the Base Case).

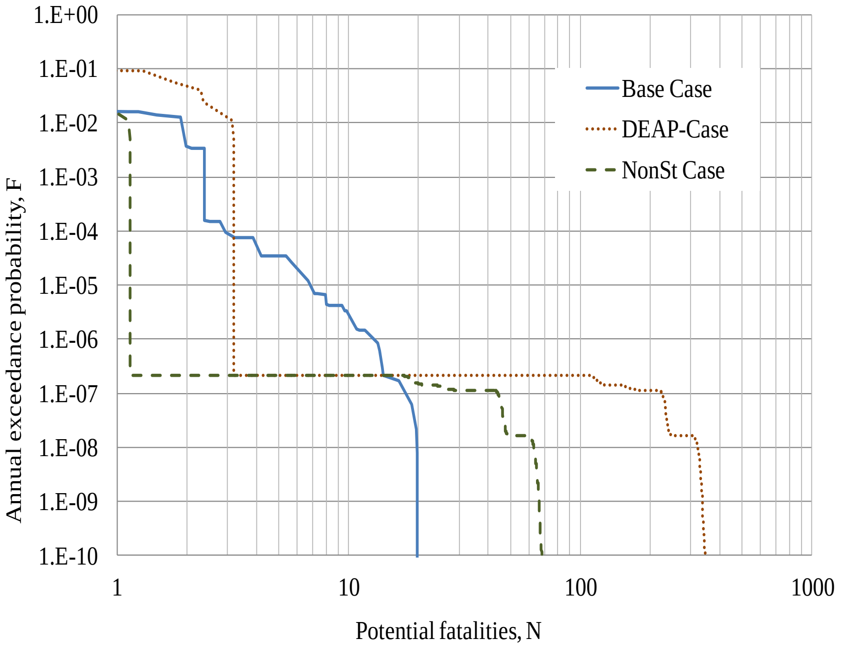

Figure 5: FN graph for a case example of integrated flood risk analysis including dam failure. Three scenarios: base-case, DEAP and non-structural measures. Source: (Castillo-Rodríguez et al., 2014)

4. CONCLUSIONS: FUTURE CHALLENGES AND STRATEGIES TOWARDS SMART DAM SAFETY GOVERNANCE

The dam safety management context in Spain is evolving as a result of new regulation and best practices. This paper has presented an overview of this changing context and how Risk Analysis arises as a tool to guide dam owners towards an integrated dam safety management and governance.

In future years, dam owners will face challenges driven by a changing society, environment and regulatory context. The new risk paradigm provides dam owners with information that is essential to establish strategies for dam safety management for present and future scenarios.

In this context of highly dynamic and complex scenarios, it is worth to remark that increased capacity for effective risk governance will only be possible with the extensive and willing participation of all concerned actors, including international collaboration as a way of improving, validating and maximizing the benefits of enhanced risk governance.

Beyond dam safety, the risk paradigm is an integrative one. As stated before, examples of this integrative paradigm are considering different hazards for flood risk characterization.

Successful pilot cases can be found at national and international scale for which the benefits of applying risk analysis techniques have been proved, supporting prioritization of risk reduction measures and improving dam knowledge, operation and maintenance.

These pilot cases represent the first steps of a journey for dam owners, aiming at achieving efficient, transparent and robust dam safety governance.

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