UNIVERSITAT POLITÈCNICA DE VALÈNCIA

máster en ingeniería hidráulica y medio ambiente
mihma

Título del Trabajo Fin de Máster:

FLOOD RISK MANAGEMENT INTEGRATING PLUVIAL AND RIVER FLOODING AND STRUCTURAL COLLAPSE

Intensificación:

RECURSOS HÍDRICOS

Autor:

CASTILLO RODRÍGUEZ, JESICA TAMARA

Director/es:

DR. ESCUDER BUENO, IGNACIO

Fecha:

SEPTIEMBRE, 2012

This page intentionally left blank

UNIVERSITAT POLITÈCNICA DE VALÈNCIA

máster en ingeniería hidráulica y medio ambiente
mihma

Título del Trabajo Fin de Máster:
FLOOD RISK MANAGEMENT INTEGRATING PLUVIAL AND RIVER FLOODING AND STRUCTURAL COLLAPSE

Autor: ***CASTILLO RODRÍGUEZ, JESICA TAMARA***

Tipo	**A** ☐ **B** ☒	**Lugar de Realización**	***VALENCIA***
Director	***ESCUDER BUENO, IGNACIO***		
Codirector1	**-**		
Codirector2	**-**	**Fecha de Lectura**	***SEPT. 2012***
Tutor	**-**		

Resumen:

CASTELLANO

El concepto de Gestión Integral del Riesgo de Inundación (GIR) promueve un enfoque integral de la gestión del riesgo, con el objetivo de combinar el uso eficiente de las áreas potencialmente inundables con la reducción de las consecuencias potenciales por inundación. Por ello, este enfoque requiere de la consideración de medidas tanto legislativas y financieras como estructurales y de ordenación territorial.

El marco conceptual de la GIR puede encontrarse en diversas fuentes de la literatura ('Tool for Integrated Flood Management', 2008; 'FLOODsite', 2009). En ellas, se presenta como una gestión completa del riesgo que debe considerar todas las posibles causas de inundación, la respuesta del sistema a dichas amenazas y su vulnerabilidad en un contexto social, económico y medioambiental, incluyendo las interrelaciones entre los agentes intervinientes en la gestión del riesgo, en materia de organización, comunicación, coordinación y participación pública.

Por tanto, la GIR debe incorporar los resultados del análisis del riesgo de inundación con el fin de identificar medidas efectivas de reducción del mismo. Las metodologías existentes abordan este análisis desde el punto de vista cualitativo o semi-cuantitativo, aplicadas generalmente a casos de estudio específicos.

Por ello, existe la necesidad de desarrollar una herramienta que permita un análisis cuantitativo del riesgo. Esta metodología debe poder integrar diferentes causas de inundación y obtener el riesgo tanto en términos de pérdida potencial de vidas humanas como en costes económicos, proporcionando información clara y robusta que sea útil en la toma de decisiones.

La metodología presentada en este Trabajo Fin de Máster se basa en las investigaciones derivadas del proyecto SUFRI 2009-2011 ('Sustainable Strategies of Urban Flood Risk Management with non-structural measures to cope with the residual risk', 2nd CRUE ERA-Net Funding Initiative), presentadas durante la 'Tercera Semana Internacional del Análisis de Riesgos, Seguridad de Presas y Gestión de Infraestructuras Críticas' (Valencia, Octubre 2011), así como en el artículo aceptado para publicación en 'Natural Hazards and Earth Systems Science' (julio 2012).

Este trabajo presenta un enfoque integral que incluye el riesgo de inundación por precipitación 'in situ' (inundación de origen pluvial), desbordamiento de cauces (inundación de origen fluvial) y fallo o colapso de infraestructuras de defensa frente a inundaciones (e.g. rotura de presa). La metodología se ha aplicado a un caso de estudio con el objetivo de poner en valor los resultados y conclusiones del análisis para mejorar la gestión del riesgo de inundación.

VALENCIANO

El concepte de Gestió Integral del Risc d'Inundació (GIR) promou un punt de vista integral de la gestió del risc d'inundacions, amb l'objectiu de combinar l'ús eficient d'àrees inundables amb la reducció de les conseqüències potencials per inundació. Per això, requerix de la consideració de mesures legislatives, financeres, estructurals, d'ordenació territorial, etc.

El marc conceptual de la GIR pot trobar-se en diverses fonts d'informació ('Tool for Integrated Flood Management', 2008; 'FLOODsite' project, 2009) on el concepte de GIR es presenta com una gestió completa del risc d'inundació que ha de considerar totes les possibles causes, la resposta del sistema i caracteritzar la seua vulnerabilitat en un context social, econòmic i mediambiental. A més, la GIR ha d'incloure les interrelacions entre tots els agents intervinents, centrant-se en la definició d'esquemes avançats d'organització, comunicació, coordinació i participació pública.

Per tant, la GIR ha d'incorporar els resultats de l'anàlisi del risc d'inundació a fi d'identificar mesures efectives per a la seua reducció. Les metodologies existents en aquest àmbit aborden l'anàlisi des del punt de vista qualitatiu o semi-cuantitatiu, aplicades generalment a casos d'estudi específics.

Per això, existeix la necessitat de desenvolupar una metodologia que permeta un anàlisi quantitatiu del risc d'inundació, integrant diferents causes d'inundació i obtenint el risc tant en pèrdua potencial de vides humanes com danys econòmics. Aquesta metodologia ha de proporcionar informació clara que siga útil en la presa de decisions.

La metodologia presentada en aquest Treball Fi de Màster es basa en les investigacions i recomanacions derivades del projecte SUFRI 2009-2011 ('Sustainable Strategies of Urban Flood Risk Management with non-structural measures to cope with the residual risk', 2ª CRUE ERA-Net Funding Initiative), presentades durant la 'Tercera Setmana Internacional de l'Anàlisi de Riscos, Seguretat de Preses i Gestió d'Infraestructures Crítiques' (3IWRDD, València, Octubre 2011), així com en l'article acceptat per publicació (juliol 2012) a 'Natural Hazards and Earth Systems Science'.

Aquest treball presenta un punt de vista integral que inclou el risc d'inundació per precipitació «in situ» (inundació d'origen pluvial), desbordament de rius (inundació d'origen fluvial) i col•lapse d'infraestructures de defensa. La metodologia ha sigut aplicada a un cas d'estudi amb l'objectiu de millorar la gestió del risc d'inundació.

INGLÉS

The concept of Integrated Flood Risk Management (IFRM) promotes an integrated and holistic, rather than fragmented, approach to flood management. It 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.

Its conceptual framework can be found in the literature in several examples ('Tool for Integrated Flood Management', 2008; 'FLOODsite' project, 2009).

In these examples, IFRM is presented as comprehensive risk management that should consider all sources of flood hazard, the "system" response and characterize vulnerability within a social, economic, and environmental context.

In addition, IFRM incorporates all interrelationships between stakeholders, with focus on establishing advance schemes of risk communication, organization, public participation and coordination.

Therefore, IFRM should incorporate outcomes of flood risk analysis with the aim of identifying efficient risk reduction measures. Current methodologies for flood risk analysis have been developed in qualitative or semi-quantitative terms and they have been generally applied to site specific cases.

In this context, a general applicable methodology for quantitative flood risk analysis is still required. In addition, it should be able to integrate different sources of hazard and obtain both societal and economic risk in quantitative terms. By combining risk analysis and evaluation it should provide

clear and solid information to support decision making.
The methodology presented in this Thesis is based on findings of the SUFRI project 2009-2011 (‘Sustainable Strategies of Urban Flood Risk Management with non-structural measures to cope with the residual risk’, 2nd CRUE ERA-Net Funding Initiative), presented during the ‘3rd International Forum on Risk Analysis, Dam Safety, Dam Security, and Critical Infrastructure Management’ (Valencia, October 2011) and published in its final report, along with a paper accepted for publication in ‘Natural Hazards and Earth Systems Science’ in July 2012.
An integrated approach - combining pluvial, river flooding and structural collapse - is presented and applied to a case study. Results and conclusions from risk analysis are used to provide guidance towards an improved flood risk management.

Palabras clave:
Riesgo de inundación, análisis de riesgos, modelos de riesgo, medidas de reducción del riesgo.
Flood risk; risk analysis; risk models; risk reduction measures

This page intentionally left blank

FLOOD RISK MANAGEMENT IN URBAN AREAS INTEGRATING PLUVIAL AND RIVER FLOODING AND STRUCTURAL COLLAPSE

Jesica Tamara Castillo Rodríguez

Universitat Politècnica de València

Director: Ignacio Escuder Bueno

UNIVERSITAT POLITÈCNICA DE VALÈNCIA

September 2012

This page intentionally left blank

Master's Degree in Hydraulic Engineering and Environment

Master Thesis

Máster en Ingeniería Hidráulica y Medio Ambiente

Trabajo Fin de Máster

Jesica Tamara Castillo Rodríguez

Universitat Politècnica de València (UPV)

Research Institute of Water and Environmental Engineering (IIAMA)

Instituto de Ingeniería del Agua y Medio Ambiente (IIAMA)

jecasrod@upvnet.upv.es

This page intentionally left blank

PROLOGUE / PRÒLEG / PRÓLOGO

This document presents the final report of the research activities which have been developed to satisfy the requirements of the Master Degree in Hydraulic Engineering and Environment at Universitat Politècnica de València, Spain.

The work is presented for consideration as part of the required research activities within the first stage of the PhD programme on Water and Enviromental Engineering at Universitat Politècnica de València, Spain.

The research has been supported through a predoctoral research grant (with reference BES 2011-043710) from the Spanish Ministry of Science and Innovation (MICINN), under a R&D&I project entitled "INCORPORATING HUMAN-INDUCED RISK COMPONENTS INTO INTEGRATED DAM SAFETY MANAGEMENT (BIA 2010-17852)", also funded by MICINN as part of the 2008-2011 National R&D&I Plan.

The work presented in this thesis has been supported by the Spanish Ministry of Science and Innovation (MICINN) through the grant to the budget of the SUFRI project (EUI 2008-03933) and of the iPRESARA project (BIA 2010-17852).

//

El present document correspon a la memòria del treball de Fi de Màster per a l'obtenció del títol de Màster en Enginyeria Hidràulica i Medi Ambient, impartit en la Universitat Politècnica de València.

Este treball de fi de Màster es presenta per a la seua consideració per part de la Comissió de Doctorat (CAD) com a treball d'investigació per a l'admissió al període d'investigació del doctorat en Enginyeria de l'Aigua i Mediambiental de la Universitat Politècnica de València.

La investigació ha sigut realitzada durant la fase de beca de l'Ajuda, amb referència BES 2011-043710, del Subprograma de Formació de Personal Investigador del Ministeri de Ciència i Innovació (Subprograma FPI-MICINN), en el marc del Plan Nacional de Investigación Científica, Desarrollo e Innovación Tecnológica 2008-2011, i vinculada al projecte 'INCORPORACIÓ DELS COMPONENTS DE RISC ANTRÒPIC ALS SISTEMES DE GESTIÓ DE SEGURETAT DE PRESES I EMBASSAMENTS'.

El treball d'investigació presentat ha sigut financiat pel Ministeri de Ciència i Innovació (MICINN), en el marc dels projectes SUFRI (EUI 2008-03933) i iPRESARA (BIA 2010-17852).

//

El presente documento corresponde a la memoria del Trabajo Fin de Máster desarrollado para la obtención del título de Máster en Ingeniería Hidráulica y Medio Ambiente, impartido en la Universitat Politècnica de València.

Este Trabajo Fin de Máster se presenta para su consideración por parte de la Comisión de Doctorado (CAD) como trabajo de investigación para la admisión al periodo de investigación del programa de doctorado en Ingeniería del Agua y Medioambiental de la Universitat Politècnica de València.

La investigación presentada se ha desarrollado en el marco de las actividades realizadas durante la fase de beca de la Ayuda, con referencia BES 2011-043710, del Subprograma de Formación de Personal Investigador del Ministerio de Ciencia e Innovación (Subprograma FPI-MICINN), en el marco del Plan Nacional de Investigación Científica, Desarrollo e Innovación Tecnológica 2008-2011, y vinculada al proyecto “INCORPORACIÓN DE LOS COMPONENTES DE RIESGO ANTRÓPICO A LOS SISTEMAS DE GESTIÓN INTEGRAL DE SEGURIDAD DE PRESAS Y EMBALSES (BIA 2010-17852)”.

Los trabajos realizados han sido financiados por el Ministerio de Ciencia e Innovación (MICINN), en el marco de los proyectos SUFRI (EUI 2008-03933) e iPRESARA (BIA 2010-17852).

ABSTRACT / RESUM / RESUMEN

The concept of Integrated Flood Risk Management (IFRM) promotes an integrated and holistic, rather than fragmented, approach to flood management. It 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.

The conceptual framework for IFRM can be found in the literature in examples such as the 'Tool for Integrated Flood Management' published by the World Meteorological Organization (WMO) and the Global Water Partnership (GWP) in 2008 or the final report of the FLOODsite project.

In these examples, IFRM is presented as comprehensive risk management that should consider all sources of flood hazard, the "system" response to such hazard and characterize vulnerability within a social, economic, and environmental context.

In addition, IFRM incorporates all interrelationships between stakeholders, with focus on establishing advance schemes of risk communication, organization, public participation and coordination.

IFRM incorporates outcomes of flood risk analysis with the aim of identifying efficient risk reduction measures. Current methodologies for flood risk analysis have been developed in qualitative or semi-quantitative terms. In addition, these methodologies have been generally applied to site specific cases (examples may be found in research projects of the 1st and 2nd CRUE ERA-Net funding initiative).

In this context, a general applicable methodology for quantitative flood risk analysis is still required. This methodology should allow its application from simplified to high-detailed analyses. In addition, it should be able to integrate different sources of hazard and obtain both societal and economic risk in quantitative terms. By combining risk analysis and evaluation it should provide clear and solid information to support decision making.

The methodology presented in this Thesis is based on findings of the SUFRI project 2009-2011 ('Sustainable Strategies of Urban Flood Risk Management with non-structural measures to cope with the residual risk', 2nd CRUE ERA-Net Funding Initiative), presented during the 3rd International Forum on Risk Analysis, Dam Safety, Dam Security, and Critical Infrastructure Management (3IWRDD, Valencia, October 2011) and published in its final report, along with a paper submitted to Natural Hazards and Earth Systems Science 'NHESS' in December 2011 and accepted for publication in July 2012.

An integrated approach - combining pluvial, river flooding and structural collapse - is presented and applied to a case study. Results and conclusions from risk analysis are used to provide guidance towards an improved flood risk management.

//

El concepte de Gestió Integral del Risc d'Inundació (GIR) promou un punt de vista integral de la gestió del risc d'inundacions, amb l'objectiu de combinar l'ús eficient d'àrees potencialment inundables amb la reducció de les conseqüències potencials per inundació. Per això, requerix de la consideració de mesures legislatives, financeres, estructurals, d'ordenació territorial, etc.

El marc conceptual de la GIR pot trobar-se en diverses fonts d'informació. Alguns exemples són la publicació amb títol 'Tool for Integrated Flood Management' (World Meteorological Organization (WMO) i Global Water Partnership (GWP) en 2008) o l'informe final del projecte FLOODsite. El concepte de GIR es presenta com una gestió completa del risc d'inundació que ha de considerar totes les possibles causes, la resposta del sistema i caracteritzar la seua vulnerabilitat en un context social, econòmic i mediambiental. A més, la GIR ha d'incloure les interrelacions entre tots els agents intervinents en la gestió del risc d'inundació, centrant-se en la definició d'esquemes avançats d'organització, comunicació, coordinació i participació pública.

Per tant, la GIR ha d'incorporar els resultats de l'anàlisi del risc d'inundació a fi d'identificar mesures efectives per a la seua reducció. Les metodologies existents en aquest àmbit aborden l'anàlisi des del punt de vista qualitatiu o semi-cuantitatiu. A més, aquestes metodologies s'han aplicat generalment a casos d'estudi específics (poden trobar-se exemples als projectes d'investigació de la CRUE ERA-Net).

Per això, existeix la necessitat de desenvolupar una metodologia que permeta un anàlisi quantitatiu del risc d'inundació i que puga aplicar-se en estudis de diferent nivell de detall. A més, aquesta metodologia ha de poder integrar diferents causes d'inundació i obtindre el risc d'inundació tant en pèrdua potencial de vides humanes com danys econòmics. Sobre la base de l'anàlisi i avaluació del risc, aquesta metodologia ha de proporcionar informació clara que siga útil en la presa de decisions.

La metodologia presentada en aquest Treball Fi de Màster es basa en les investigacions i recomanacions derivades del projecte SUFRI 2009-2011 ('Sustainable Strategies of Urban Flood Risk Management with non-structural measures to cope with the residual risk', 2ª CRUE ERA-Net Funding Initiative), publicades al seu informe final i presentades durant la Tercera Setmana Internacional de l'Anàlisi de Riscos, Seguretat de Preses i Gestió d'Infraestructures Crítiques (3IWRDD, València, Octubre 2011), així com en l'article enviat a Natural Hazards *and Earth Systems Science 'NHESS' al desembre de 2011 i acceptat per a publicació el passat mes de juliol.*

Aquest treball presenta un punt de vista integral que inclou el risc d'inundació per precipitació «in situ» (inundació d'origen pluvial), desbordament de rius (inundació d'origen fluvial) i col·lapse d'infraestructures de defensa. La metodologia presentada s'ha aplicat a un cas d'estudi amb l'objectiu de millorar la gestió del risc d'inundació, basant-se en els resultats i conclusions obtinguts de l'anàlisi.

//

El concepto de Gestión Integral del Riesgo de Inundación (GIR) promueve un enfoque integral de la gestión del riesgo de inundaciones, con el objetivo de combinar el uso eficiente de las áreas potencialmente inundables con la reducción de las consecuencias potenciales por inundación. Por ello, este enfoque requiere de la consideración de medidas tanto legislativas y financieras como estructurales y de ordenación territorial.

El marco conceptual de la GIR puede encontrarse en diversas fuentes de la literatura. Algunos ejemplos son la herramienta publicada en 2008 por la World Meteorological Organization (WMO) y el Global Water Partnership (GWP) con título "Tool for Integrated Flood Management" o el informe final del proyecto FLOODsite. En estos ejemplos, el concepto de GIR se presenta como una gestión completa del riesgo de inundación que debe considerar todas las posibles causas de inundación, la respuesta del sistema a dichas amenazas y así como caracterizar su vulnerabilidad en un contexto social, económico y medioambiental. Además, la GIR debe incluir las interrelaciones entre todos los agentes intervinientes en la gestión del riesgo de inundación, centrándose en la definición de esquemas avanzados de organización, comunicación, coordinación y participación pública.

Por tanto, la GIR debe incorporar los resultados del análisis del riesgo de inundación con el fin de identificar medidas efectivas de reducción del mismo. Las metodologías existentes en materia de análisis del riesgo de inundación abordan dicho análisis desde el punto de vista cualitativo o semi-cuantitativo. Además, estas metodologías se han aplicado generalmente a casos de estudio específicos (pueden encontrarse ejemplos en los proyectos de investigación desarrollados en el marco de la 1ª y 2ª CRUE ERA-Net Funding Initiative).

Por ello, existe la necesidad de desarrollar una herramienta que permita un análisis cuantitativo del riesgo de inundación y que pueda aplicarse en estudios de diferente nivel de detalle. Además, esta metodología debe poder integrar diferentes causas de inundación y obtener el riesgo de inundación tanto en términos de pérdida potencial de vidas humanas como en costes económicos. Combinando el análisis y evaluación del riesgo, esta herramienta debe proporcionar información clara y robusta que sea útil en la toma de decisiones.

La metodología presentada en este Trabajo Fin de Máster se basa en las investigaciones y recomendaciones derivadas del proyecto SUFRI 2009-2011 ('Sustainable Strategies of Urban Flood Risk Management with non-structural measures to cope with the residual risk', 2nd CRUE ERA-Net Funding Initiative), publicadas en su informe final y presentadas durante la Tercera Semana Internacional del Análisis de Riesgos, Seguridad de Presas y Gestión de Infraestructuras Críticas (3IWRDD, Valencia, Octubre 2011), así como en el artículo enviado a Natural Hazards and Earth Systems Science 'NHESS' en diciembre de 2011 y aceptado para publicación el pasado mes de julio.

Este trabajo presenta un enfoque integral que incluye el riesgo de inundación por precipitación in situ (inundación de origen pluvial), desbordamiento de cauces (inundación de origen fluvial) y fallo o colapso de infraestructuras de defensa frente a inundaciones (e.g. rotura de presa). La metodología presentada se ha aplicado a un caso de estudio con el objetivo de poner en valor los resultados y conclusiones del análisis para mejorar la gestión del riesgo de inundación.

ACKNOWLEDGEMENTS / AGRADECIMIENTOS

I would like to express my gratitude to all people who have take part during these first years of research at the UPV, especially during the development of this Master Thesis. But I would like especially to thank the following people, without their support this study would not have been completed:

First and foremost, I would like to thank my supervisor, Prof. Dr. Ignacio Escuder, for his guidance, patience, and giving me the opportunity of being part of an excellent research team. His advice has always been (and will be) of great help, both academically and personally.

I am also very grateful to Dr. Armando Serrano and Dr. Luis Altarejos for their suggestions and discussions about this research in our workshops. Especially, I would like to thank Armando for his "lessons" and patience to solve my questions on computational science (including my "conflicts").

I would like to thank Sara Perales for her help and guidance in the application of the methodology to the city of Benaguasil. I would like to offer my special thanks also to the City Council of Benaguasil for their willingness to collaborate in this research. In addition, I would like to thank all our colleagues of the SUFRI project for their comments during the development of the methodology.

I would like to thank also my colleagues in the department. Especially, I would like to thank Adrián and Javier for these last years, for their help and friendship. Thanks for being such good friends, for making me smile, for our lunch-breaks and "after-works".

Special thanks to my parents and friends. I can never be thankful enough for all the support that you gave me. Finally, I would like to thank Joaquín for being *there*, for being always optimistic, for his understanding and future patience during the next years of PhD research…

//

Me gustaría expresar mi agradecimiento a todos aquellos que han formado parte de mis primeros años de investigación en la UPV, especialmente durante el desarrollo de esta Tesina de Máster. Pero me gustaría mostrar mi especial agradecimiento a quienes han participado en este trabajo, cuyo apoyo ha sido esencial:

En primer lugar, quiero agradecer al Prof. Dr. Ignacio Escuder la oportunidad de formar parte de este equipo. Agradecerle también su apoyo, paciencia y consejos, que han sido (y serán) de gran ayuda en el ámbito académico, profesional y personal.

También quiero mostrar mi agradecimiento a los doctores Armando Serrano y Luis Altarejos por sus sugerencias y comentarios sobre este trabajo durante nuestros "workshops". En especial, a Armando por sus clases y por su paciencia para resolver mis dudas de programación (y mis "conflictos").

También me gustaría agradecer a Sara Perales su irreemplazable ayuda en la aplicación de la metodología al caso de estudio de Benaguasil. En este punto, también quiero mostrar mi agradecimiento al Ayuntamiento de Benaguasil por su disposición a colaborar en esta investigación. Además, me gustaría agradecer todos los comentarios recibidos por los socios del proyecto SUFRI durante el desarrollo de la metodología.

A mis compañeros del departamento. Especialmente a Adrián y Javier por estos últimos años. Gracias por vuestra amistad y ayuda, por hacerme sonreír, por nuestros descansos y "after-works".

Quiero dar las gracias a mis amigos, y en especial, a mis padres. Nunca estaré lo bastante agradecida por todo el apoyo que me han dado. Finalmente, quiero dar las gracias a Joaquín por estar ahí, por su optimismo y comprensión, y sobre todo por su futura paciencia durante los próximos años de doctorado…

CONTENTS

LIST OF FIGURES

LIST OF TABLES

Chapter 1. INTRODUCTION AND OBJECTIVES

1.1. Introduction

In the recent past, flooding from a wide range of sources (river, pluvial, coastal or maritime flood events) seem to happen more frequently with snowballing effects for humans, their lives, properties and the landscape (**Escuder-Bueno et al., 2012**). In fact, one-third of annual natural disasters are flood related (**Douben, 2006**) and, in the period 1975-2001, floods due to drainage problems, flash floods and river floods accounted for 9% of all deaths from natural disasters, claiming about 175,000 fatalities worldwide (**Jonkman, 2003**).

Urban areas may present high flood risk levels due to their population density rates and number of inhabitants, 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.

As a result, social demand for higher levels of safety has become a major challenge for the governments of European countries. This demand requires methods to identify areas which may be potentially affected by floods and to estimate societal as well as economic flood risk. Moreover, the effect of flood defence measures has to be addressed including non-structural flood protection measures such as flood forecasting, warning, emergency management, etc.

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* (**EC, 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 does 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 Floods Directive; **EC, 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 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, the EU Floods Directive was transposed into national legislation in July 2010 by the RD 903/2010 (*RD 903/2010, de 9 de julio, de evaluación y gestión de riesgos de inundación*). This decree containes all actions, and the corresponding deadlines, established by this Directive.

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 a 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 initiative centred on risk assessment and management (**CRUE, 2009**) and the second on flood resilient communities and managing the consequences of flooding (**Thieken and Beurton, 2012**).

Fourteen research projects were conducted in the period 2007-2011 (**Thieken and Beurton, 2012**). Results, key findings and recommendations for policymakers have been published and presented in different forums (Graz, Austria, **UFRIM, 2011**; Valencia, Spain, **Escuder-Bueno et al., 2011c**).

More recently, 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**).

Flood risk analyses are conducted from translational to local levels. At local scale, damage caused by floods may vary across countries and regions depending on social and economic aspects (differing in flood extent, water depth, flow velocity, number of inhabitants and economic activity, etc.). Flood consequences may also vary depending on the source of hazard.

Therefore, flood risk analyses have been carried out from simplified to partially quantitative high-detailed studies depending on the case study. Hence, from the point of view of risk analysis, there is 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.

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 (**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 analyse measures for flood risk reduction.

In this context, this Thesis proposes a comprehensive methodology for urban flood risk analysis, integrating pluvial flooding, river flooding and structural collapse.

1.2. Objectives and structure

The focus of this Thesis is to provide a comprehensive methodology for flood risk analysis in urban areas to inform decision making on flood risk management thus aiming at the reduction of adverse consequences by considering the use of non-structural measures (in addition to structural measures).

Besides the aforementioned main purpose, this Thesis aims also to achieve the following objectives:

- Summarize and analyse the state-of-the-art on flood risk analysis and management.
- Provide a general description of existing risk estimation tools.
- Provide a new methodology to assess flood risk by integrating pluvial, river flooding and structural collapse.
- Go forward in the evaluation of non-structural measures and propose how to capture their effect on flood risk.
- Apply the proposed methodology to a case study.

Therefore, this Thesis aims to provide the following contributions:

- An updated state-of-the-art on flood risk analysis and management.
- A methodology for urban flood risk analysis by integrating pluvial, river flooding and structural collapse to inform decision making.
- The application of the methodology to show how results and conclusions of the analysis may be used to inform local authorities, e.g. for developing a Municipal Action Plan against Flood Risk.

Consequently, this Thesis is structured as follows: after introducing the background and aim of the Thesis in Chapter 1, a summary of the state-of-the-art on flood risk management is presented in Chapter 2. Chapter 3 describes the proposed methodology for urban flood risk analysis. Next, the methodology is applied in Chapter 4 to a case study. Conclusions and further research lines are discussed in Chapter 5.

Chapter 2. STATE-OF-THE-ART: FLOOD RISK MANAGEMENT

In this chapter, definitions and basic concepts, along with a review of the state-of-the-art on flood risk management, are described as the theoretical basis of this Thesis.

2.1. Basic concepts

2.1.1. Definition of risk

A wide range of definitions for the term *risk* can be found in the literature (**Gouldby and Samuels, 2005; IEC, 2009**). Attempts to develop common understanding on risk management concepts and terms among organizations are relatively new (**ISO GUIDE 73:2009**) or in process. The term *risk* may present multiple dimensions relating to safety, security, 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, there is potential for misunderstanding in technical terminology since technical distinctions are made between words which are commonly used as synonyms. The project FLOODsite (**Gouldby and Samuels, 2005**) put substantial effort in defining basic concepts related to flood risk analysis.

First of all, a distinction between the words *hazard* and *risk* should be established. First, *hazard* can be defined as 'a physical event, phenomenon or human activity with the potential to result in harm', i.e. 'source of potential harm' (**ISO GUIDE 73:2009**). Although, *hazard* does not necessarily lead to harm, for a risk to arise there must be a hazard that consists of a source of potential consequences.

Consequently, the definition of risk may be established by the identification of several components (**Gouldby and Samuels, 2005**):

- nature and probability of the hazard (p)
- degree of exposure to the hazard (e).
- susceptibility to the hazard (s)
- value of the potential consequences (v)

Therefore, risk can be expressed according to Eq.(1):

$$\text{Risk} = f\,(p, e, s, v) \qquad (1)$$

In this context, vulnerability is defined as a sub-function of risk. This definition encompasses the characteristics of a system that describes its potential to be harmed and it can be considered as a combination of susceptibility and value. It can be expressed in terms of all functional relationships between expected damage and system characteristics for the whole range of hazards, i.e., in functional form:

Vulnerability = f (s, v) (2)

In practice, exposure and vulnerability are often captured in consequence analysis. Therefore, risk can be expressed in simple terms (with probability understood to be probability of 'hazard+ exposure') as:

Risk = Hazard x (exposure) x vulnerability (3)

or:

Risk = Probability x consequence (4)

Accordingly, risk can be defined in a simplified manner as 'probability multiplied by consequences', where consequences are the impact in terms of economic, social, cultural or environmental damage that may result from a flood. Consequences may be expressed quantitatively (e.g. monetary value) or descriptively (e.g. high, medium, low).

Therefore, risk may be calculated according to Eq.(3) or Eq.(4). However, attention should be paid to the aforementioned definitions of vulnerability and consequences since there is no univocal relationship between hazard and probability (as probability includes also the exposure) neither between vulnerability and consequences (Figure 1).

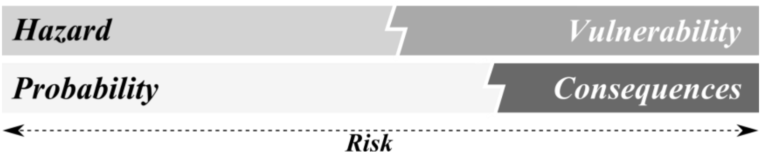


Figure 1. Hazard-Vulnerability vs. Probability-Consequences.

2.1.2. Flood risk

Flood risk may be defined as the product of the probability of potential flood events and their consequences, or, alternatively, as the product of flood hazard and society's vulnerability to floods (**Klijn et al., 2008**), emphasizing the fact that equal attention should be paid to hazard and vulnerability. Other authors define flood risk as the expected annual average damage of flooding, where damage covers economic as well as social and environmental negative consequences (**Kubal et al., 2009**).

The EU Floods Directive gives the following definitions:

- ‘Flood’ means the temporary covering by water of land not normally covered by water. This includes floods from rivers, mountain torrents, Mediterranean ephemeral water courses, and floods from the sea in coastal areas, and may exclude floods from sewerage systems.
- ‘Flood risk’ means the combination of the probability of a flood event and of the potential adverse consequences for human health, the environment, cultural heritage and economic activity associated with a flood event.

For the purpose of this Thesis, floods from runoff events which exceed the capacity of drainage systems are included.

2.1.3. Economic, societal and ecological risk

In general, potential adverse consequences of flooding can be classified in three categories:

- Consequences for human health;
- Consequences for cultural heritage and economic activity; and,
- Consequences for the environment

Accordingly with these three dimensions of potential adverse consequences, 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 multicriteria flood risk assessment and mapping approaches which 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.) due to differences on the definition, nature and characterization of each type.

Indeed, these three dimensions of risk are generally evaluated at different level of detail and description (e.g. quantitative or qualitative), depending on available data and existing methodologies for characterization of vulnerability (e.g. life-loss methods, inundation-depth-damage curves, etc.). In most cases, ecological risk is not evaluated due to a lack of applications of quantitative risk assessment in terms of potential consequences for the environment.

For the purpose of this Thesis, 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, including ecological risk.

2.1.4. Risk reduction: Structural and non-structural measures

Risk reduction can be achieved by different measures. 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 their combination).

These measures for risk reduction 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 policies, awareness, knowledge development, public commitment, methods and operating practices (**Escuder-Bueno et al., 2011a; FLOO-ERA, 2009**).

In general, risk cannot be entirely eliminated since structural measures handle the consequences until a specific severe event, typically called 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 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 on such existing flood risk.

2.2. From Risk Analysis to Risk Management

2.2.1. General

Before describing how flood risk may be analyzed and evaluated, it is necessary to define the terms *risk analysis*, *evaluation*, *assessment* and *management*. These four terms are connected and they can be classified into three stages within the risk management process:

- In a first stage, two concepts have to be distinguished: *risk analysis* and *risk evaluation*. Risk analysis can be defined as the methodology which aims to determine risk by characterizing, calculating, analyzing and combining both risk components: probabilities and consequences. Risk evaluation includes the consideration of legal regulations, guidelines and tolerability criteria which are applicable for the study area.
- In a second stage, *risk assessment* comprises understanding, evaluating and interpreting the perceptions of risk and societal tolerances of risk to inform decision making and actions within the flood risk management process. It requires the combination of results from risk analysis and evaluation. In this level, *risk control* measures are also included as part of the process. These measures include re-evaluation and risk reduction by monitoring flood defence infrastructures and the application of current risk reduction measures.
- The third stage gathers all previous ones into the overall flood risk management framework.

The conventional concept of flood risk management was based on flood defence, flood protection, flood control and flood risk reduction from the point of view of the hazard, i.e. mainly focused on the consideration of structural measures. However, in recent years, more attention has been paid on acting directly to reduce vulnerability, preventing people and property to be damaged by the flood (**Klijn et al., 2008**). In such approach, non-structural measures have been more frequently proposed and applied to reduce flood risk. Consequently, current risk approaches should consider not only the flood but the consequence component also.

However, risk management does not necessarily imply reduction of the level of risk, as the reduction or acceptance of a certain level of risk depends on the established tolerability criteria and the analysis of costs and benefits of risk reduction measures.

Several definitions of *flood risk management* can be found in the literature. As an example, here it is considered the definition given by FLOODsite (**Gouldby and Samuels, 2005**), established as 'the continuous and holistic societal analysis, assessment and mitigation of flood risk'. However, flood risk management involves a wide range of considerations that cannot be easily reproduced in a concise statement.

Among other aspects, flood risk management involves three essential points (**Klijn et al., 2008**):

- *The objective of flood risk management should focus on managing risk, not the flood.*

  As it has been mentioned above, both risk components should be analyzed when possible.
- *Equal consideration has to be made of structural and non-structural measures.*

  This means that decision makers should consider both types of risk reduction measures.
- *Flood risk management is a continuing cycle of assessing, implementing and maintaining measures to achieve acceptable residual risk in view of sustainable development.*

  Actions and measures have to be applied following the principles of sustainable development as far as possible.

If the third point is considered more in detail, sustainable flood risk management involves the following principles (**Gouldby and Samuels, 2005**):

- Ensuring quality of life by reducing flood damages being prepared for floods;
- Mitigating the impact of risk management measures on ecological systems at a variety of spatial and temporal scales;
- Promoting rational use of resources in providing, maintaining and operating measures; and,
- Maintaining appropriate economic activity (agricultural, industrial, commercial, residential, etc.) on the flood plain.

Hence, risk management combines results, conclusions and recommendations from risk analysis and assessment with the aim of achieving all previous principles. Outcomes are used as key information for the definition and prioritization of risk reduction measures.

For that reason, in this chapter, different tools for risk analysis and evaluation are here presented and discussed.

2.2.2. Tools for risk analysis

As defined in section 2.1, risk is commonly expressed by the notation *Risk = Hazards x Vulnerability* (or Probability x Consequences). Accordingly, tools for flood risk analysis can be classified depending on whether they obtain one component (hazard or vulnerability), or complete, if they estimate both components. In addition, they can be classified depending on whether they provide or not a numerical value of risk (quantitative or qualitative). Hence, these tools can be divided into four categories (**Escuder-Bueno et al., 2010**):

- *Partial and qualitative*: methods based on the knowledge of the reality and historical flood events. These tools are generally used for estimating environmental and cultural losses (**ANCOLD, 2003**);
- *Complete and qualitative*: methods that estimate both risk components by combining qualitative methods to obtain flood components separately (e.g. risk maps that combine flood hazard maps and land use maps with qualitative descriptions of potential consequences);
- *Partial and quantitative*: tools that compute numerically either probability (e.g. flood hazard maps) or consequences (e.g. land use maps with economic rates of potential consequences). Tools which compute only flood consequences may be useful to make a first approximation to the consequences of a severe flood. It is also possible to find more sophisticated methodologies that include shelter, warning and evacuation procedures, such as the LIFESim model (**Bowles and Aboelata, 2007**); and,
- *Complete and quantitative:* tools that obtain a numerical value of both risk components (e.g. risk maps which are elaborated by combining flood hazard and consequence maps with quantitative values). As an example, F-N curves are classified in this group. These curves are a graphical representation of the probability of flood events causing a specified level of consequences (**IEC 31010**).

Among these four groups, complete and quantitative tools are the most convenient but high-demanding option. Data and time requirements for these tools are usually more demanding than other methods, though results may pay back by providing significant conclusions and recommendations for decision makers.

In this Thesis, the use of F-N curves is proposed for flood risk analysis as it provides a comprehensive and robust method to represent quantitative societal and economic risk.

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 which represent the annual cumulative probability of exceedance of a certain level of potential economic damages (D).

The basis of the use of F-N curves for urban flood risk analysis are described in Chapter 3 and included in the *SUFRI Methodology for pluvial and river flooding risk analysis in urban areas to inform decision making (***Escuder-Bueno et al., 2011a***)*, developed within the SUFRI project (2nd CRUE ERA-Net funding initiative, in the period 2009-2011) (**Jöbstl et al., 2011**).

2.2.3. Tools for risk evaluation: tolerability criteria

The evaluation of the existing risk by tolerability criteria or standards is the basis for a proper risk management. In fact, the concept of tolerable risk is fundamental to risk-informed decision making (**Munger et al., 2009**).

A central question in risk management refers to the acceptance of risk by the public and decision makers. From an engineering point of view, a general framework for acceptability criteria has been developed (**HSE, 2001**). This framework involves the definition of the following elements (Figure 2):

- an upper-bound on individual or societal risk levels (or tolerable risk limit): beyond this limit, risks are unacceptable;
- a lower-bound on individual or societal risk levels (or broadly acceptable risk level): risks are considered as acceptable below this limit; and,
- an intermediate region between both limits (ALARP region): further individual and societal risk reduction actions are required to achieve a level considered 'as low as reasonably practicable' (the so-called ALARP principle). In this region, risks are tolerable only if risk reduction is impracticable or benefits are only marginally greater (or not significantly greater) than costs.

Figure 2 shows the aforementioned limits and the three resulting regions of risk tolerability. The first range is the unacceptable region, where risk can only be justified in extraordinary circumstances. The second region is the range of tolerability, where risk is under the tolerability risk limit. In this region the analysis of risk is crucial because this risk will be accepted by the society only if it cannot be lowered in an economically efficient way. The third region is the broadly acceptable region where risk can be defined as insignificant or negligible and can be controlled adequately (**HSE, 2001**).

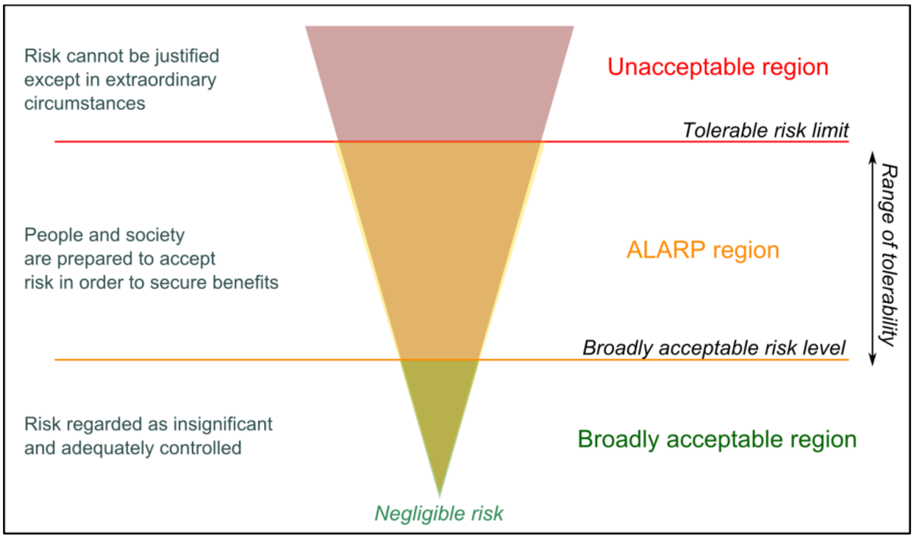


Figure 2. ALARP criteria. Adapted from HSE, 2001 and Gouldby and Samuels, 2005.

The ALARP method raised from industrial applications thus it has often considered an engineering rather than "social science" heritage (**Gouldby and Samuels, 2005**). The domains of acceptance and non-acceptance of Figure 3 may differ significantly between regions or countries (also between persons). Therefore, public consensus on risk acceptance may not exist. Furthermore, this framework does not answer the question of how acceptance should be measured.

Apart from the ALARP principle, equity is another fundamental principle from which alternatives for risk reduction can be prioritized and tolerability guidelines are derived (**ICOLD, 2005**). In general, it should be considered that there may be conflict in achieving equity and efficiency (**Munger et al., 2009**). Hence, the need for reducing flood risk cannot overcome the right of individuals and their interests to be protected (**Escuder-Bueno et al., 2012**).

Due to local characteristics, little research has been conducted to establish standards for flood risk analysis in urban areas. However, several individual and societal criteria can be found in the literature (**Vrijling, 2001**), but it is still required a development of tolerability guidelines on urban flood risk.

Some examples of these criteria are here presented, classified in two groups: tolerability guidelines for individual risk and for societal risk. These examples show how results of risk analysis can be compared and represented along with tolerability limits in F-N curves, providing a method to evaluate risk.

Tolerability criteria for individual risk

Individual risk can be defined as the probability that an average unprotected person, permanently present at a certain location, is killed due to an accident resulting from a hazardous activity (**Jonkman et al., 2011**).

As an example of tolerability criteria for individual risk, the Dutch Ministry of Housing, Urban Planning and Environment (VROM) limits individual risk in urban areas to 10^{-6}. In addition, limitation of individual risk proposed by the Dutch Technical Committee for Advising in Defence Constructions (TAW) is established by the following expression (**Vrijling, 2007**):

$$IR < \beta \cdot 10^{-4} \tag{5}$$

where IR denotes individual risk and β is the policy factor, which varies accordingly to the degree to which participation in the activity is voluntary and with the perceived benefit. Proposed values for this factor are between 0.01 for involuntary activities and 100 for voluntary activities for personal benefit. Typical values of this factor are shown in Figure 3.

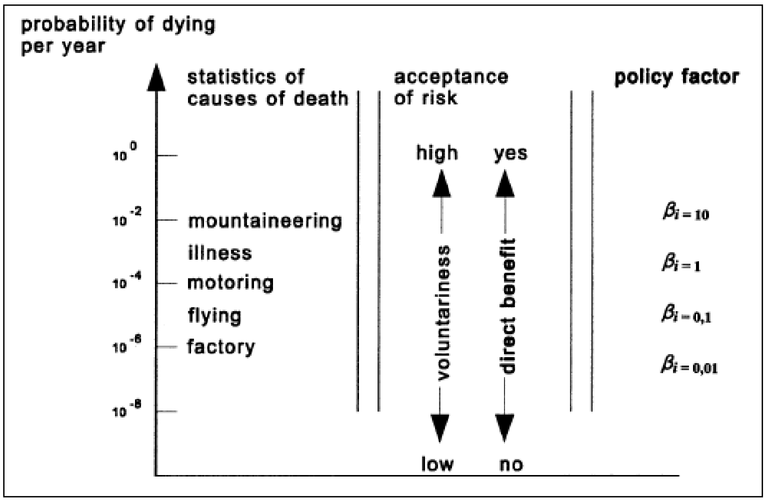


Figure 3. Personal risks in western countries from statistics of causes of death and number of participants per activity (Vrijling, 2007).

For example, in case of dikes protecting urban areas from flooding, the β factor usually used ranges from 0.1 to 1.

Tolerability criteria for societal risk

It is generally accepted that individual risk criteria must be accompanied with societal risk limits (**Jonkman et al., 2011**). *Societal risk* is defined as the resulting risk obtained when risk consequences are computed in number of victims (typically by year).

The best known criterion for evaluating societal risk formulated in terms of F-N curves was proposed by **Vrijling** (2007), establishing the tolerable risk by means of the following equation:

$$1 - F_N < \frac{C_i}{n^\alpha} \quad (6)$$

where F_N is the cumulative flood probability of occurrence, C_i is a coefficient that determines the vertical position of the F-N limit line, n is the number of potential fatalities and α is the risk aversion coefficient that determines the steepness of the F-N limit line (where the most usual value is α = 2). Risk aversion refers to the observation that events with the same damage expectation might be perceived very differently (**Merz et al., 2009**).

The value of C_i depends on two factors: the policy factor β used for the limit of the individual risk and population at risk. Results of the application of these limits in the province of South Holland with two different values of C_i (4 and 100) are shown in Figure 4.

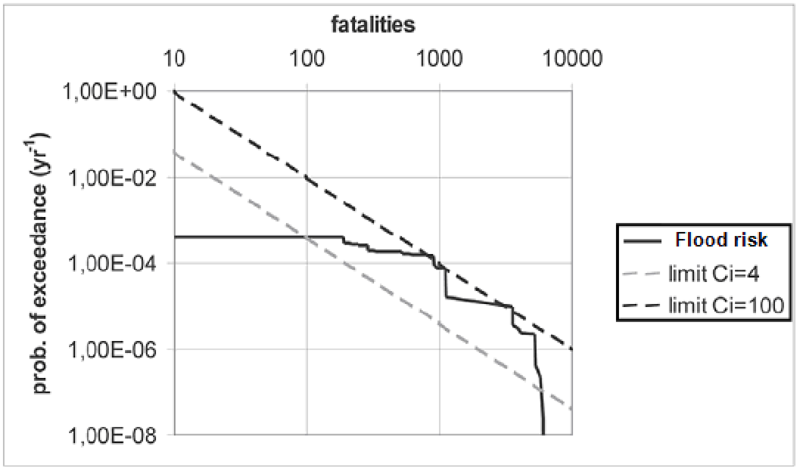


Figure 4. Tolerability limits for a case study in The Netherlands (Vrijling, 2007).

Furthermore, some tolerability criteria have been developed for incremental societal flood risk due to the existence of large dams. These criteria are also usually drawn in F-N curves as the criteria proposed by **ANCOLD** (2003). These criteria were developed for incremental risk thus they cannot be used to evaluate total societal risk as the equation proposed by **Vrijling** (2007).

F-N curves arise as a convenient tool to represent results of risk analysis as they allow to compare existing risk with tolerability criteria (e.g. the examples described above) if available. In any case, these curves are appropriate for comparison of risks from different situations, such as the comparison between the situation with and without a set of non-structural measures (**Escuder-Bueno et al., 2012**).

2.3. Integrated Flood Risk Management

The concept of Integrated Flood Risk Management (IFRM) promotes an integrated and holistic, rather than fragmented, approach to flood management (**WNO/GWP, 2008**). It aims at combining the effective use of flood plains and the reduction of potential consequences due to flooding. Consequently, it requires a combination of policy, regulatory, financial and physical measures which focus on coping with residual risk.

The conceptual framework for IFRM can be found in the literature in examples such as the 'Tool for Integrated Flood Management' published by World Meteorological Organization (WMO) and the Global Water Partnership (GWP) in 2008 (**WNO/GWP, 2008**) or the final report of the FLOODsite project (**de Bruijn et al., 2008**).

In these examples, IFRM is presented as comprehensive risk management that should consider all sources of flood hazard, the system response to such hazard and characterize vulnerability within a social, economic, and environmental context.

In addition, IFRM incorporates all interrelationships between stakeholders, with focus on establishing advance schemes of risk communication, organization, public participation and coordination.

IFRM incorporates outcomes of flood risk analysis with the aim of identifying efficient risk reduction measures. Current methodologies for flood risk analysis have been developed in qualitative or semi-quantitative terms. In addition, these methodologies have been generally applied to site specific cases (examples may be found in research projects of the 1st and 2nd CRUE ERA-Net funding initiative).

In this context, a general applicable methodology for quantitative flood risk analysis is still required. This methodology should allow its application from simplified to high-detailed analyses.

In addition, it should be able to integrate different sources of hazard and allows to estimate both societal and economic risk in quantitative terms. By combining risk analysis and evaluation it should provide clear and understandable information to support decision making.

2.3.1. The use of risk models and F-N curves towards an Integrated Flood Risk Management

The use of F-N (or F-D) curves has been already presented in this document as a method to compare and evaluate risk with tolerability criteria. However, the proposed method to carry out risk estimation has not been described.

In this point, the use of risk models is proposed to combine both risk components, probability and consequences, to characterize and compute the existing risk.

A risk model is a tool which allows to incorporate all information related to the case study that it is necessary to develop the analysis. Results of the risk model can be used to support decision making (**Serrano-Lombillo, 2011**).

Any risk model is generally divided into three parts: loads, system response and consequences. Loads and system response will include all information required to characterize (conditional) probabilities.

In this context, the term *system* includes all features, elements, infrastructures, measures, etc. that can be found within the study area and characterize the case study. It also includes urban and river catchments, river courses, existent flood defence infrastructures, implemented non-structural measures and elements within the study area (e.g. assets, building constructions, infrastructures, services, etc.).

The process for the definition of the risk model architecture is described in Chapter 3. However, the tools commonly used in risk analysis to represent and develop risk models are presented here. These tools are influence diagrams and event trees:

- An influence diagram is a very compact approach to repre sent a risk model (**Serrano-Lombillo, 2011**).
- An event tree is a detailed representation of all the possibilities that can lead to flooding and it can be used to carry out risk calculations.

Consequently, an event tree can be used as a detailed representation of all potential flood events.

An event tree starts by selecting an initiating event (**Srivastava et al., 2000**). State and response of the system to this initiating event can be modelled by different functions or lines which diverge to perform new events (Figure 5). Branches are not allowed to interconnect and each line has a particular probability that can be assigned or estimated, e.g. by expert judgement or a fault tree analysis. Consequently, different paths from the initiating event are modelled and each path is further related to potential consequences. Hence, probabilities on the event tree are conditional probabilities as each line represents the probability that all events in that path will occur.

An event tree can be represented in a compact conceptual representation as an influence diagram (**Serrano-Lombillo, 2011**) as shown in Figure 5.

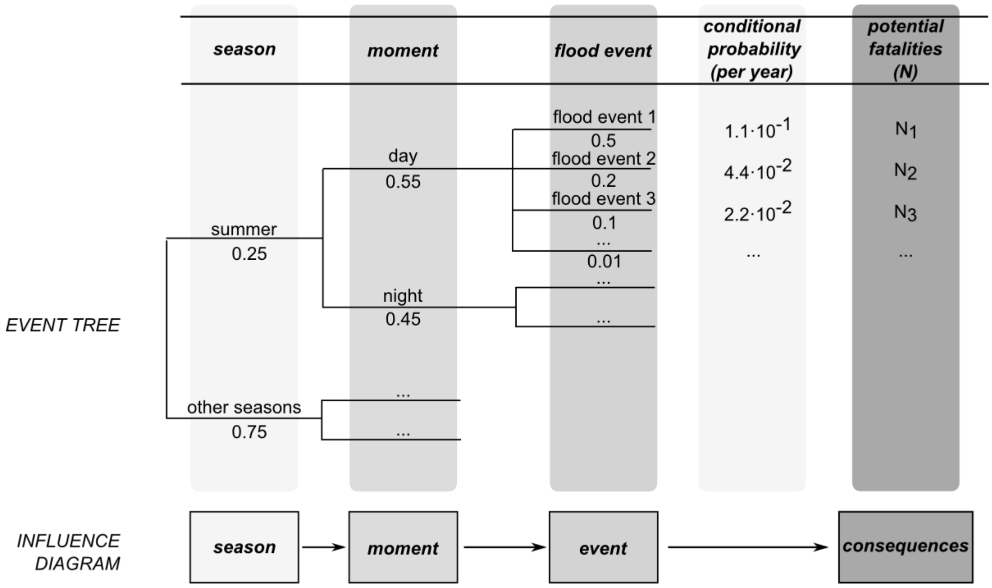


Figure 5. Example of an event tree and influence diagram (Escuder-Bueno et al., 2012).

Event trees are commonly used in dam safety risk analysis modelling. There are some available software tools for performing event tree analyses such as DAMRAE (**Srivastava et al., 2000**) or iPresas, developed at Universitat Politècnica de València (**Serrano-Lombillo et al., 2009**).

In this Thesis, iPresas software is used to perform risk calculations as it allows to solve any event tree scheme by means of influence diagrams (**Serrano-Lombillo et al., 2009**). Influence diagrams are built instead of directly using event trees, providing a clear, concise and visual workflow. The software algorithm transforms influence diagrams into event trees and it can be used for any problem that may arise in the field of risk analysis. Results obtained from calculations may be represented in F-N (or F-D) curves to analyze risk.

In addition, the use of risk models also allows to integrate different sources of flood hazard as it will be described in Chapter 3. This Thesis integrates the analysis of three different sources:

- *Pluvial flooding*: Pluvial flooding can be defined as flooding derived when the amount of rainfall either excess the infiltration capacity of the ground or exceeds the capacity of the drainage system (**WHBC, 2009**). It is then related to drainage problems. This type of flood presents generally a limited threat to life due to low water levels than river flooding and causes mainly economic damages (**Jonkman, 2005**).
- *River flooding*: River flooding can be defined as flooding of the river outside its regular boundaries. It can be caused by high precipitation rates, not necessarily in the flooded area, or other causes such as melting snow or blockage of the flow. In this case, there is usually a

longer lag time between the peak of rainfall and the peak of flooding and, in general, extreme river discharges can be predicted in advance (**Jonkman, 2005**).

- *Structural collapse*: Flooding due to failure of flood defence infrastructures is commonly analyzed as part of river flooding. However, it may be analyzed separately due to differences with river flooding such as higher peak discharges, shorter wave arrival times and higher potential consequences.

In conclusion, risk analysis is conducted in this Thesis from the societal and economic point of view. The analysis includes three sources of flood hazard (pluvial, river flooding and structural collapse) based on a proposed methodology which aims to combine the use of risk models and F-N curves. This methodology provides a comprehensive and quantitative tool for flood risk analysis to inform decision making on flood risk management in urban areas.

Chapter 3. METHODOLOGY

The purpose of this chapter is to describe the proposed methodology for integrating pluvial, river flooding and structural collapse into flood risk analysis to inform decision making on flood risk management. This chapter is divided into four sections:

- section 3.1 presents the basis for the use of risk models to integrate different sources of flood hazard into risk analysis and the use of F-N and F-D curves to represent risk;
- section 3.2 describes the phases of the methodology based on the general scheme proposed in the *SUFRI Methodology for pluvial and river flooding risk analysis in urban areas to inform decision making* (**Escuder-Bueno et al., 2011a**). An approach for quantitative flood risk analysis in urban areas with integration of social research data was developed after the SUFRI project and described within a paper submitted to Natural Hazards and Earth Science Systems (**Annex I**). In this Thesis, the analysis of structural collapse is incorporated. This part of the methodology has been developed within the iPRESARA project "Incorporating human-induced risk components into integrated dam safety management";
- section 3.3 includes a description on how to incorporate the analysis of risk reduction measures, and,
- section 3.4 includes comments on uncertainty and sensitivity analysis.

The methodology here described is flexible enough for performing different risk models as required in any urban area.

3.1. Basis

As described in chapter 2, risk may be divided into two components: probability and consequences. The proposed methodology describes how to estimate probabilities and potential consequences of flood events for the three considered flood hazards. This information is used as input data for a risk model, whose architecture is also part of the methodology. The model is further used to calculate risk and results are plotted on F-N and F-D curves. Representations are then used to visualize different situations (e.g. existent risk, situations with new risk reduction measures, etc.). The basis on how to incorporate information into risk models to calculate risk and its representation using F-N and F-D curves is described ahead.

3.1.1. Flood risk analysis using risk models

The use of event trees to compute flood event probabilities and consequences allows to characterize all events that can lead to flooding and obtain risk estimations that can be represented in F-N or F-D curves.

Event tree analysis uses inductive reasoning to translate probabilities of different initiating events into possible outcomes (**ISO 31010**), in this case, potential consequences of flooding. It can be used to represent mutually exclusive sequences of events following an initiating event (e.g. a rainfall event).

Despite the strengths on the use of event trees for risk quantification, event trees may result in thousands of paths and they may become inappropriate for graphical representation. Consequently, influence diagrams arise as a compact representation of the logic of the system and include the relationships between loads, system response and consequences.

Figure 6 shows a generic scheme which includes the main procedures for the development of a risk model for any study area.

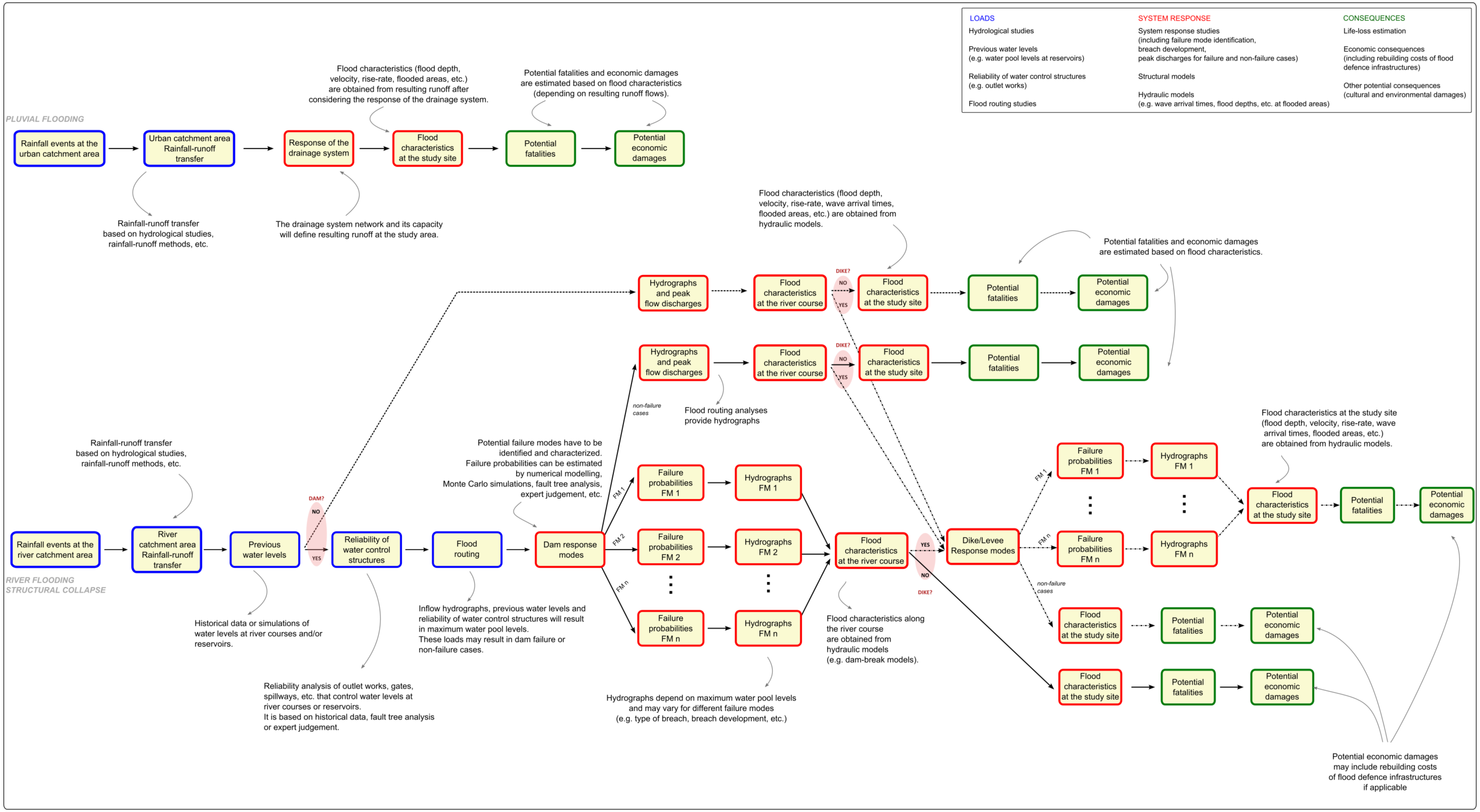


Figure 6. Generic diagram for risk model architecture on flood risk analysis integrating pluvial, river flooding and structural collapse.

This page intentionally left blank

This generic diagram distinguishes between loads (nodes in blue colour), system response (nodes in red colour) and potential consequences (nodes in green colour):

- Nodes referring to *loads* require information from hydrological studies, previous water levels at reservoirs or river courses, reliability of water control structures of flood defence infrastructures (e.g. dams, levees, dikes, etc.), flood routing studies, etc.
- Nodes referring to *system response* will require the identification of potential failure modes of flood defence infrastructures (e.g. dam break due to overtopping, internal erosion, etc.), quantification of failure probabilities, characterization of failure characteristics (e.g. breach development time) and the analysis of non-failure cases (e.g. overtopping of small dikes and levees, discharges from flood routing in large dams, etc.). All these aspects can be studied based on structural models, hydraulic models, fault tree analysis, expert judgement, etc.
- Nodes referring to *consequences* will include information based on estimation of potential economic damages and potential casualties. These estimates may be obtained using different methods which include the use of hydraulic models to calculate flood characteristics at the river course and at the study site. Flood depths, velocities, arrival wave times, flood severity levels, flood exposure, etc. are obtained to estimate potential consequences.

This generic influence diagram includes two independent schemes that start with different (and hypothetically 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 at the river course which may lead to flooding at the study site.

Consequently, the first scheme is proposed to analyze pluvial flooding and the second scheme for the analysis of river flooding and/or structural collapse.

Regarding *pluvial flooding*, the first scheme shows a generic diagram that may be used to analyze flooding from rainfall events at any *urban catchment area*. Information for this diagram will include the following aspects:

- rainfall events and return periods;
- rainfall-runoff transformation based on the characteristics of the urban catchment area;
- capacity of the drainage system network;
- resulting runoff rates after considering the response of the drainage system network;
- characteristics of the flood at the study site based on runoff rates, and,

- potential consequences (fatalities and economic damages) estimated for the aforementioned flood characteristics at the study site.

Regarding *river flooding* and *structural collapse*, the second scheme shows a generic diagram that may be used to analyze flooding from rainfall events at the *river catchment area*. The scheme diverges in different branches depending on the existence of flood defence infrastructures (dams, dikes or levees).

Information for this second diagram in case of *river flooding* will include the following aspects:

- rainfall events and return periods;
- rainfall-runoff transformation based on the characteristics of the river catchment area;
- previous water levels (flow discharges) at the river course;
- flood routing along the river course;
- flood characteristics at the study site (e.g. flood depths, velocities, flooded areas, duration of the flood, etc.).

After analyzing the response of the river catchment area and obtaining resulting runoff rates, information on flood characteristics at the river course and at the study site are necessary to estimate potential consequences due to river flooding.

The influence diagram for analyzing *structural collapse* may vary depending on existing flood defence infrastructures. In this proposed overall scheme (Figure 6), the existence of dams and dikes is considered. In this scheme, it is assumed that dikes (or levees) are built in the proximity of the study site and downstream the dam. Consequently, the risk model includes the analysis of structural collapse of dikes or levees after analyzing dam failure.

Dam failure is analyzed by considering reliability analysis of water control structures and flood routing analyses to estimate maximum pool levels at the reservoir. Then, potential failure modes are characterized and conditional probabilities have to be estimated. These estimations can be carried out based on information of dam reviews, structural models, fault tree analysis, expert judgement, Monte Carlo simulations, etc. Resulting hydrographs in failure and non-failure cases are used to obtain flood characteristics at the river course (e.g. by hydraulic modelling, dam-break models, etc.).

If dikes or levees are built downstream the dam, potential failure of these infrastructures should be analyzed for failure and non-failure cases. Dike response modes have to be also characterized based on flood characteristics at the river due to dam failure or discharges from flood routing.

Flood characteristics at the study site will vary for each combination of dam/dike response. Potential consequences have to be estimated for all cases, including rebuilding costs of these infrastructures in case of structural collapse.

The overall scheme given in Figure 6 is proposed as a reference diagram (risk model architecture) and it should be adapted for each case study.

3.1.2. Flood risk evaluation from F-N and F-D curves

Among the existing tools and techniques for risk analysis, these can be classified by applicability in terms of risk identification, risk analysis and risk evaluation (**ISO 31010**). Event trees are highly applicable for risk identification and analysis but not for risk evaluation. F-N and F-D curves highlight for being strongly applicable in risk evaluation.

As mentioned in chapter 2, F-N curves are a graphical representation of the probability of events causing a specified level of harm and show the cumulative frequency (F) at which N or more potential fatalities will result from flooding.

High values of N that may occur with a high frequency F are of significant interest because they may be socially and politically unacceptable depending on the existing standards or tolerability criteria (section 2.2.3).

F-N curves provide a representation of the level of risk describing the full range of variation of different flood events rather than a single point representing a probability-consequences pair. As a result, these curves represent the whole range of events which vary from ‘high probability - low consequences’ to ‘low probability - high consequences’ outcomes. Figure 7 shows the F-D curve for a hypothetic case study as an example.

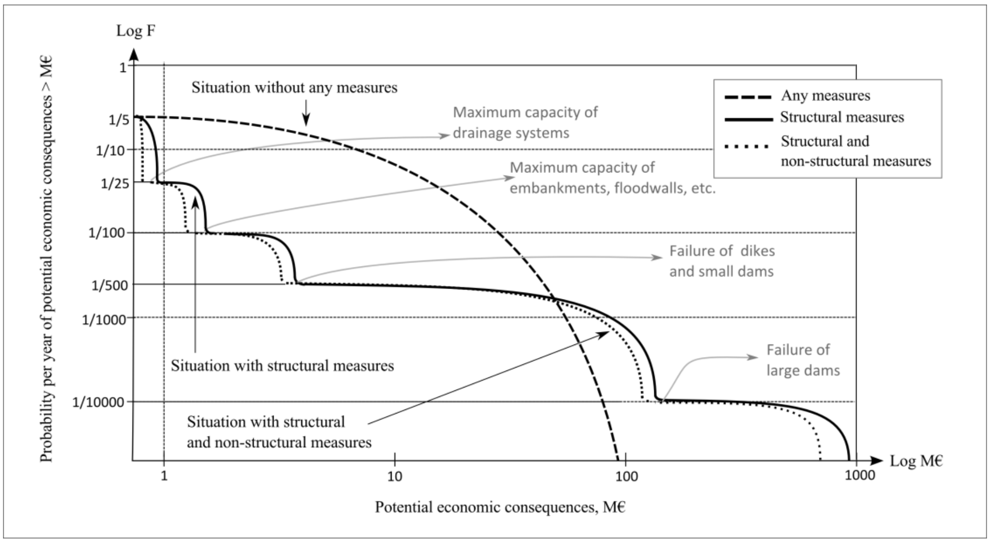


Figure 7. Example of F-D curves of a hypothetic case study (Escuder-Bueno et al., 2012).

It shows three situations to reflect the effect of structural and non-structural measures on flood risk. It uses typical (but fictitious) values in both axes (annual exceedance probability, F, and estimated economic damages, M€). Axes are represented in logarithmic scale. Values of both axes vary depending on the case study and have to be properly assessed for each case.

These three curves present the cumulative annual exceedance probability of the estimated level of potential economic damages. The area under the curve corresponds to total economic risk for each situation.

The three curves represent the following situations:

- the situation without any protection measures (dashed line);
- the situation of the study area with structural measures such as drainage systems, dikes, small and large dams (solid line); and,
- the situation with both structural and non-structural measures (dotted line).

On one hand, depending on what type of structural measure is considered, the F-D (or F-N) curve may capture a decrease on the annual exceedance probability (e.g. the impact of the existence of a drainage system or river embankments which reduces runoff flows for low rainfall events). However, the existence of a structural measure such as a large dam may simultaneously increase the estimated consequences for events which exceed its design event. In general, the design event is related to low probabilities, but the situation with structural measures (solid line) may result in higher potential consequences in comparison with the situation without any measures (dashed line). This increase may be captured by the F-D curve as it is shown in Figure 7 (e.g. the increase of potential damages shown in this figure in case of failure of large dams).

On the other hand, if a situation with structural and non-structural measures is considered (dotted line), the existence of non-structural measures such as emergency planning, warning systems, communication procedures in case of emergency, etc. may reduce potential consequences. Non-structural measures mitigate potential consequences but have no impact on probabilities (i.e. the F-D curve for this situation moves to the left of the figure in comparison with the situation with only structural measures).

Consequently, F-N and F-D curves may capture the impact of both structural and non-structural measures in flood risk reduction. This impact may be captured by a change in frequency (in terms of annual exceedance probabilities) and/or magnitude (in terms of potential consequences). Hence, resulting flood risk for each alternative can be analyzed and compared.

In addition, risk reduction can be quantitatively estimated by comparing the area under the curve.

Furthermore, flood risk evaluation may be addressed by comparing F-N and F-D curves with existing tolerability criteria or standards (as the examples given in section 2.2.3).

3.2. Phases of the methodology

Flood risk analysis aims to obtain the existent flood risk and analyze the current situation and other alternatives with risk reduction measures. With that purpose, the general diagram shown in Figure 7 has to be developed for any case study.

The proposed methodology describes the main phases of this process. The methodology is divided into ten different phases following the scheme proposed in the SUFRI project (**Escuder-Bueno et al., 2012 and 2011a**).

Figure 8 shows these ten phases which are summarized in this section and described in more detail in the final report of the SUFRI methodology (**Escuder-Bueno et al., 2011a**).

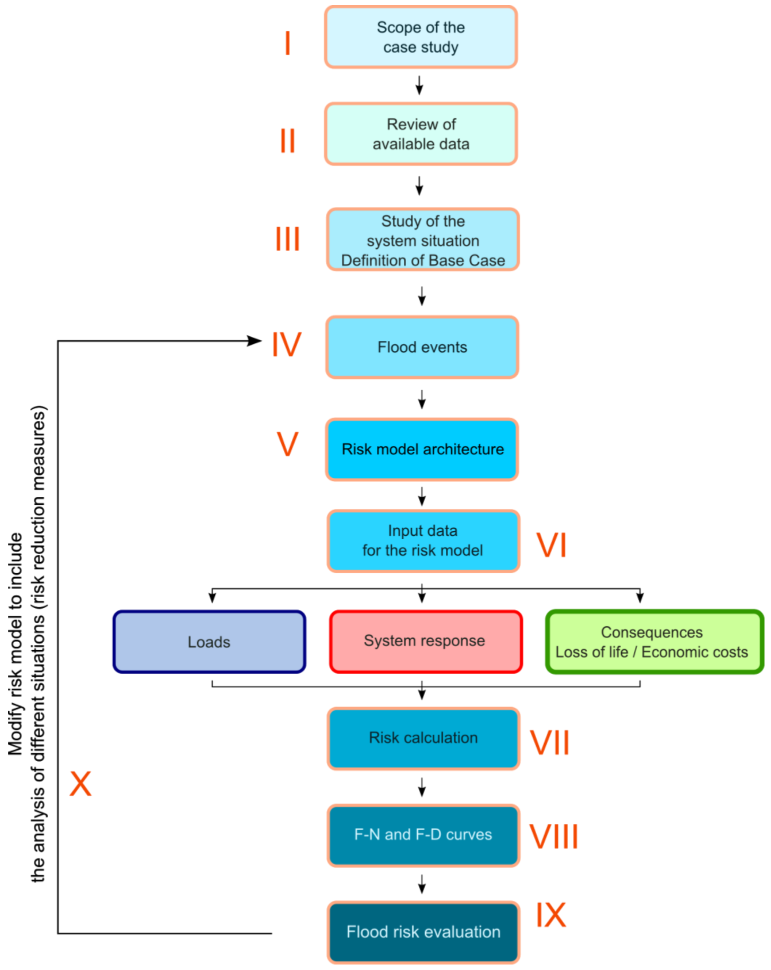


Figure 8. Phases of the methodology for flood risk analysis (Escuder Bueno et al., 2011a).

These ten phases are:

- Definition of the scope and aim of the study
- Review of available data
- Study of the current situation: Definition of the Base Case
- Definition of flood events
- Definition of risk model architecture
- Estimation of input data for the risk model
- Risk calculation
- Representation of F-N and F-D curves
- Flood risk evaluation
- Analysis of different situations and comparison with the Base Case

The objective and main aspects of each phase are here described:

Phase I: Scope of the case study

The first stage of flood risk analysis includes the definition of the scope of the study and the objectives of the analysis (e.g. prioritize risk reduction measures based on the existent situation and comparison of results). The level of detail may depend on data availability.

Definition of the scale is also an important point in this first stage. Although urban flood risk analysis refers to local scale, the methodology can be applied also to other levels (e.g. regional, national scale, etc.). Data and time requirements vary for each scale as shown in Table 1.

Table 1. Requirements for different scale levels (Escuder-Bueno et al., 2011a).

Scale	***Study area***	***Management levels***	***Level of detail***	***Level of resources***	***Data requirements***
Macro-scale	National	Flood reduction policies	Low	Low	Low
Meso-scale	Regional	Large-scale strategies for flood reduction	Medium	Medium	Medium
Micro-scale	Local	Individual protection measures	High	High	High

In general, higher levels of data and resources are necessary to carry out analyses at local scale. However, available information will differ for different case studies depending on historical flood events, the existence of previous analyses, existing protection measures, etc. This methodology can be applied from basic to high-detailed analyses by adapting the risk model architecture and estimations of input data to available information.

Phase II: Review of available data

The level of uncertainty on risk estimations will depend on available information (previous studies, data collection, site visits, etc.). Gathering information may include factors such as historical data of past flood events, hydraulic and hydrological studies, characteristics of urban and river catchment areas, existing infrastructures (including design events, behaviour during past flood events, etc.), flood prone areas, seasonal and daily variations on population, density rates, value of assets, land use distribution, etc.

Phase III: Study of the current situation. Definition of the Base Case

It is necessary to study the current situation of the case study (defined as Base Case) to analyze the existent risk.

The Base Case is the basis to compare different situations with risk reduction measures to obtain their impact on flood risk.

The Base Case should include the response of existent flood defence infrastructures, including also existent non-structural measures (e.g. an implemented Dam Emergency Action Plan).

Characterization of all elements and relevant aspects which characterize the system is required to capture important information within the risk model. For example, if different failure modes of a flood defence infrastructure lead to different flooding characteristics, then these alternatives should be considered and captured.

Phase IV: Flood events

The risk model of the Base Case should consider the range of possible flood events, taking into account the three sources of flood hazard: pluvial flooding, river flooding and structural collapse. With that purpose, flood events may include the following situations:

- flooding from rainfall occurred at the urban catchment area (runoff exceeds the capacity of the drainage system and water flows along streets of the urban area);
- floods due to an increase of peak flow discharges at the river course after rainfall events at the river catchment area, and,
- floods due to failure cases of all existent infrastructures (e.g. levees, dikes, dams, etc.) and also non-failure cases (i.e. flooding due to discharges produced by flood routing of defence infrastructures).

Each flood event will be characterized by a certain annual probability of exceedance. This probability is obtained based on the corresponding initiating event (i.e. the rainfall event) and conditional probabilities are related to system response.

Flood events are typically identified by the return period of the initiating rainfall event or of maximum flow discharges at the study site. In this point, some general comments are included:

- *Pluvial flooding*: In pluvial flooding, flood events are generally identified by the return period (T) of the corresponding rainfall event at the urban catchment area.
- *River flooding*: Flood events are identified by flow discharges at the study site for different rainfall events at the river catchment area. Hydrographs at the study site are obtained after considering flood routing along the river course. In general, despite the source of flooding, each flood event can be identified by the resulting maximum flow discharge at the study site (e.g. natural flow regime, Q_{max}, or flood routing of small infrastructures and non-failure cases of large infrastructures, Q_{nbr}).
- *Structural collapse*: Flood events can be identified by the hydrograph (or maximum flow discharge in case of failure, Q_{br}) which results from the combination of loads that cause the failure of the flood defence infrastructure.

The risk model uses the aforementioned attributes and variables (T, Q_{max}, Q_{br} or Q_{nbr}) to relate probabilities to potential consequences.

In general, the considered range of initiating rainfall events which result in flooding may vary depending on the case study. In pluvial flooding, return periods ranging from 1 to 100 years are usually analyzed. In river flooding, higher return periods might be necessary when analyzing flood defence infrastructures (e.g. 500 or 1,000 years). For a highly defended areas (e.g. with large dams or levees), return periods up to 10,000 years could be necessary for the analysis.

Phase V: Risk model architecture

As shown in Figure 8, the risk model can be divided in three generic parts: loads, system response and consequences.

The risk model architecture of the case study may vary from simple to more complex schemes depending mainly on existent flood defence infrastructures and identified failure modes.

In this phase, it is important to define a risk model architecture that represents correctly all relevant factors which characterize the case study.

In addition, it is also important to identify those nodes that will be modified for the analysis of risk reduction measures (e.g. nodes of potential consequences in case of non-structural measures). This will allow to incorporate new input data after the analysis of the current situation, using the risk model architecture of the Base Case as a reference.

Phase VI: Input data for the risk model

Similarly to the classification of nodes of the influence diagram, input data can be classified in three categories: loads, system response and consequences.

Information from hydrological studies of the urban and river catchment areas, analyses of system response (failure modes, hydraulic characteristics of the flood, etc.) and estimations on life-loss and economic damages are used as input data to calculate societal and economic risk.

In this point, an overall description is given for the three categories. References are given for detailed descriptions on estimation of input data.

Loads

Flood risk analysis requires the evaluation of the full range of hydrologic loading conditions. These conditions may initiate possible failure mechanisms of flood defence infrastructures.

Upper bounds for this range may vary depending on the analysis. A single, deterministic flood estimate such as the Probable Maximum Flood (PMF) has been traditionally used as an upper limit for flood frequency extrapolations.

Hydrologic studies of the urban and river catchment area should provide information on rainfall magnitudes, probable maximum precipitation characteristics, rainfall-runoff transfer, hydrographs, peak flow frequencies, annual probabilities of exceedance (AEP), etc. Then, the response of the catchment area and resulting loads to the system may be characterized (e.g. inflow rates at the reservoir or runoff at the urban area).

In case of existing flood defence infrastructures (e.g. levees or dams), this part of the model includes:

- data from previous water pool levels at the reservoir or river courses;
- reliability of water control structures (e.g. outlet works that influence the resulting water levels);
- resulting maximum water pool levels at the reservoir due to flood routing.

Resulting loads will drive the type and progress a potential structural collapse.

In addition, the natural river flow regime may also be analyzed to obtain characteristics of the flood at the study site to be compared with the existent situation.

System response

<u>Pluvial flooding</u>

In this section, main aspects of models typically used for modelling urban drainage or sewer systems are provided. The focus is to give an overview rather than detailed explanations on how to establish this modelling, as these can be found in the literature (e.g. **Beven, 2001**).

There exist different models and software tools (e.g. XP-SWMM or RisUrSim, **Schmitt et al., 2004**) that simulate urban drainage or sewer systems. Models may vary from simple to complex dual models (i.e. models that consider the interaction of surface and sewer flow).

In general, dual models include the following main stages (**Schmitt et al., 2004**):

- rainfall-runoff transformation;
- hydraulic surface flow modelling;
- dynamic sewer flow modelling; and,
- interaction of surface and sewer flow.

These models can provide flood hydraulic characteristics. However, dual models require detailed information on the drainage network and are time-consuming. For that reason, in small areas, the analysis may be performed by simplified models, empirical flow formula (e.g. Manning's equation) or 1D models.

Flood hydraulic characteristics at the study site have to be obtained, including peak flow rates, flooded areas, width of the flooded area, flood depths, velocities, arrival wave times, etc. These characteristics are later used to estimate consequences in economic and societal terms.

River flooding

There exist different hydraulic models for the analysis of water surface elevation for river floods. In general, these models can be classified in four categories:

- one-dimensional steady flow models;
- one-dimensional unsteady flow models;
- two-dimensional steady flow models; and,
- two-dimensional unsteady flow models.

Some examples of the first group are HEC-RAS (U.S. Army Corps of Engineers) or XP-SWMM (XP Solutions). Within the second group, models such as HEC-RAS, FLDWAV (National Weather Service, USA) or MIKE 11 (DHI Water and Environment) are commonly used. Some of these models solve the fully dynamic equations of motion for one- and two-dimensional flow in open channels and river flood plains, including modelling of small channels, culverts, weirs, gates, bridges and other defence/control structures like dams (e.g. MIKE FLOOD).

Hydraulic models should provide flood characteristics at the study site, including peak flow rates, flooded areas, width of the flooded area, flood depths, velocities, arrival wave times, etc. These characteristics are used to estimate consequences in economic and societal terms.

Structural collapse

The analysis of structural collapse includes identification and characterization of potential failure modes, estimating conditional probabilities and obtaining a clear understanding of the process. This analysis requires and benefits from all available information (historic records and photos, engineering analyses, reports, site visits, etc.).

Potential failure mode analyses are site specific, as they vary for each infrastructure. However, general outcomes include:

- data gathering of all possible information;
- involvement of all people who play an important role in managing or operating the infrastructure;
- identification and documentation of potential failure modes and scenarios;
- definition of relevant monitoring and surveillance activities;
- identification of better operating practices and emergency preparedness for risk reduction.

Failure mode identification and characterization is commonly carried out in group sessions. Participants are generally owners, inspectors, consultants, engineers, personnel, etc. who are involved on operation and management. In these sessions, all of them have the opportunity to provide their knowledge, understanding and views on potential failure modes, consequences and possible risk reduction measures (**USBR, 2010**).

The risk model incorporates information on identified failure modes and probabilities. These probabilities may be estimated from different methods such as expert judgement, artificial neural networks, Bayesian networks, etc. Probability estimates should be assigned by an expert group. Either if resources are available for that or if it has to be done through a smaller group, detailed justification of the reason for such elicitation should be clearly provided (**Ayyub, 2001**).

Hydraulic models provide resulting hydrographs due to failure and non-failure cases. Flood characteristics are used to estimate consequences in economic and societal terms.

Consequences

A detailed description on how to estimate potential consequences due to pluvial and river flooding is given in the SUFRI methodology (**Escuder-Bueno et al., 2011a**). In this Thesis, a summary is included, describing the main differences between pluvial flooding, river flooding and structural collapse for estimating potential loss of life and economic damages.

In general, the number of potential fatalities is obtained by multiplying population at risk by the fatality rate for each flood event. However, fatality rates for pluvial and river flooding have been obtained from different methods and historical data. Therefore, differences can be found on the estimation process.

Economic losses are assessed by identifying homogenous areas, defining reference costs, estimating percentages of damage, etc. to calculate direct and indirect costs. Although flood depths due to pluvial flooding are in general lower than in river flooding or flooding due to structural collapse, methods to estimate potential economic damages do not show high differences. Depth-damage curves are obtained for flood depths ranging from some centimetres to several meters. Therefore, the same process is proposed for estimating potential economic damages for all sources of flood hazard.

Potential loss of life - Pluvial flooding

In pluvial flooding, potential loss of life can be estimated as the combination of *population exposed* to the flood and *fatality rates* related to flood characteristics.

The chance of people being exposed to the flood depends on where they are. For example, they may stay outdoors, in a vehicle or in a building.

In general, existent studies on life-loss estimation are developed in countries with building typologies that differ from others. For example, fatality rates in U.S. have to be corrected for the case studies in Spain as, in general, households present higher building heights. In addition, flooded areas used to establish fatality rates may differ from the case study.

Therefore, two recommendations are given to obtain people exposed to the flood:

- First, a factor is suggested to reduce the amount of people within the urban area for calculations, using a density value (d_C) lower than the existent density population at the urban area (d). Then, population at the study area is reduced to a number of people at risk (PR).
- Second, it may be considered that population at risk can be divided into two groups: people located outside buildings during the flood and people who remains in their households. Therefore, two values should be determined to establish the percentage of people outside (f_{out}) and people in their households (f_{in}). Consequently, two values of people exposed to the flood are obtained as follows:

$$PR_{out} = f_{out} \cdot PR = f_{out} \cdot d_C \cdot A \quad (7)$$

$$PR_{in} = f_{in} \cdot PR = f_{in} \cdot d_C \cdot A \quad (8)$$

Consequently, different fatality rates can be applied to estimated people outside/inside their households.

With the purpose of establishing reference *fatality rates* for pluvial flooding, a classification of five flood severity levels (from S0, where low victims are expected, to S4, extreme severity) was established within the SUFRI methodology, based on a set of data collected from literature review (e.g. **Témez, 1991; Reiter, 2001**; **Nanía, 2002**; **Gómez and Russo, 2009**), including theoretical studies and experimental data.

After representing all available data together, five flood severity levels were defined (S0-S4) by the combination of different hydraulic parameters such as flood depth, velocity, dragging and sliding parameters (Figure 9 and Table 2).

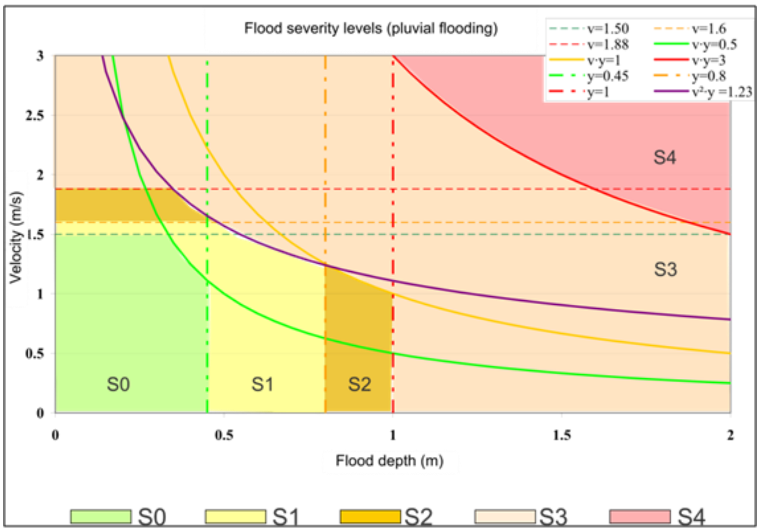


Figure 9. Flood severity levels for estimating consequences in pluvial flooding (Escuder-Bueno et al., 2011a).

Table 2. Flood severity levels for estimating consequences in pluvial flooding (Escuder-Bueno et al., 2011a).

	Flood severity levels (S)	*Depth y (m)*	*Velocity v (m/s)*	*Dragging parameter v·y (m²/s)*	*Sliding parameter v²·y (m³/s²)*
S0	No victims are expected. People expected to survive	<0.45	<1.50	<0.50	<1.23
S1	Low severity Pedestrians may suffer loss of stability. People in danger	<0.80	<1.60	<1.00	<1.23
S2	Medium severity Significant loss of stability. Cars can lose road holding. Floating	<1.00	<1.88	<1.00	<1.23
S3	High severity High risk for people outside Low risk for buildings	>1.00	>1.88	>1.00	>1.23
S4	Extreme severity Structural damages on buildings	>1.00	>1.88	>3.00	>1.23

Once each flood severity level had been defined based on hydraulic characteristics of the flood, fatality rates may be obtained based on the method proposed by **Penning-Rowsell et al.** in 2005. This method focuses on the estimation of the total number of people located in flood-prone areas and the proportion of this one that is likely to be exposed to it, injured or killed.

With the aim of providing different fatality rates based on the existence of warning systems and their impact on potential loss of life, three different levels of flood warning are proposed (Table 3).

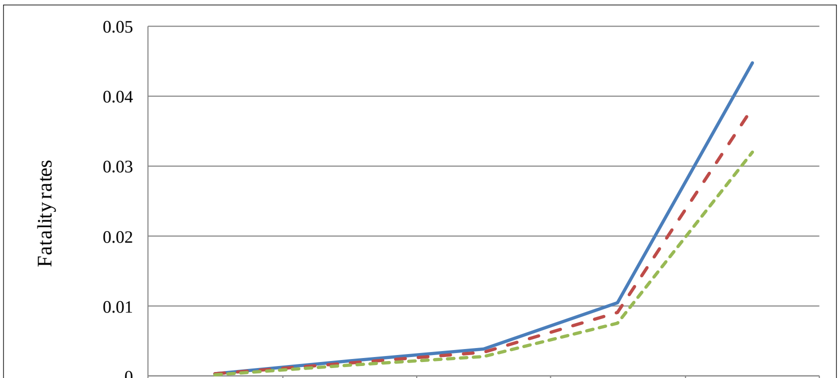
Table 3. Categories for defining fatality rates in pluvial flooding (Escuder-Bueno et al., 2011a)

ID	*Category*	*FW parameter (Penning-Rowsell et al. 2005)*
C_{p1}	No warning systems are available	3
C_{p2}	Warning systems do exist but not used	2
C_{p3}	Verified and advanced warning systems	1

These levels are based on the three factors proposed by **Penning-Rowsell et al.** (2005) to characterize area vulnerability (depending on flood warning, speed of onset and nature of area). Flood warning is captured by the FW parameter. This factor ranges from 1 to 3 depending on available warning systems which are characterized in terms of emergency planning, awareness and preparedness of the affected population, and preparing and issuing flood warnings. Consequently, any urban area can be classified in one of the three categories shown in and linked to one of the three values of FW.

For each category (C_{p1} to C_{p3}) and flood severity level (S0 to S4), fatality rates are estimated using mean values for building typology (**Penning-Rowsell et al., 2005; Escuder-Bueno et al 2011a**), people vulnerability and the so-called area vulnerability factors (except for the FW parameter, Table 3). If other characteristics of the population are considered, fatality rates should be corrected following the guidelines given in **Penning-Rowsell et al.** (2005). In addition, mean values of water depth and velocity were used for each flood severity level to provide a reference value for each category, C_p, and flood severity level, S.

Consequently, fifteen fatality rates have been proposed as shown in Figure 10.



	S0	S1	S2	S3	S4
CP1	0.0003	0.0021	0.0038	0.0105	0.0448
CP2	0.0003	0.0018	0.0033	0.009	0.0384
CP3	0.0002	0.0015	0.0027	0.0075	0.032

Figure 10. Fatality rates for pluvial flooding (Escuder Bueno et al., 2012).

Finally, potential fatalities are obtained by combining population exposed to the flood and fatality rates for each flood event.

Potential loss of life - River flooding

In case of river flooding, flood hydraulic characteristics (e.g. water depths, velocities, rise-rate, flood areas, etc.) differ from pluvial flooding. Therefore, casualties due to river flooding have been historically higher than in pluvial flooding.

Therefore, different methods can be found in the literature (e.g. **Graham, 1999; Reiter, 2001; Jonkman, 2008**). Consequently, different values for fatality rates have to be used and the definition of flood severity levels differs in these cases.

Fatality rates in river flooding are applied to population at risk since reference fatality rates have been generally estimated based on historical data of past flood events and inhabitants within affected areas. Therefore, population at risk in river flooding is defined as population within the study area when the flood occurs.

For the definition of fatality rates, a classification of ten categories (**Escuder-Bueno et al., 2011a**) is proposed to assess potential loss of life in case of river flooding (Table 4). This classification can also be used in case of structural collapse. It provides ten categories (C1 to C10) that have been developed depending on the existence of public education on flood risk, warning systems, risk communication and coordination between emergency agencies and authorities.

Each category is linked to a certain level of flood severity understanding based on a compilation of historical data and existing reference values on loss of life (**Graham, 1999**; **USBR, 2001**). Consequently, different fatality rates are considered for each category (C1 to C10) depending on available warning times (from 0 to 24 hours) and three flood severity levels.

These three severity levels (low, medium and high) depend on flood characteristics such as the peak discharge in the flooded area, mean annual peak discharge at the river course and flood extent (**Graham, 1999**).

Table 4. Fatality rates in case of river flooding (Escuder-Bueno et al., 2011a).

ID	Category for the case study (C)	Warning time TW (h)	Flood severity (Sv)		
			High (3)	Medium (2)	Low (1)
C1	- There is no public education on flood risk terms. - No warning systems, no EAP. - There is no coordination between emergency agencies and authorities. - No communication mechanisms to the public.	0	0.9	0.3	0.02
		0.25	0.9	0.3	0.02
		0.625	0.7	0.08	0.015
		1	-	0.06	0.0006
		1.5	-	0.0002	0.0002
		24	-	0.0002	0.0001
C2	- There is no public education on flood risk terms. - There is no EAP, but there are other warning systems. - There is no coordination between emergency agencies and authorities. - No communication mechanisms to the public.	0	0.9	0.3	0.02
		0.25	0.9	0.3	0.02
		0.625	0.675	0.075	0.014
		1	-	0.055	0.00055
		1.5	-	0.0002	0.0002
		24	-	0.0002	0.0001
C3	- There is no public education on flood risk terms. - There is EAP, but it has not been applied yet. - Some coordination between emergency agencies and authorities (but protocols are not established). - No communication mechanisms to the public.	0	0.9	0.3	0.02
		0.25	0.85	0.2	0.015
		0.625	0.6	0.07	0.012
		1	-	0.05	0.0005
		1.5	-	0.0002	0.0002
		24	-	0.0002	0.0001
C4	- There is no public education on flood risk terms. - EAP is already applied. - Coordination between emergency agencies and authorities (there are protocols). - No communication mechanisms to the public.	0	0.9	0.3	0.02
		0.25	0.75	0.15	0.01
		0.625	0.5	0.04	0.007
		1	-	0.03	0.0003
		1.5	-	0.0002	0.0002
		24	-	0.0002	0.0001
C5	- There is no public education on flood risk terms. - EAP is already applied. - Coordination between emergency agencies and authorities (there are protocols). - Communication mechanisms to the public (not checked yet).	0	0.9	0.3	0.02
		0.25	0.75	0.15	0.01
		0.625	0.5	0.0375	0.0065
		1	-	0.0275	0.000275
		1.5	-	0.0002	0.0002
		24	-	0.0002	0.0001
C6	- There is no public education on flood risk terms. - EAP is already applied. - Coordination between emergency agencies and authorities (there are protocols). - Communication mechanisms to the public.	0	0.9	0.3	0.02
		0.25	0.75	0.15	0.01
		0.625	0.475	0.035	0.006
		1	-	0.025	0.00025
		1.5	-	0.0002	0.0002
		24	-	0.0002	0.0001
C7	- Public education. - EAP is already applied. - Coordination between emergency agencies and authorities (there are protocols). - Communication mechanisms to the public.	0	0.9	0.3	0.02
		0.25	0.65	0.1	0.0075
		0.625	0.4	0.02	0.002
		1	-	0.01	0.0002
		1.5	-	0.0002	0.0002
		24	-	0.0002	0.0001
C8	- Public education - EAP is already applied. It has been proved or used previously. - Coordination between emergency agencies and authorities (there are protocols). - Communication mechanisms to the public.	0	0.9	0.3	0.02
		0.25	0.55	0.06	0.006
		0.625	0.35	0.01	0.0015
		1	-	0.005	0.00015
		1.5	-	0.0002	0.00015
		24	-	0.0002	0.0001
C9	- Public education. - EAP is already applied. It has been proved or used previously. - High coordination between emergency agencies and authorities (there are protocols). - Communication mechanisms to the public.	0	0.9	0.3	0.02
		0.25	0.55	0.06	0.006
		0.625	0.35	0.008	0.0015
		1	-	0.004	0.000125
		1.5	-	0.0002	0.0001
		24	-	0.0002	0.0001
C10	- Regular activities and plans for public education. - EAP is already applied. It has been proved or used previously. - High coordination between emergency agencies and authorities (there are protocols). - Communication mechanisms to the public.	0	0.9	0.3	0.02
		0.25	0.5	0.03	0.005
		0.625	0.3	0.005	0.001
		1	-	0.002	0.0001
		1.5	-	0.0002	0.0001
		24	-	0.0002	0.0001

Note: Category C7 also used for case studies which correspond to categories C8, C9 or C10 if dam break occurs with no-hydrologic scenario.

Once the existing public education, emergency management, communication and coordination mechanisms are evaluated for the urban area, a certain category is used to associate fatality rates with the analyzed flood events.

Accordingly, the existence of non-structural measures (e.g. a public education programme on flood risk with information and advice to the public) can be analyzed by establishing a new category with respect to the Base Case.

In addition to river flooding, the analysis of non-failure cases of existent flood defence infrastructures is necessary to estimate potential consequences due to these events.

Potential loss of life - Structural collapse

In case of structural collapse, resulting flood depths, velocities, flooded areas, etc. may be much higher than flood characteristics from the natural flow regime or discharges from flood routing.

The same definition of flood severity levels can be used for structural collapse than in river flooding. In general, high flood severity is only applied in cases due to structural collapse and flooded areas which are at a short distance of the infrastructure. For that reason, Table 4 does not show values of reference fatality rates in case of high flood severity for warning times higher than one hour.

The existence of an Emergency Action Plan for any flood defence infrastructure (e.g. large dams) can also be considered in this classification, as listed in Table 4. The degree of implementation of the plan will also influence the definition of the category.

Potential economic damages- Pluvial flooding, river flooding and structural collapse

A detailed study of economic damages would include several factors such as flood depth, velocity, duration of the flood, debris, etc. In this Thesis, estimation of potential economic damages is proposed using depth-damage curves. These curves are widely used for analyzing economic flood risk (e.g. **Dawson, 2003; Scawthorn et al., 2006**).

The process for estimating potential economic damages includes the following steps:

- identification of homogenous subareas (e.g. depending on land uses, value of assets, etc.);
- definition of reference costs for each of these areas (the reference cost reflects the economic loss that occurs in case of total destruction of the area);
- estimation of a percentage of damage based on flood depths and depth-damage curves, and,
- calculation of direct and indirect costs.

All assets that would be damaged in a flood event have to be considered, including residential and industrial areas, schools, hospitals, etc., along with artistic and cultural heritage.

Reference costs can be estimated from regional or national studies, market prices, statistics, etc. In general, reference values can be obtained from different sources. Information of previous studies should be converted to the present value and adjusted by GDP (Gross Domestic Product) indicators if data is obtained from other countries. As an example, the following two documents can be found in the Spanish context and they include reference values for assets depending on several land use categories:

- PATRICOVA: "*Plan de Acción Territorial de carácter sectorial sobre prevención del Riesgo de Inundación en la Comunidad Valenciana"* (**COPUT, 2002**), published in 2002 by the Department of Infrastructure, Planning and Environment of the Valencian Goverment; and,
- INUNCAT (2009): "*Plan Especial de Emergencias por Inundación* (**INUNCAT, 2009**), published in 2009 by the Catalan Water Agency.

These two studies are widely used in Spain to establish economic losses in case of flooding. Their reference values can be found in English version in the SUFRI methodology (**Escuder-Bueno et al., 2011a,** Appendix 5).

The percentage of damage can be estimated from depth-damage curves. These functions relate flood characteristics and damage for a certain category of elements at risk. Several studies that propose depth-damage curves are found in the literature (e.g. **Dawson, 2003; Scawthorn et al., 2006; Messner et al., 2007**). Some examples are given in Figure 11 (**COPUT 2002**) and Figure 12 (**Elsner et al., 2003**). Consequently, flooded areas, reference costs and these curves are used to estimate direct costs for each flood event.

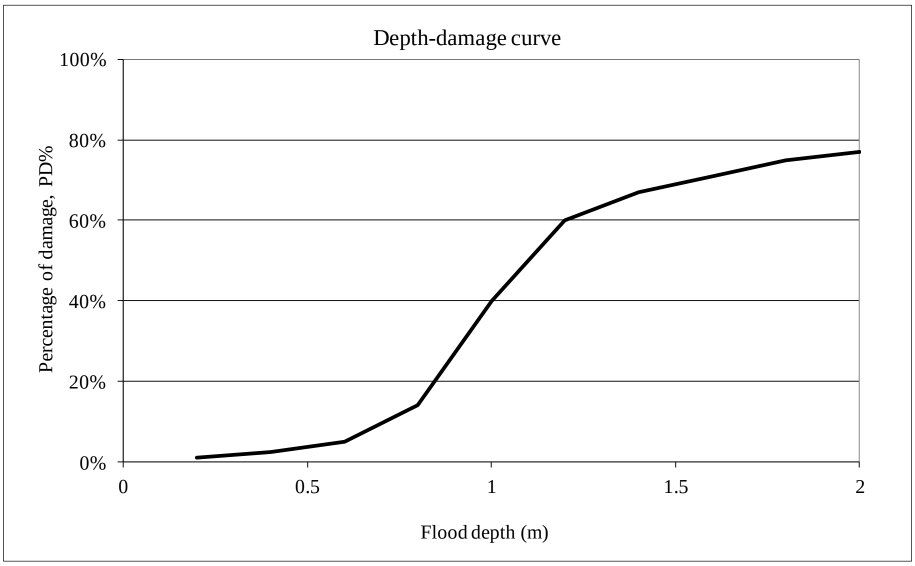


Figure 11. Depth-damage curve (COPUT, 2002).

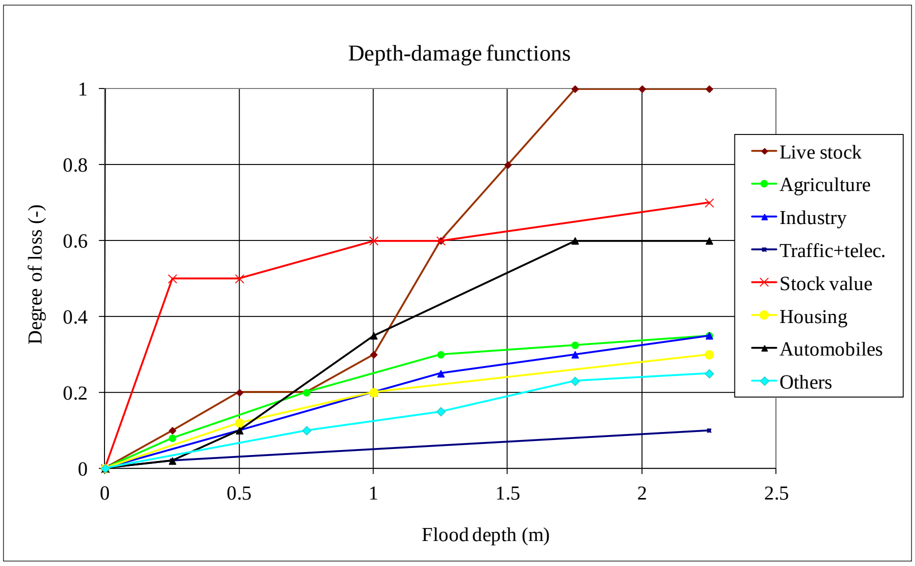


Figure 12. Depth-damage curves for multiple land uses (Elsner et al., 2003).

Estimation of indirect costs (**Messner et al., 2007**; **DHS, 2011**) requires more detail information of the urban area, including, e.g., loss of production, traffic disruption, costs of emergency services or existence of critical infrastructures (**EC, 2008**). A more detailed analysis of indirect costs may be necessary in the following cases:

- Flood events of long duration (several weeks);
- Large areas (a whole region or country);
- Existence of highly specialized or hazardous industries;
- Damage on relevant points or road links (transport, energy, etc.); or,
- Low stock rates (shortage of resources).

In general, a simplified method can be used to estimate indirect costs of flooding (**COPUT, 2002; Escuder-Bueno et al., 2011a**). Indirect costs may be obtained from a percentage of total direct costs, usually ranging from 0% to 55% (**COPUT, 2002**). This rate depends on the characteristics of the case study (e.g. infrastructures, economic centres, etc.).

Phases VII: Risk calculation

The risk model of the Base Case combines information provided in each node to obtain conditional probabilities and potential consequences of all branches of the resulting event tree.

Phase VIII: Development of F-N and F-D curves

Once risk calculations have finished, different results can be obtained such as total societal and economic risk or all pairs of annual probabilities of exceedance and potential consequences.

Consequently, annual exceedance probabilities and consequences can be represented in F-N and F-D curves by different editing tools (e.g. Excel sheets).

Phase IX: Risk evaluation

If tolerability criteria are available and can be applied to the case study, societal and economic risk may be potentially compared with standards to evaluate the existent flood risk. In addition, results may be compared with information of past flood events to validate the Base Case.

Phase X: Study of risk reduction measures

Before analysing new risk reduction measures, the natural flow regime of the river or the situation without any flood defence infrastructures (or drainage systems) may be analyzed to compare this situation with existent risk. Consequently, the effect of existent measures can be analyzed and differences with the situation with any measures may be helpful to understand the benefits of existing flood defence infrastructures.

Different situations with new risk reduction measures can be analyzed. The risk model of the Base Case is used as a reference model. However, this model may vary depending on risk reduction measures to be considered, e.g. a new flood defence infrastructure may require the definition of new nodes to incorporate potential failure modes that were not considered for the Base Case. Hence, a review of previous phases is required to obtain new F-N or F-D curves for different alternatives.

Among existing risk reduction measures, non-structural measures do not modify loads or system response. Therefore, the risk model architecture will need minor changes to carry out the analysis of non-structural measures.

Non-structural measures for flood risk reduction cover a wide variety of different actions like, for instance, warning systems, planning instruments, etc. (**Schanze et al., 2008**). These measures can be classified based on different approaches. Here, a classification of four categories is presented (**Escuder-Bueno et al., 2012**):

- measures on public education;
- measures concerning warning systems and emergency management;
- measures concerning coordination between authorities and emergency services, and,
- measures concerning communication to the public.

Depending on the source of hazard and the previous classification, the effect of non-structural measures for risk reduction can be incorporated to the risk model in a different way. In general, this effect is captured by relating the new situation with a level of flood severity understanding and risk awareness of population potentially affected by the flood.

Consequence estimation varies for pluvial, river flooding and structural collapse (although potential consequences from the last two sources of hazard can be estimated similarly). Therefore, estimations of population at risk, people exposed to the flood, fatality rates, etc. vary depending on each measure (e.g. fatality rates in river flooding are obtained from a classification of ten levels, Table 4, where values vary depending on existing public education, communication, coordination and warning mechanisms). Section 3.3 shows examples on how to incorporate the existence of non-structural measures on consequence estimation.

To conclude the description of the methodology, Table 5 lists the most frequent data requirements to obtain information and estimate input data for the risk model.

Table 5. Summary of data requirements (Escuder-Bueno et al., 2011a).

Phase	*Description*	*Data requirements*
I	Scope of the case study	Extent and relevance of the urban area. Time and resources for the study.
II	Review of available data	Land use and cadastral maps. Topography. Statistics (demography, urbanism, economy, etc.). Building typology. Flooded areas, damages, etc. Hydrologic studies, rainfall rates, urban/river catchment areas, river network, etc.
III	Study of the current situation. Definition of the Base Case	Existing flood defence infrastructures (levees, dams, ponds, detention basins, embankments, floodwalls, drainage system, etc.). Existent non-structural measures.
IV	Flood events	Return periods of rainfall events. Flood routing analyses. Peak discharges in failure and non-failure cases.
V	Risk model architecture	Loads / System Response / Consequences. Nodes that represent all potential failure modes and combinations.
VI	Input data for the risk model	LOADS: Data from hydrological studies / Flood routing, response of subsystem elements, etc. SYSTEM RESPONSE: Failure modes and conditional probabilities / Hydraulic characteristics of each flood event (hydraulic modelling, other studies or data) / Flooded areas, depths, velocities, arrival wave times, width, etc. CONSEQUENCES: Potential loss of life / Potential economic losses.
VII	Risk calculation	Risk model results.
VIII	F-N and F-D curves	Annual probability of exceedance of each level of potential consequences.
IX	Risk evaluation	Comparison with past events, standards or tolerability criteria.
X	Study of the effect of risk reduction measures	Review of the previous phases to analyze other situations. Input data estimates to capture the existence of new measures. New results and F-N and F-D curves. Comparison with the Base Case.

Appendix A includes several schemes, including flow charts, tables and notes, which support the application of the methodology. Two main schemes are developed: first, a scheme for analyzing pluvial flooding, and a second scheme for river flooding, including structural collapse of existing flood defence infrastructures.

3.3. Incorporating non-structural measures into risk analysis

Based on the risk model of the Base Case, risk reduction measures can be analyzed by estimating new input data.

Variations will depend on the type of measures. Structural measures may need new nodes and information to characterize response and failure modes. However, non-structural measures affect only potential consequences of the flood.

For that reason, this section includes some examples on how to incorporate the existence of new non-structural measures on consequence estimation to analyze different alternatives for flood risk analysis at the urban area.

3.3.1. Potential fatalities

Phase VI summarizes the main factors which characterize the process for estimating potential fatalities and capture the existence of non-structural measures.

For example, non-structural measures concerning urban planning focus on reducing vulnerability by preventing new constructions in flood prone areas and, consequently, reducing population at risk. This effect can be similarly considered in all sources of hazard. However, the implementation of a new warning system is captured differently for pluvial or river flooding (Table 3 or Table 4). Therefore, some examples are given in this section to show how non-structural measures can be included in the risk model to capture their effect on risk reduction.

Pluvial flooding

The category of the case study, associated to a set of reference fatality rates (Table 3), depends on existing warning systems. Consequently, improvements on warning systems will result in lower reference fatality rates which vary from the Base Case.

If public education measures are considered, a reduction on the population exposed to the flood may be estimated as it is assumed that public education improves flood severity understanding and risk awareness, e.g. population at risk will know how to find shelter or protect their assets. This reduction may be defined from expert judgement, existing studies, social research data, etc. taking into account the characteristics of the case study and its population.

For example, an approach to combine social research data into quantitative risk analysis to analyze different alternatives of non-structural measures is proposed in **Escuder-Bueno et al. 2012**. This approach aims to incorporate results of opinion polls and surveys into the estimation process of potential consequences.

River flooding and structural collapse

Reference fatality rates for river flooding or structural collapse depend on existing warning, communication, coordination mechanisms, etc. (Table 4).

The category for the Base Case (from C1 to C10) will change to a higher category when new non-structural measures are incorporated into the analysis such as improvements on warning, evacuation, communication, etc.

In addition, implementation of Emergency Action Plans (e.g. in large dams) will result in higher warning times and, consequently, reference fatality rates will vary from those used for the Base Case (e.g. warning times may be 15 or 30 minutes longer than the Base Case).

3.3.2. Potential economic damages

The analysis of the effect of warning systems is captured as a reduction on economic damages. However, it may be considered that this measure should be implemented along with public education, as it is assumed that warnings are effective only if population at risk have a certain level of knowledge on how-to-act in case of flood.

Therefore, reduction on potential economic damages (e.g. from installation of waterstops to avoid water entrance in households) can be considered only if there is public education. In that case, reduction of the estimated damages can be estimated depending on flood depths.

Here, two parameters are included to incorporate the effect of removable/temporary waterstops on flood risk reduction:

- a percentage of damage reduction (RD), and,
- a factor for considering seasonal variability on population (K_{TC}).

The percentage of damage reduction can be obtained from studies that relate warning lead times and flood depths (**Parker et al, 2005**). In addition, this percentage may be modified by a factor, K_{TC}, which represents the existence of secondary residences at the urban area. In some cases, it may be expected a high number of empty households in winter and it is considered that their owners will not be able to apply any defence measure against floods. Consequently, the percentage of damage reduction is assumed to be higher if property owners are in their households.

Some examples of studies which include reduction on damages based on warning systems can be found in the literature (**Penning-Rowsell et. al., 1978, Parker et al., 2005, Messner et al., 2007).** Figure 13 shows an example for residential areas and flood of short duration (less than 12 hours).

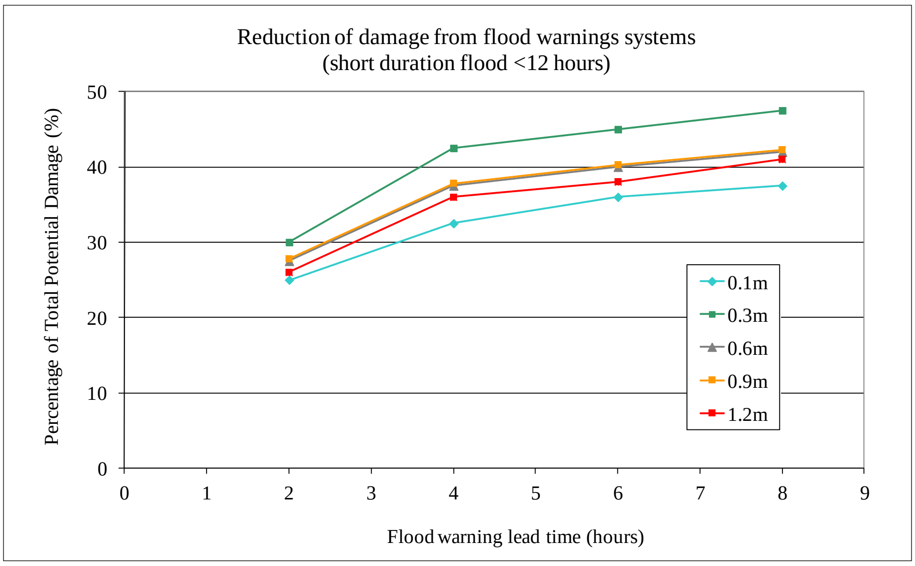


Figure 13. Percentage of damage reduction for different warning lead times (Parker et al., 2005).

This figure depicts a set of curves that represents the reduction of damage from flood warning, depending on flood warning lead times (from 2 to 8 hours) and flood depths (from 0.1 m to 1.2 m). In general, these studies define a maximum percentage of reduction (approx. 35-40%) and reduction on damages is not recommended for flood depths higher than 1.2 m.

Furthermore, several studies on estimation of damage reduction for non-residential uses have been carried out during the last years (**Parker et al., 2005**).

3.4. Uncertainty and sensitivity analysis on flood risk analysis

Uncertainty may be defined in several ways. In general, two uncertainty types can be distinguished: epistemic and aleatory uncertainty.

First, epistemic uncertainty refers to incomplete knowledge about the system under study. This type of uncertainty depends on our ability to understand, measure and describe the system (**Merz and Thieken, 2009**). Second, aleatory uncertainty results from variability of the process and it is also called natural uncertainty or inherent variability. For example, the maximum water discharge of a river course cannot be deterministically predicted due to the inherent variability of river flows.

Different procedures can be used to reduce epistemic uncertainty (aleatory uncertainty cannot be reduced). Among them, Monte-Carlo procedures are the most flexible, robust and common. These methods involve assigning probability distributions to input variables and propagating these through any given function or combination of functions (**Goudlby, 2007**).

The development of uncertainty analysis has several advantages such as the identification of weak points and critical assumptions in risk analysis (**Merz and Thieken, 2009**).

Concerning risk uncertainty, the analysis of consequence uncertainty may be of high interest to obtain economic or societal risk bounds (e.g. flood inundation maps may be obtained for several percentiles).

It is difficult to find a unique definition for sensitivity. A general definition terms *sensitivity* analysis as the study of the relationships between information flowing in and out of the model (**Saltelli, 1999**). Sensitivity analysis is then used to improve the understanding of the model. For example, replacement of uncertain quantities by either expected, median or worst-case values can affect the results of risk analysis when important parameters are highly variable.

There exist several reviews on sensitivity analysis methods (e.g. **Frey and Patil, 2002**). Among existing methods, some examples can be found in the field of flood risk (e.g. **Pappenberger et al., 2007**). Different methods can lead to a difference in ranking of importance of model factors. Procedures for sensitive analyses may include, for example, one-at-a-time methods (varying one input while other inputs remain at the same value) or variance-based techniques (e.g. **Goudlby, 2007**).

Uncertainty and sensitive analysis of outcomes of the case study presented in Chapter 4 (and new applications) are proposed as further research lines in this Thesis.

Chapter 4. CASE STUDY: BENAGUASIL

In this chapter, the application of the proposed methodology is presented and summarized. The case study of Benaguasil (Valencia, Spain) is suitable for the analysis since it is situated close to the Turia river bed, located 40 km downstream Loriguilla dam, and experiences frequent flood events (mainly due to pluvial flooding). In addition, within the SUFRI project, local authorities exposed their willingness to collaborate in the application of the methodology. The purpose of this analysis was also to provide information to develop the Municipal Action Plan against Flood Risk of this town.

In this context, the following questions are addressed:

- What is the current flood risk in this urban area?
- How would non-structural measures change flood risk in this urban area?

The analysis has followed the phases presented in Chapter 3 and it is here summarized. Results are shown to answer the aforementioned questions.

4.1. Phase I: Scope of the case study

The analysis of pluvial flooding in the city of Benaguasil was first carried out within the SUFRI project (**Escuder-Bueno et al., 2011a; 2011c**) as a pilot case. In this Thesis, 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 the case study of Benaguasil:

a) the current situation, denoted as Base Case;
b) 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 are analyzed for each situation.

Concerning estimation of potential consequences, potential loss of life and economic damages are 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 within the municipal term.

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

4.2.1. Location

Benaguasil is a town located in the east of Spain (Figure 14), 20 km inland the city of Valencia. Its municipal term is situated in the left bank of the Turia river. Figure 14 shows the location of the municipal term of Benaguasil (in red).

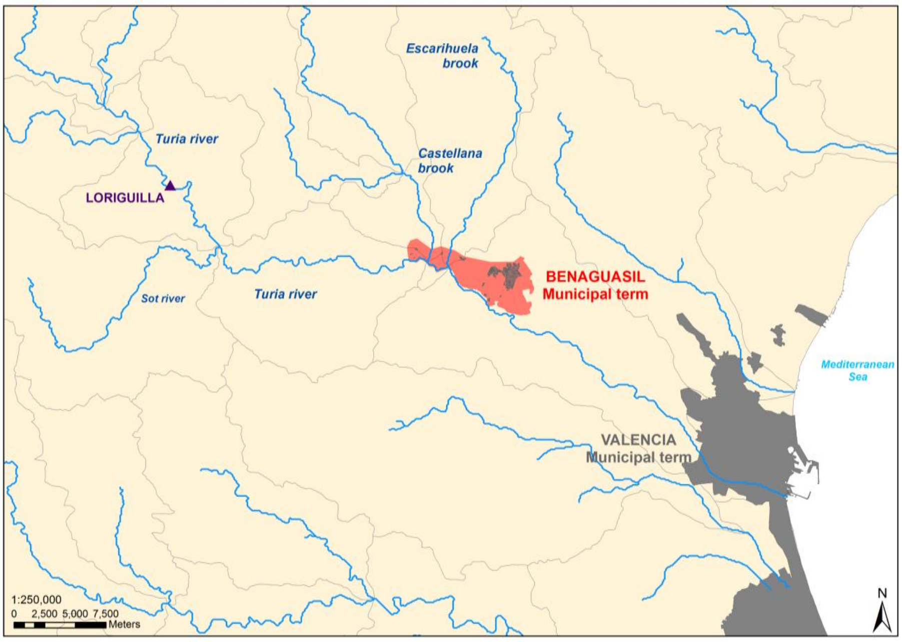


Figure 14. Location of Benaguasil municipal term.

Benaguasil is a traditional agricultural village, with a population of about 11,000 inhabitants and a surface of 25.6 km^2. A map of the municipal term of Benaguasil is included in **Appendix B4** (**Appendix B** includes auxiliary maps which describe aspects of this case study).

4.2.2. Climate

Benaguasil has a typical Mediterranean climate, with dry summers and irregular rainfall events mainly concentrated in autumn. Snow events are not common. The average annual temperature is 16ºC.

4.2.3. Topography and geology

There are three main topographic areas in Benaguasil:

- the flooding area of the Turia river, in the west part of the municipal term, with important settlement of materials from Castellana and Primera brooks. This area is typically called Plà de Montero;
- a central area, in the Tossal dels Travesses, where Triassic outcrops are found. This area consists of clays and gypsum used as construction materials, and,
- an area located in the eastern part, with important hills and irregular landscape.

The urban area of Benaguasil shows high slopes due to the existence of three hills located at the eastern part of the city (el Picador, la Mina and Montiel). This fact results in high runoff rates during rainfall events. Figure 15 shows a view of the urban area from the top of the Montiel hill.

Figure 15. View of Benaguasil from Montiel hill.

4.2.4. General description of the system

The municipal term of Benaguasil is located in the catchment areas of the Turia river (**Appendix B1 and B2**), managed by the Jucar River Authority, and two tributary rivers: Castellana and Escarihuela brooks.

There are two main networks of rain and river gauges in the Turia river catchment: the National Meteorological Institute (INM) network and the Automatic System of Hydrological Information (SAIH) network. Data from two rain gauges, Castellana and Vilamarxant, were used for the analysis, located 7.67 km and 4.58 km from Benaguasil. Three river gauges can be found near Benaguasil, with codes 08222 to 08224 (**Appendix B3**). All of them are located in irrigation channels. Both, rainfall and river gauges provide 5-minute rainfall rates.

The municipal term of Benaguasil is located 40 km downstream Loriguilla dam (Figure 16 and Figure 17), operated by the Jucar River Authority. The dam is 78.67 high and the dam crest level is at 322.5 m.a.s.l. The maximum volume reservoir is 73 Hm^3. Dam construction works were finished in 1965 and its Emergency Action Plan was formally written in 2004 (it has not been implemented yet). A risk analysis of Loriguilla dam was carried out in 2007 (**de Membrillera-Ortuño, 2007**) as part of a PhD dissertation at Universitat Politècnica de València.

Figure 16. Loriguilla dam (Spanish Association of Dams and Reservoirs, SEPREM).

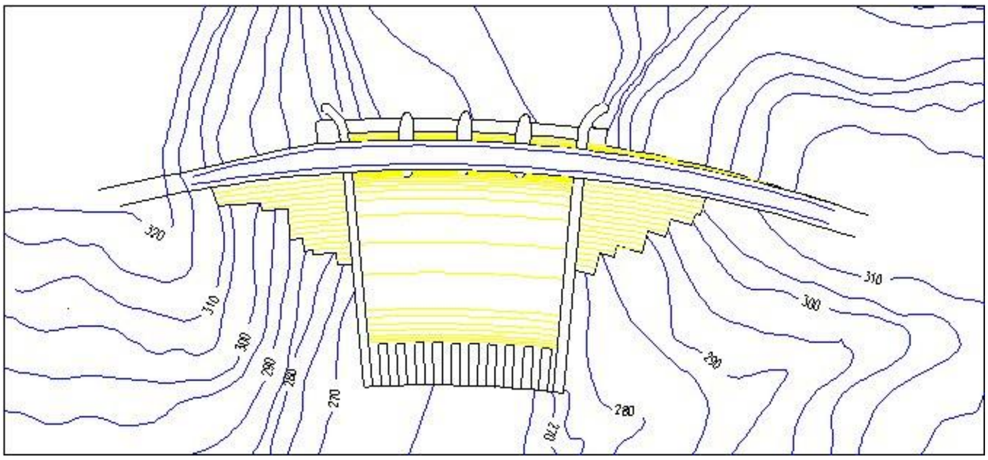


Figure 17. Top view - schematic figure (Spanish Association of Dams and Reservoirs, SEPREM).

The Emergency Action Plan (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 main potentially affected urban areas due to structural collapse of Loriguilla dam are Chulilla, Gestalgar, Bugarra, Pedralba, Villamarchante, and the metrolopolitan area of Valencia (Paterna, Manises, Quart and Valencia). The municipal term of Benaguasil is affected by the flood but no damages are expected in the urban area.

Main flooding problems in Benaguasil are due to pluvial flooding from torrential rainfall events. Important water courses overflow several streets for precipitation intensity rates higher than 20-30 mm per hour. This is due to the inability of the drainage system to convey this water. Basements and first floors are frequently affected by flooding.

Due to the proximity to Valencia, population is now increasing (more than 11.5 % in the last five years). New residential areas have been developed and connected directly to the existing drainage system, consequently flooding problems have increased.

Although some improvements in the drainage system are planned and have been developed, application of non-structural measures such as proper urban planning, forecasting and warning systems seem very convenient. Therefore, the analysis of how these measures may reduce flood risk is considered in this thesis.

4.2.5. Demography

The total amount of residents, according to available socio demographic data, has increased from 10,728 inhabitants in 2008 to 11,144 in 2010. Among them, 5,739 residents are men and 5,405 are women (**INE 2010**). Population in Benaguasil increases about 2,000-3,000 people in summer, mainly from 20th August to 20th September, when local festivities take place.

4.2.6. Economy and land use

The average salary for the Valencian Region was set in 2008 in 1,734 € (1,980 € for men and 1,433 € for women).

Around 70 % of residents in Benaguasil (especially men older than 40 years) work in agricultural activities and the other 30% works in industry and tertiary sector. Around 2,000 people work outside the urban area. The most usual schedule ranges from 9 to 14 h in the morning and from 16 to 20 h in the afternoon. In the industrial sector, about 90% of workers are from Benaguasil.

The main land uses in the urban area of Benaguasil are residential and industrial. The rest of the municipal term is mainly agricultural land (**Appendix B5**).

The average number of floors per building in Benaguasil is 1.8. The average number of households per building is 1.5 with multifamily buildings from 2 to 4 floors. The building height is quite constant in the entire city. Most of the buildings were mainly constructed 40-50 years ago. There is not detailed information about construction materials (though many of them are reinforced concrete buildings).

4.3. Phase III: Current situation. Definition of the Base Case

In this phase, the description of the system and definition of the Base Case are described.

Flood risk in the municipal term of Benaguasil is analyzed by considering the following sources of flood hazard: pluvial flooding due to rainfall events at the urban catchment area, river flooding from Castellana and Benaguasil brooks and from Turia river, including structural collapse of Loriguilla dam or flow discharges due to flood routing.

Therefore, flood events can be associated to three main sources as indicated in the conceptual scheme shown in Figure 18:

- Event 1: floods due to rainfall events that occur at the urban catchment area, which result in runoff due to the low capacity of the drainage system, urban topology characteristics and the proximity of the Montiel hill;
- Event 2: flood events due to Castellana and Benaguasil brooks (**Appendix B6**); and
- Event 3: flood events due to flow discharges from Loriguilla dam in case of structural collapse or flood routing.

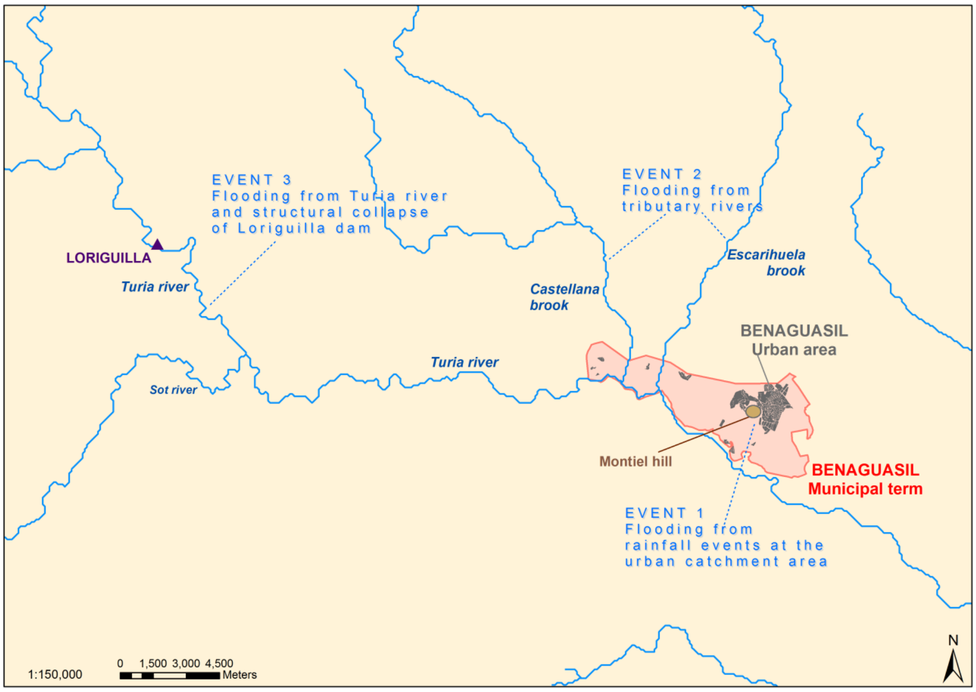


Figure 18. Conceptual scheme of events that may result in flooding at the municipal term of Benaguasil.

In Phase V (Sect. 4.5), three risk models are described, based on the aforementioned three types of flood event.

Depending on the source of flood hazard, affected areas within the municipal term vary. Figure 19 identifies main potentially affected areas, classified in four zones (Zone A, B, C and D).

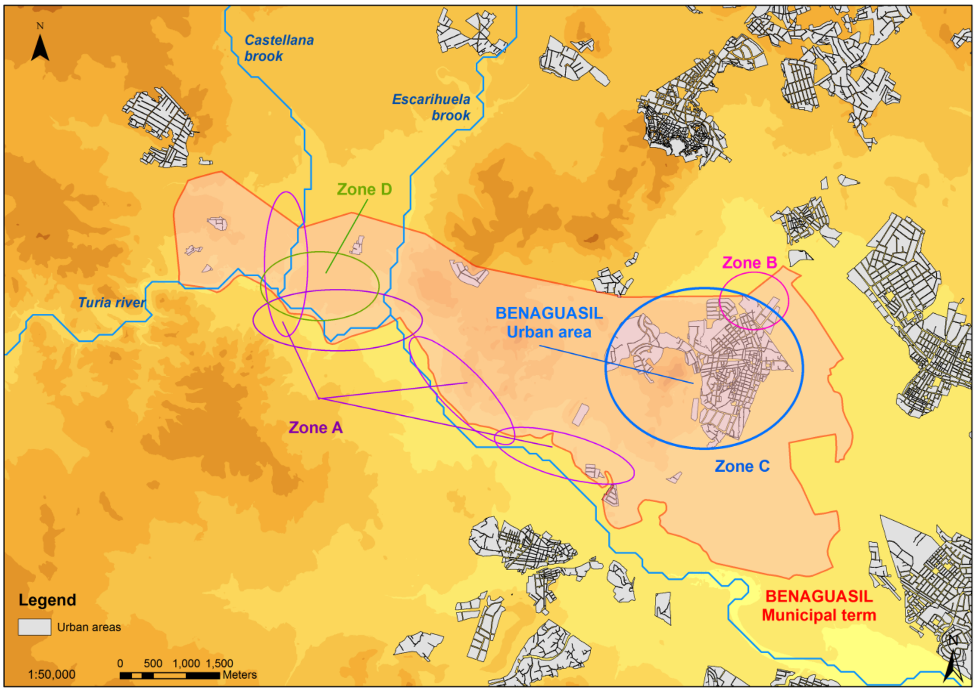


Figure 19. Overall scheme of affected areas in the municipal term of Benaguasil.

First, Zone A includes potentially affected areas by river flooding from Castellana brook in the proximity of the Turia river course (**Appendix B6**). Second, Zone B includes potentially affected areas by river flooding from Benaguasil brook (**Appendix B6**), as identified in PATRICOVA (**COPUT, 2002**). Next, Zone C refers to the entire urban area of Benaguasil and it is considered for estimating flood risk due to pluvial flooding. Finally, Zone D includes areas where the EAP of Loriguilla dam identifies elements potentially affected by structural collapse.

4.4. Phase IV: Flood events

The analysis considers 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.

4.5. Phase V: Risk model architecture

Three risk models have been developed ad hoc for the case study of Benaguasil, 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.

The first risk model scheme, Figure 20, allows to incorporate all information regarding pluvial flooding and potential consequences (zone C, Figure 19). It is divided into six nodes:

- nodes ‘season’ and ‘day/night’ include probabilities to incorporate seasonal and daily variations of population at risk
- nodes ‘rainfall event’ and ‘runoff’ include rainfall events and runoff rates at the study site,
- the last two nodes, ‘lives(plu)’ and ‘econ (plu)’, include estimations of potential loss of life and economic damages.

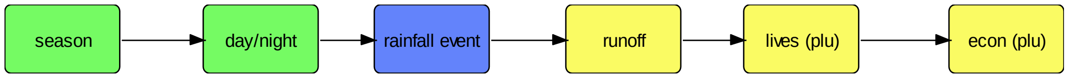


Figure 20. Risk model scheme 1. Pluvial flooding.

The second risk model scheme, Figure 21, includes flood risk due to river flooding from Castellana and Benaguasil brooks (zones A and B, Figure 19). The risk model architecture is similar to pluvial flooding:

- nodes ‘season’ and ‘day/night’ include probabilities to incorporate seasonal and daily variations of population at risk
- nodes ‘rainfall event’ and ‘river flooding’ include rainfall events at the river catchment areas and resulting flood characteristics at the study site,
- the last two nodes, ‘lives(riv)’ and ‘econ (riv)’, include estimations of potential loss of life and economic damages.

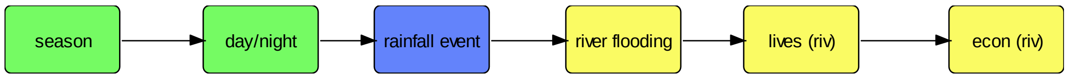


Figure 21. Risk model scheme 2. River flooding (Castellana and Benaguasil brooks).

The third risk model scheme, Figure 22, allows to analyze flood risk due to river flooding from Turia river and the existence of Loriguilla dam (zone D, Figure 19).

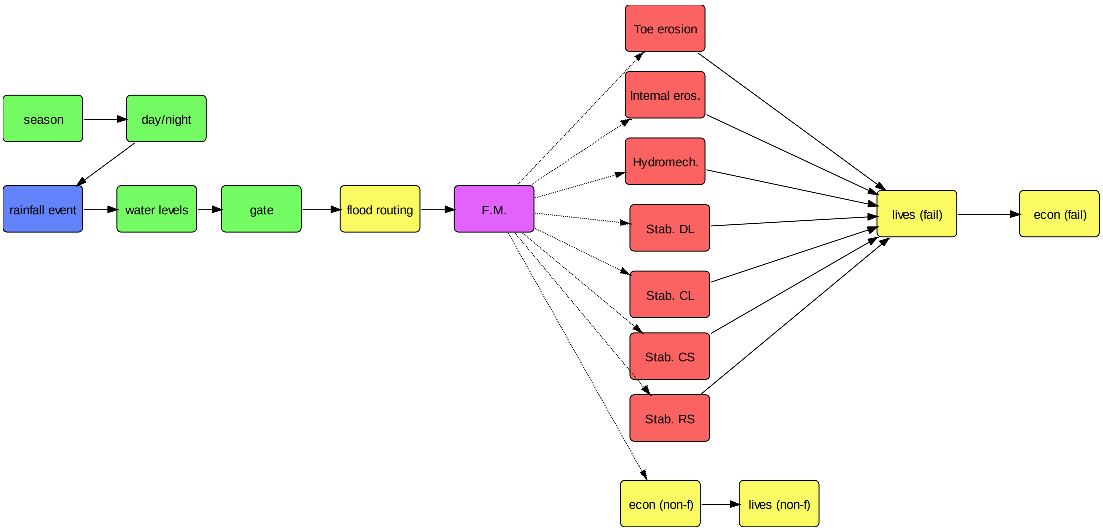


Figure 22. Risk model scheme 3. River flooding (Turia river), including structural collapse.

All information required to characterize loads, system response and consequences is included in the following nodes:

- nodes 'season' and 'day/night' include probabilities to incorporate seasonal and daily variations of population at risk
- node 'rainfall event' includes the range of return periods related to inflow hydrographs into the reservoir,
- nodes 'water levels', 'gate' and 'flood routing' define previous water pool levels, gate functionality of outlet works and provide maximum water levels and peak flow discharges from flood routing analyses,
- node 'F.M.' incorporates different failure modes into the risk model,
- seven failure modes (red nodes) are characterized and conditional probabilities of failure are included,
- nodes 'lives(fail)' and 'econ (fail)' include estimations of potential loss of life and economic damages in case of failure, and,
- nodes 'lives(non-f)' and 'econ (non-f)' include estimations of potential loss of life and economic damages due to flooding from flood routing.

Table 6 summarizes the main aspects of the three risk models for the case study of Benaguasil, potentially affected areas and consequences for each situation: Base Case and NonSt-Case.

Table 6. Summary of the proposed analysis for the case study of Benaguasil.

Source of hazard: *Situation:*	***Pluvial flooding (Model 1)***	***River flooding of Castellana and Benaguasil brooks (Model 2)***	***Turia river and structural collapse (Model 3)***
Base Case Current situation	*Affected area:* Zone C *Potential consequences:* Current potential loss of life and economic damages	Affected area: Zones A and B *Potential consequences:* Current potential loss of life and economic damages	Affected area: Zone D *Potential consequences:* 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 consequences:* Potential loss of life and economic damages for higher flood severity understanding and warning systems	*Affected area:* Zones A and B *Potential consequences:* Potential loss of life and economic damages for higher flood severity understanding and warning systems	*Affected area:* Zone D *Potential consequences:* Potential loss of life and economic damages with EAP

Results of the aforementioned risk models are combined to obtain total flood risk (due to pluvial flooding, river flooding from Castellana and Benaguasil brooks and from Turia river including structural collapse) using an overall model. The scheme of this model is shown in Figure 23.

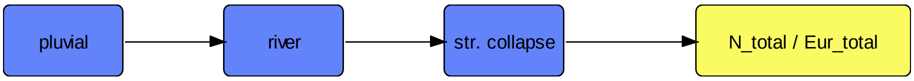


Figure 23. Overall model to compute total flood risk.

Results in terms of F-N and F-D pairs from risk models 1, 2 and 3 are included in the first three nodes (Figure 23). Hence, these nodes include all possible flood events from pluvial flooding, river flooding from Castellana and Benaguasil brooks and Turia river flooding along with structural collapse, respectively. Consequently, a new event tree is developed where each branch represents a flood event that combines all sources of flood hazard and it is related to the corresponding conditional probabilities. Potential consequences are estimated combining inputs from the three types of flood events (Figure 18), adapting input data to avoid double counting in areas affected by several sources of hazard.

Figure 24 shows a general scheme of the process for combining F-N and F-D results from independent risk models.

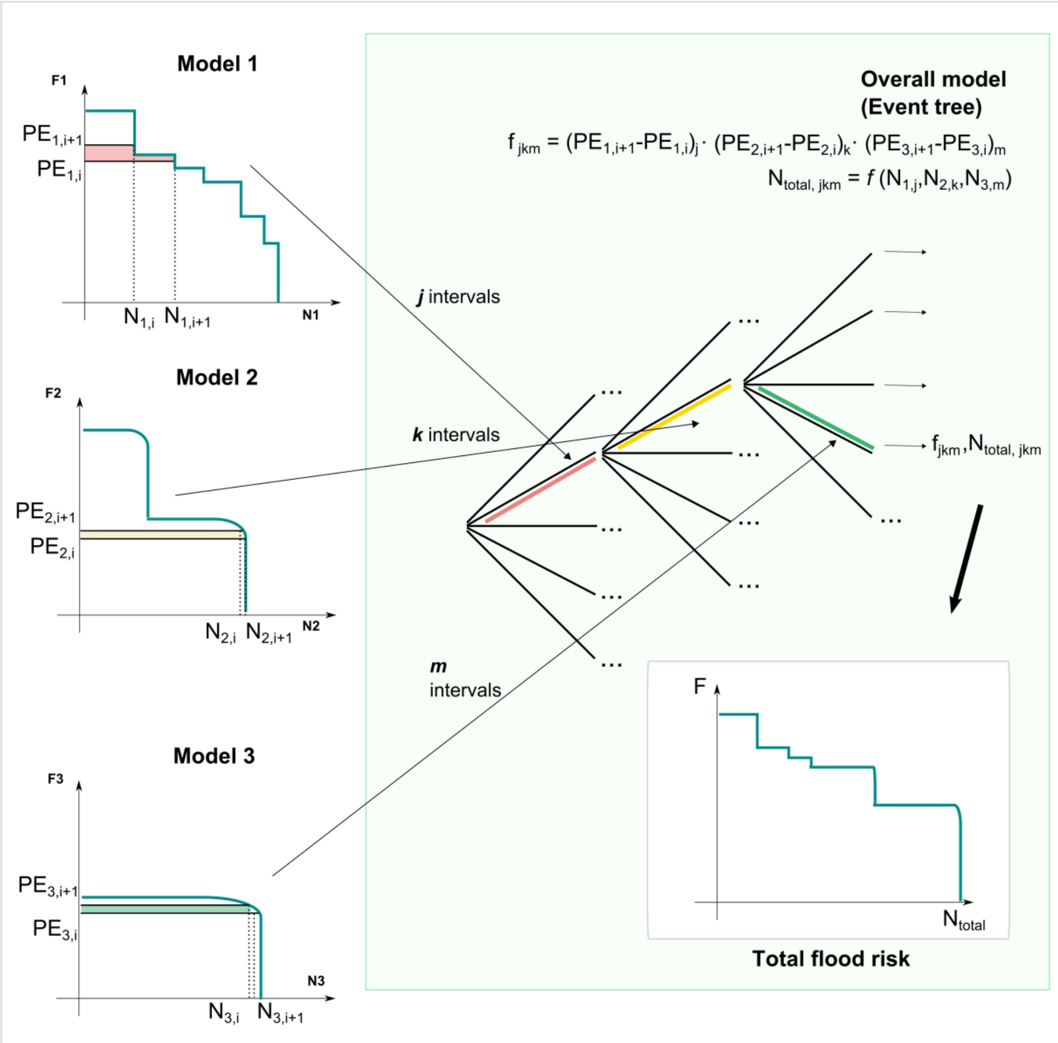


Figure 24. Combination of outcomes of risk models.

The exceedance probability function of each risk model is discretized into a number of intervals. Each interval (branch of the event tree) 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 branch, 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 $prob = PE_{i+1} - PE_i$. Finally, the overall model obtains the F-N (or F-D) curve which represents flood risk by integrating the three sources of flood hazard.

4.6. Phase VI: 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.

Detailed information on calculations to characterize loads, system response and consequences due to pluvial flooding can also be found in the final report of the SUFRI project (**Jöbstl et al., 2011**). Data to characterize flood risk in case of structural collapse of Loriguilla dam is mainly based on information used in the analysis carried out by **de Membrillera-Ortuño,** in 2007. The content of the Emergency Action Plan of Loriguilla dam has been also to gather information.

4.6.1. Loads

Pluvial flooding

Flood events are established based on rainfall events for return periods up to 500 years. Maximum annual daily rainfall rates are listed in Table 7. These values have been obtained from hydrological studies carried out during the SUFRI project and the methodology published by the Spanish Ministry of Public Works in 1999 (**Ministerio de Fomento, 1999**).

Table 7. Maximum annual daily rainfall rates (Escuder-Bueno et al., 2011a)

T (years)	*2*	*5*	*10*	*15*	*25*	*50*	*100*	*500*
Maximum annual daily rainfall rate (mm)	53	79	98	110	125	146	170	273

The maximum daily rainfall of 273 mm was obtained for a return period of 500 years, a variation coefficient C_v=0.51, K_t=3.899 and an average daily rainfall of 70 mm (**Ministerio de Fomento, 1999**). This value is considered as the maximum plausible rainfall event based on the characteristics of the urban catchment area. Potential consequences for rainfall events with higher return periods are assumed to be negligibly higher than those estimated for the 500-year rainfall event. Flood events due to these rainfall events are further denoted from T1 (2 years) to T8 (500 years).

River flooding: Castellana and Benaguasil brooks

River flooding for the Base Case includes the analysis of potentially flooded areas by Castellana and Benaguasil brooks for return periods up to 500 years (**COPUT, 2002**).

River flooding from Turia river and structural collapse of Loriguilla dam

Loads for analysing structural collapse are the resulting maximum water pool levels for all considered combinations of inflow rates at the reservoir, previous water pool levels and expected gate functionality.

Inflow rates at the reservoir are obtained from previous studies (**de Membrillera-Ortuño, 2007**). In addition, historical data allows to define the probability of expected water pool levels at the reservoir. Gate functionality and probabilities for different combinations are then estimated.

Maximum water pool levels are used to estimate failure probabilities and resulting hydrographs in failure and non failure cases of Loriguilla dam.

4.6.2. System response

Pluvial flooding

The urban catchment area of Benaguasil can be divided into 6 subcatchment areas (from BNG1 to BNG6), following the main water paths inside the town. These areas are shown in Figure 25. Eight different zones within the urban area are defined for calculations. These are denoted as BNG1, BNG2, BNG126, BNG3, BNG4, BNG45, BNG345 and BNG0. In four cases, these zones are equivalent to four subcatchment areas. Their characteristics are listed in Table 8.

.

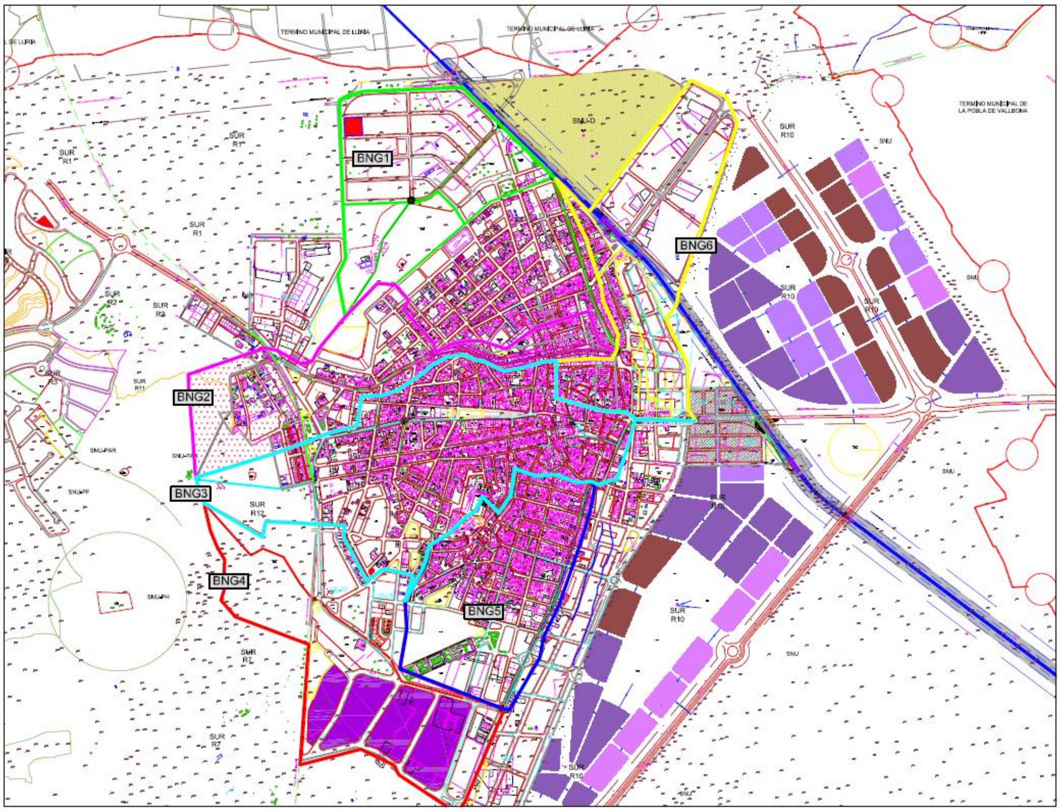


Figure 25. Subcatchment areas within the urban area of Benaguasil.

Table 8. Characteristics of subcatchment areas within the urban area of Benaguasil.

ID Sub-area	*Catchment area*	*Surface (m^2)*	*Length (m)*	*Width b (m)*	*Slope (m/m)*
BNG1	BNG1	423,932	1,482	10.00	0.008
BNG2	BNG2	233,496	1,505	6.00	0.028
BNG126	BNG1+BNG2+BNG6	769,360	1,902	8.00	0.001
BNG4	BNG4	323,195	1,112	12.00	0.072
BNG45	BNG4+BNG5	559,089	1,813	12.00	0.004
BNG3	BNG3	396,014	1,207	10.00	0.038
BNG345	BNG3+BNG4+BNG5	955,103	2,228	8.00	0.008
BNG0	ALL AREAS	1,659,622	2,228	10.00	0.026

A preliminary analysis of the drainage network was carried out to characterize its capacity in several points of the urban area. Therefore, 13 streams were analyzed (Table 9) and runoff rates were estimated for different rainfall events (from 2 to 100 years) using the Rational Method (**Témez, 1991**). Runoff rates and capacity rates in these streams were compared.

Table 9. Main characteristics of 13 selected streams of the drainage network.

Stream	*Diameter (m)*	*Manning's coefficient n*	*Velocity (m/s)*	*Capacity Q (m^3/s)*
L1a	0.40	0.011	4.53	0.57
L1b	1.00	0.014	1.76	1.38
H1	1.00	0.014	2.59	2.03
L2	1.00	0.014	5.35	4.20
H2	1.00	0.014	4.70	3.69
L3	0.50	0.011	4.10	0.80
H3	1.00	0.014	5.49	4.31
L4	0.40	0.011	5.23	0.66
L5	0.50	0.011	1.56	0.31
H5	0.50	0.011	1.59	0.31
L6	1.00	0.014	0.99	0.78
H345	0.30	0.011	1.77	0.13
U7	1.00	0.014	3.86	3.03

Results are shown in Table 10. In general, all cases resulted in higher runoff rates than the expected capacity of the drainage network (except for cases depicted in green color).

Table 10. Runoff rates at different points of the urban area.

Zone	*T1* 2 years	*T2* 5 years	*T3* 10 years	*T4* 15 years	*T5* 25 years	*T6* 50 years	*T7* 100 years
BNG1	2.90	5.26	7.08	8.26	9.74	11.85	14.27
BNG2	1.38	2.68	3.73	4.42	5.31	6.58	8.07
BNG126	4.22	7.71	10.42	12.18	14.40	17.55	21.19
BNG4	1.50	3.04	4.30	5.14	6.23	7.80	9.64
BNG45	2.83	5.31	7.27	8.55	10.17	12.49	15.18
BNG3	3.36	6.07	8.15	9.49	11.19	13.59	16.35
BNG345	4.99	9.18	12.44	14.56	17.24	21.06	25.47
BNG0	9.04	16.63	22.56	26.40	31.27	38.19	46.20

In a subsequent analysis, three different runoff thresholds (P_o) were defined according to three categories of land typology: rural areas, low and high density urban areas. These values are 23, 8 and 5 mm, respectively. These values were defined with the aim of obtaining runoff coefficients (C) around 0.40, 0.75 and 0.85 for a return period of 10 years. Table 11 shows the resulting runoff coefficients for each rainfall event. More details of rainfall-runoff transfer calculations can be found in **Escuder-Bueno et al., 2011a**.

Table 11. Runoff coefficients.

	Return period, T (years)							
	2	5	10	15	25	50	100	500
Po (mm)	23			Upstream/rural areas				
C	0.19	0.31	0.38	0.42	0.47	0.52	0.57	0.72
Po (mm)	8			Low density residential areas				
C	0.54	0.67	0.73	0.76	0.80	0.83	0.86	0.93
Po (mm)	5			High density residential areas				
C	0.69	0.80	0.85	0.87	0.89	0.91	0.93	0.97

Hydraulic models of the drainage system are not available thus flood hydraulic calculations were obtained by considering the Manning's equation and mean characteristics of streets. Flood depths and velocities were obtained based on this approach.

Flood depths were estimated in 21 reference locations within the urban area and calibrated with data provided by the Police Department of Benaguasil from past flood events, by comparing pictures and related rainfall records.

River flooding: Castellana and Benaguasil brooks

A regional river flooding analysis was published in 2002 (**COPUT, 2002**). This study includes potential flooded areas, expected flood depths and return periods of floods from Castellana and Benaguasil brooks.

In Castellana brook, the analysis concluded that the identified area may be affected by floods with return periods lower than 25 years and expected flood depths higher than 0.8 m. In Benaguasil brook, identified potential flood areas may be affected by floods with return periods lower than 25 years and expected flood depths lower than 0.8 m.

River flooding from Turia river and structural collapse of Loriguilla dam

Several hydraulic models of the Turia river downstream Loriguilla dam have been conducted in previous studies (e.g. **de Membrillera, 2007**). Results of affected elements, flood depths, etc. included in the EAP of Loriguilla dam are used to estimate potential consequences in the municipal term of Benaguasil in failure and non-failure cases.

Three failure hypotheses are described within the EAP (the second hypothesis is considered in this Thesis):

- Hypothesis H2: Failure scenario for maximum inflow and water level at dam crest level.
- Hypothesis EH2: Failure of Benageber and Loriguilla dams (Loriguilla dam is located 18 km downstream Benageber dam);
- Hypothesis A1: Spillway failure under normal operation and normal maximum water pool levels.

Failure mode characterization of Loriguilla dam was conducted by Dr. Manuel G. De Membrillera (**de Membrillera, 2007**) as part of his PhD dissertation. The following failure modes were considered:

- FM1: toe erosion.
- FM2: internal erosion.
- FM3: collapse of hydromechanic systems in outlet works.
- FM4: deep sliding within the foundation of a lateral block.
- FM5: sliding within the foundation of a lateral block.
- FM6: sliding within the foundation of the concrete gravity spillway section (closed gates).
- FM7: sliding within the foundation in the right abutment.

Based on breach type, breach development and maximum water pool levels at the reservoir, peak flow discharges in case of failure were obtained and are incorporated into risk model 3, along with conditional probabilities for each failure mode.

4.6.3. Consequences

Potential loss of life

<u>General</u>

Population in Benaguasil is estimated in 11,144 inhabitants (2010). However, daily and seasonal variations are found based on available demographic data. For that reason, four time categories are set as shown in Table 12.

Table 12. Time categories and population rates.

Time category ID	*Category*	*Population (inhabitants)*	*Season probability*	*Time category probability*
TC1	Summer / day	11,644	0.25	0.25·0.625=0.156
TC2	Summer / night	13,644	0.25	0.25·0.375=0.094
TC3	Winter / day	9,144	0.75	0.75·0.542=0.407
TC4	Winter / day	11,144	0.75	0.75·0.458=0.344

Pluvial flooding

Potentially affected areas by pluvial flooding are related to 21 locations were flood depths and velocities are estimated.

Flood severity levels are established based on the classification given in the methodology. As an example, results for the Base Case in locations 13-17 are shown in Figure 26 along with the thresholds given in Figure 9. Results for all locations are summarized in Figure 27.

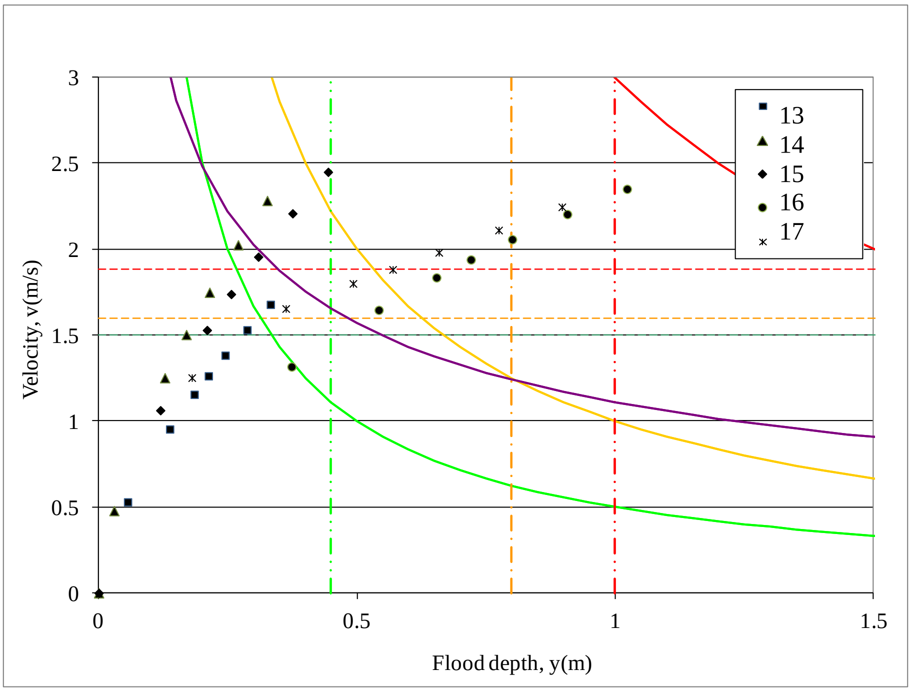


Figure 26. Flood severity levels at five location points. Base case.

Location	T1	T2	T3	T4	T5	T6	T7	T8
1			0	0	0	0	0	1
2		0	0	0	0	1	1	3
3	0	0	0	1	1	1	1	3
4		0	0	0	0	0	0	0
5	0	0	0	0	1	2	2	3
6	0	0	0	0	0	0	0	1
7	0	0	0	0	0	0	0	0
8						0	0	2
9		0	0	0	0	1	2	3
10		0	0	1	2	3	3	3
11	0	0	0	0	1	1	3	3
12	0	0	0	0	1	1	1	2
13	0	0	0	0	0	1	2	3
14		0	0	1	2	3	3	3
15		0	1	2	3	3	3	3
16	0	3	3	3	3	3	3	4
17	0	2	3	3	3	3	3	4
18	0	0	0	0	0	1	1	3
19	0	0	0	0	0	1	1	1
20	0	0	0	0	0	1	1	1
21	0	0	0	0	0	1	1	1

Figure 27. Flood severity levels for each flood event and area. Base Case.

Figure 27 shows flood severity levels at each location ranging from green to red colours for levels S0 to S4, respectively. Grey cells denote cases where the capacity of the drainage system is higher than estimated runoff (no flooding).

Potential fatalities (N) for each time category and flood event are obtained by multiplying population exposed to the flood and fatality rates.

Population exposed to the flood (P_{ex}) is obtained as a percentage (f) of the number of inhabitants in the affected area (A_f) based on time categories and flood severity understanding. The level of flood severity understanding can be estimated by expert judgement based on social research data (**Escuder-Bueno et al., 2012**). Table 13 shows factors of flood exposure for the Base Case.

Table 13. Factors of flood exposure for the Base Case.

Time category	TC1	TC2	TC3	TC4
Factor f, Pex=f·PAR (PAR=d·A$_f$)	20%	2%	10%	1%
Density, d (inhabitants/km²)	10,457	12,253	8212	10,008

Fatality rates are estimated based on flood severity levels and reference fatality rates, which depend on warning systems. Benaguasil corresponds with the first category as no warning systems are available (Table 3 and Figure 10). The number of potential fatalities (N) for the Base Case is given in Table 14.

Table 14. Potential fatalities for the Base Case. Pluvial flooding.

Time category	*Return period (2-500 years)*							
	T1	*T2*	*T3*	*T4*	*T5*	*T6*	*T7*	*T8*
TC1	0	1	1	2	2	3	4	9
TC2	0	0	0	0	0	0	0	1
TC3	0	0	1	1	1	2	2	4
TC4	0	0	0	0	0	0	0	0

<u>River flooding: Castellana and Benaguasil brooks</u>

Potential affected elements (e.g. households, industrial areas, etc.) due to river flooding from Castellana and Benaguasil brooks are located within zones A and B, respectively (Figure 19). Potential damages in zone A include several households, a quarry located in the western part of the municipal term and, in general, rural areas located close to the Turia river course. Potential damages in zone B include residential areas at the eastern part of the urban area, industrial areas and the municipal sports centre. The following tables show the main characteristics of the identified elements (type and surface).

Table 15. Identified potential affected elements in Zone A. Castellana brook.

ID	*Name /Description*	*Type*	*Surface (m^2)*
A1	Bco. del Tollo	Households (13)	2,730
A1	Other areas Bco.Tollo	Agricultural areas	181,548
A2	Quarry	Industrial areas	100,758
A2	Other areas A2	Agricultural areas	267,203
A2	Castellana Left bank	Households (1)	200
A3	La Fenosa	Households (1)	200
A3	Other areas A3	Agricultural areas	99,894

Table 16. Identified potential affected elements in Zone B. Benaguasil brook.

ID	*Name /Description*	*Type*	*Surface (m^2)*
B1	Benaguasil brook Houses	Households	28,633
B2	Benaguasil brook Industrial area	Industrial areas	19,424
B3	Benaguasil brook Sports centre	Other	30,074

Based on flood characteristics of zones A and B (flood depth higher and lower than 0.8 m, respectively), population at risk is obtained by quantifying the number of affected households and estimated inhabitants. Fatality rates are obtained for medium (zone A) and low (zone B) flood severity and category C5 of Table 4. An available warning time of 1 hour is set for both zones (no differences are established between time categories). Resulting potential fatalities are shown in Table 17 and Table 18.

Table 17. Potential fatalities. River flooding. Castellana brook. Base Case.

Time category	TC1	TC2	TC3	TC4
Category	C5			
Warning time (h)	1	1	1	1
Flood depth (m)	>0.8			
Flood severity	Medium			
Fatality rate	0.0275			
Population at risk (households)	22.5	22.5	7.5	7.5
Number of potential fatalities	0.6	0.6	0.2	0.2
Population at risk (quarry)	6	0	6	0
Number of potential fatalities	0.2	0.0	0.2	0.0

Table 18. Potential fatalities. River flooding. Benaguasil brook. Base Case.

Time category	TC1	TC2	TC3	TC4
Category	C5			
Warning time (h)	1	1	1	1
Flood depth (m)	<0.8			
Flood severity	Low			
Fatality rate	0.000275			
Density rate Residential areas	9227	9390	9065	9227
Density rate Industrial areas	4613.5	4695	4532.5	4613.5
Sports centre (total)	200	0	100	0
Population at risk	554	360	448	354
Number of potential fatalities	0.2	0.1	0.1	0.1

River flooding from Turia river and structural collapse of Loriguilla dam

The EAP of Loriguilla dam includes results of hydraulic modelling for the hypothesis H2. Regarding flooding due to flood routing of Loriguilla dam, results from hydraulic modelling of non-failure cases are not available. Therefore, results of hypothesis H2 are also used. Table 19 summarizes the main results of the hydraulic model for Loriguilla dam, including maximum flood depths and arrival wave times at affected elements within the municipal term of Benaguasil.

Table 19. Identified elements within the municipal term of Benaguasil. Hypothesis H2.

Name	*EAP ID point*	*D (km)*	*Z (m.a.s.l.)*	*Flood depth (m)*	*Nmax (m.a.s.l.)*	*Tw Nmax(h)*	*Type*	*Damage*
H.V. Line	55	38.33	130.4	0.64	131.04	1.62	Infrastructures	High
Quarry	57	38.99	117.98	11.18	129.16	1.65	Industrial	Moderate
Quarry	58	39.15	118	10.96	128.96	1.67	Industrial	Moderate
Houses	60	40.98	120	0.76	120.76	1.75	Residential	High
Bridge	61	42.16	110	7.53	117.53	1.78	Infrastructures	Very High

Based on this information, population at risk is estimated by quantifying the number of affected households and estimating the number of residents. Warning times are obtained from the formula proposed in the SUFRI project (**Escuder-Bueno et al., 2011a**) by combining arrival wave times, breach development time and hydrologic scenario.

Fatality rates are obtained for medium flood severity and category C3 of Table 4. Finally, the number of potential fatalities for the H2 hypothesis is obtained (Table 20 and Table 21).

Table 20. Potential fatalities (households). Structural collapse. Hypothesis H2. Base Case.

Time category	TC1	TC2	TC3	TC4
Category	C3			
Arrival wave time (h)	1.25			
Warning time (h)	1	0.75	1	0.75
Flood depth (m)	0.76			
Flood severity	Medium			
Fatality rate	0.05	0.063	0.05	0.063
Number of households	25			
Population at risk	37.5	37.5	12.5	12.5
Number of potential fatalities	1.9	2.4	0.6	0.8

Table 21. Potential fatalities (quarry). Structural collapse. Hypothesis H2. Base Case.

Time category	TC1	TC2	TC3	TC4
Category	C3			
Arrival wave time (h)	1.25			
Warning time (h)	1	0.75	1	0.75
Flood depth (m)	10.96			
Flood severity	Medium			
Fatality rate	0.05	0.063	0.05	0.063
Population at risk	6	0	6	0
Number of potential fatalities	0.3	0	0.3	0

Potential economic damages

General

Five land use categories are established in Benaguasil to estimate economic damages: residential (low and medium density), industrial, agricultural and other uses.

According to existing studies, the following rates are considered, based on a scale ranging from 0 to 100, where 100 is equivalent to an economic value of 82 €/km^2 (**COPUT, 2002**):

- Residential areas (Medium density – High magnitude: Rate 56.3 out of 100);
- Residential areas (Low density – High magnitude: Rate 45.5 out of 100);
- Industrial areas (Medium density – High magnitude: Rate 16.9 out of 100);
- Other land uses in urban areas (e.g. sports centres) (Low density – High magnitude: Rate 45.5 out of 100); and,
- Agricultural areas (Irrigated crops: Rate 0.34 out of 100).

Present values of these rates are calculated based on IPC index of 2011. Table 22 shows the estimated reference values.

Table 22. Reference costs (Source: INE).

Category		*Value (euros/km²)*
Rate of each land use (s/100)	2002	2009
Residential areas (medium density): 56.3	46.2	55.5
Residential areas (low density): 45.5	45.5	44.9
Industrial areas: 16.9	13.9	16.7
Other land uses in urban areas: 35	35	34.5
Agricultural areas: 0.34	0.3	0.3

Total costs are estimated by adding direct and indirect costs. Indirect costs are estimated as a 27% percentage of direct costs. Direct costs are obtained by multiplying the percentage of damages, and reference cost of the affected area. Percentage of damages is obtained from flood depths based on the depth-damage curve proposed by PATRICOVA (Figure 11, **COPUT, 2002**).

Pluvial flooding

Affected areas by pluvial flooding vary for each flood event. In addition, three different perimeters at each (21) reference location are estimated depending on the following categories:

- flood depths ≤ 0.15 m → affected area 1;
- flood depths ≤ 0.45 m → affected area 2; and,
- flood depths > 0.45 m → affected area 3.

It is assumed that flood events with depths lower than 0.15 m do not affect adjacent streets near the reference location. Table 23 lists total costs (CT) for the Base Case.

Table 23. Potential economic damages. Pluvial flooding. Base Case.

	Return period (2-500 years)							
	T1	***T2***	***T3***	***T4***	***T5***	***T6***	***T7***	***T8***
Total costs	35,047	111,210	218,279	284,981	380,877	649,916	1,027,565	2,957,931

River flooding: Castellana and Benaguasil brooks

Despite the fact that agricultural areas are affected by river flooding, available data due to structural collapse do not allow estimation of damages. Therefore, this category is not included.

Potential economic damages include households and industrial areas (quarry) in zone A (Castellana brook) and include households, industrial areas and the municipal sports centre in zone B (Benaguasil brook).

The number of households in zone A is obtained from cartographic information available at the website of CITMA (*Conselleria d'Infrastructures, Territori i Medi Ambient)* and an average surface of 200 m^2/household is assumed. Affected areas within zone B are estimated by comparing potentially affected areas with maps of the urban area.

The quarry located close to Castellana brook is considered as industrial activity but economic damages are obtained considering only potentially affected facilities and equipment.

Table 24 and Table 25 list total costs due to river flooding for the Base Case.

Table 24. Potential economic damages. River flooding. Castellana brook. Base Case.

ID	*Name /Description*	*Land use*	*Surface (m^2)*	*Ref. cost (€/m^2)*	*PD (%)*	*Direct costs (€)*
A1	Bco. del Tollo	Low density residential areas	2,730	44.9	40	48,980
A2	Quarry	Industrial areas	100,758	16.7	40	67,306
A2	Castellana Left bank	Low density residential areas	200	44.9	40	3,358
A3	La Fenosa	Low density residential areas	200	44.9	40	3,358

Table 25. Potential economic damages. River flooding. Benaguasil brook. Base Case.

ID	*Name /Description*	*Land use*	*Surface (m^2)*	*Ref. cost (€/m^2)*	*PD (%)*	*Direct costs (€)*
B1	Benaguasil brook Houses	Medium density residential areas	28,633	55.5	14	222,478
B2	Benaguasil brook Industrial area	Industrial areas	19,424	16.7	14	45,413
B3	Benaguasil brook Sports centre	Other	30,074	34.5	14	145,257

Total costs for the Base Case due to river flooding from Castellana and Benaguasil brooks are shown in Table 26. No damages are estimated for return periods lower than 25 years.

Table 26. Potential economic damages. River flooding (Castellana and Benaguasil brooks). Base Case.

	Return period (2-500 years)							
	T1	*T2*	*T3*	*T4*	*T5*	*T6*	*T7*	*T8*
Total costs	0	0	0	0	681,497	681,497	681,497	681,497

River flooding from Turia river and structural collapse of Loriguilla dam

There is no available information to characterize quarries identified within the EAP of Loriguilla dam. Therefore, data obtained to identify the surface of the quarry located close to Castellana brook is used. Percentage of damages at the quarry site is considered up to 100% (flood depth is higher than 10 m). A percentage of 14% is considered for households affected by structural collapse. The number of households is obtained from cartographic information available at the website of CITMA (*Conselleria d'Infrastructures, Territori i Medi Ambient*), with an average surface of 200 m^2/household. Table 27 lists total costs (CT) for the Base Case.

Table 27. Potential economic damages. Structural collapse. Base Case.

Name	*EAP ID point*	*D (km)*	*Z (m.a.s.l.)*	*Flood depth (m)*	*Type*	*Reference cost (€/m^2)*	*PD (%)*	*Surface (m^2)*	*Direct cost (€)*
Quarry	57	38.99	117.98	11.18	Industrial	0.1·16.7	100	100,758	213,698
Quarry	58	39.15	118	10.96	Industrial				
Houses	60	40.98	120	0.76	Residential	44.9	14	5,000	39,916
Total									253,613

4.7. Phase VII: Risk calculations

All previous information on loads, system response and consequences is incorporated to the risk models defined in section 4.5. Results are obtained to represent F-N and F-D curves for the Base Case.

4.8. Phase VIII: F-N and F-D curves

Flood risk for the current situation, integrating pluvial flooding, river flooding and structural collapse of Loriguilla dam, is represented in Figure 28 and Figure 29.

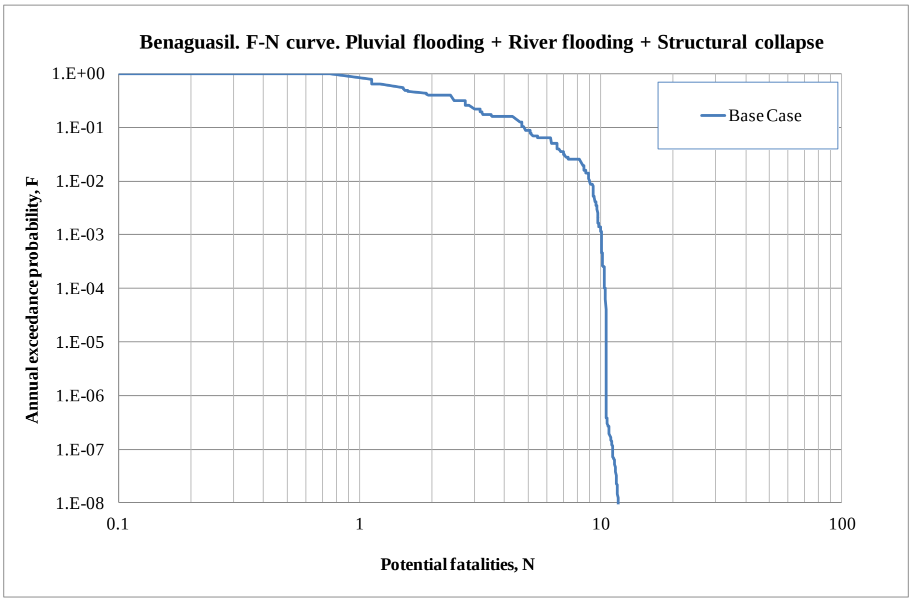


Figure 28. F-N curve integrating pluvial flooding, river flooding and structural collapse. Base Case.

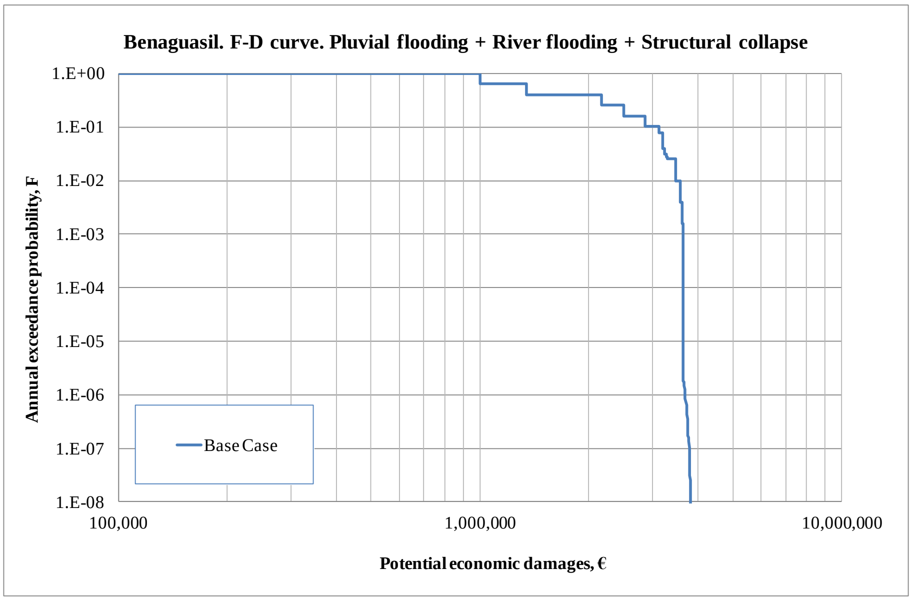


Figure 29. F-D curve integrating pluvial flooding, river flooding and structural collapse. Base Case.

Total societal and economic risks for the Base Case result in values of 2.3 fatalities/year and 1,730,000 eur/year, respectively. Results show that societal risk presents significant potential fatalities for high probability values as the F-N curve reaches N=10 for a cumulative exceedance probability around $1 \cdot 10^{-3}$. In addition, potential economic damages show also significant values for high probabilities (approx. 3,000,000 eur for F=0.1).

The impact on flood risk of a potential structural collapse of Loriguilla dam is small in comparison with pluvial flooding or river flooding from Castellana and Benaguasil brooks as it is shown in the F-N and F-D curves. There is no a significant change on these curves in the range of probabilities related to dam failure (approx. $1 \cdot 10^{-6}$).

4.9. Phase IX: Risk evaluation

There are no applicable standards or tolerability criteria in terms of urban flood risk to evaluate flood risk in Benaguasil. However, results for the Base Case have been presented to local authorities with the aim of discussing and validating outcomes of this analysis.

4.10. Phase X: Study of risk reduction measures

After analyzing the current situation, other situations can be considered to obtain the impact of risk reduction measures on flood risk. In this Thesis, an additional situation is analyzed: a hypothetic situation after implementing non-structural measures including public education and warning systems.

Non-structural measures act reducing potential consequences in case of flood. Therefore, input data on loads and system response do not vary in this case.

In this Thesis, these measures include a public education programme on flood risk, the implementation of warning systems, and the EAP of Loriguilla dam.

A public education programme provides information to the public on how to act in case of flooding, self-protection measures, general advice, etc. It may include annual activities, updated information on local websites, information campaigns, etc. This measure is captured by the methodology as an increase on flood severity understanding and public risk awareness.

Implementation of warning systems is considered as a combined measure along with public education to enhance flood severity understanding of population at risk. Warning systems may range from basic to advance mechanisms. In this case, a specific procedure for local authorities in case of impending flooding is considered. It includes a set of standard messages to the public that vary depending on the meteorological alert published by the National Meteorological Agency. These messages can be addressed through speakers within the urban area, police patrols, messages to mobile phones, etc.

Implementation of the EAP of Loriguilla dam is expected to increase available warning times and improve communication mechanisms.

The hypotheses assumed to capture the existence of these measures are here described based on estimations carried out for the Base Case.

Potential consequences

Pluvial flooding

Measures of public education and warning may be included as a reduction of people exposed to the flood (P_{ex}), which depends on flood severity understanding, and a change on the category used to estimate fatality rates. Values for this situation are given in Table 28. All values are reduced up to 50% of estimates for the Base Case. A lower bound of 1% is considered.

Table 28. Factors of flood exposure for the NonSt-Case.

Time category	TC1	TC2	TC3	TC4
Factor f ***Pex=f·PAR*** ***(PAR=d·A_f)***	10%	1%	5%	1%
Density, d (inhabitants/km²)	9227	9390	9065	9227

In this situation, Benaguasil belongs to the third category given in the methodology ($C_{p3,}$ Table 3). Potential fatalities (N) for the situation with non-structural measures are shown in Table 29.

Table 29. Potential fatalities. Pluvial flooding. NonSt-Case.

Time category	*Return period (2-500 years)*							
	T1	*T2*	*T3*	*T4*	*T5*	*T6*	*T7*	*T8*
TC1	0.0	0.3	0.4	0.5	0.7	1.2	1.3	3.1
TC2	0.0	0.0	0.0	0.1	0.1	0.1	0.1	0.3
TC3	0.0	0.1	0.2	0.3	0.4	0.6	0.6	1.5
TC4	0.0	0.0	0.0	0.1	0.1	0.1	0.1	0.3

Concerning potential economic damages, previous studies (**Parker et al., 2005**) have developed curves which relate flood depth and reduction on damages depending on available warning times. The existence of efficient warning systems and a high level of risk awareness may reduce damages in households as population is aware of the risk and they know how to protect themselves and their assets by means of, for example, waterstops, barriers, sand bags, etc. For this situation, an available warning time of 3 hours is estimated in case of pluvial flooding as warning messages would be addressed by local authorities based on weather forecasting. Values of reduction on damages for different levels of flood depth are shown in Table 30 (**Parker et al., 2005**). No reduction on damages is considered for flood depths higher than 1.2 m. Table 31 includes total costs (CT) for the situation with non-structural measures.

Table 30. Reduction on damages for different levels of flood depth.

Water depth y (m)	0	0.1	0.3	0.6	0.9	1.2
Reduction on damages RD	0.29	0.29	0.36	0.33	0.33	0.31

Table 31. Potential economic damages. Pluvial flooding. NonSt-Case.

	Return period (2-500 years)							
	T1	*T2*	*T3*	*T4*	*T5*	*T6*	*T7*	*T8*
Total costs	23,518	73,369	144,092	188,972	252,878	432,417	687,972	2,007,707

River flooding: Castellana and Benaguasil brooks

Non-structural measures of public education and warning are analyzed in river flooding as a variation of the category for selecting reference fatality rates. In this case, fatality rates are obtained for medium (zone A) and low (zone B) flood severity for category C7 of Table 4. Available warning times are estimated in 3 hours in zone B (this area is located within the urban area thus affected households will receive warning messages) and 1 hour in zone A (reception of warning messages cannot be guaranteed). Resulting estimations of potential fatalities are shown in Table 32 and 33.

Table 32. Potential fatalities. River flooding. Castellana brook. NonSt-Case.

Time category	TC1	TC2	TC3	TC4
Category	C7			
Warning time (h)	1	1	1	1
Flood depth (m)	>0.8			
Flood severity	Medium			
Fatality rate	0.01			
Population at risk (households)	22.5	22.5	7.5	7.5
Number of potential fatalities	0.2	0.2	0.1	0.
Population at risk (quarry)	6	0	6	0
Number of potential fatalities	0.1	0.0	0.1	0.0

Table 33. Potential fatalities. River flooding. Benaguasil brook. NonSt-Case.

Time category	TC1	TC2	TC3	TC4
Category	C7			
Warning time (h)	3	3	3	3
Flood depth (m)	<0.8			
Flood severity	Low			
Fatality rate	0.0002			
Density rate Residential areas	9227	9390	9065	9227
Density rate Industrial areas	4613.5	4695	4532.5	4613.5
Sports centre (total)	200	0	100	0
Population at risk	554	360	448	354
Number of potential fatalities	0.11	0.07	0.09	0.07

Reduction on potential economic damages in zone A (Castellana brook) is not considered as it can only be assumed for warning times higher than 2 hours. However, in zone B (Benaguasil brook), higher warning times can be expected. A 33% of damage reduction is considered (flood depth=0.8 m). Consequently, for this situation, potential economic damages in zone B are shown in Table 34.

Table 34. Potential economic damages. River flooding. Benaguasil brook. NonSt-Case.

ID	*Name /Description*	*Land use*	*Surface (m^2)*	*Ref. cost (€/m^2)*	*PD (%)*	*RD (%)*	*Direct costs (€)*
B1	Benaguasil brook Houses	Medium density residential areas	28,633	55.5	14	33	149,061
B2	Benaguasil brook Industrial area	Industrial areas	19,424	16.7	14	33	30,427
B3	Benaguasil brook Sports centre	Other	30,074	34.5	14	33	97,322

Finally, total costs for the situation with non-structural measures are shown in Table 35.

Table 35. Potential economic damages. River flooding. NonSt-Case.

	Return period (2-500 years)							
	T1	***T2***	***T3***	***T4***	***T5***	***T6***	***T7***	***T8***
Total costs	0	0	0	0	508,346	508,346	508,346	508,346

<u>River flooding from Turia river and structural collapse of Loriguilla dam</u>

Regarding structural collapse, the implementation of the EAP of Loriguilla dam is analyzed by considering Category C4 of Table 4 to obtain reference fatality rates for medium flood severity. Consequently, an implemented EAP results in lower reference fatality rates in comparison with the Base Case and warning times in case of structural collapse can be considered 30 minutes higher. Therefore, fatality rates are obtained from the new category and considering warning times given in the following tables.

Regarding potential economic damages, reduction could be only for warning times higher than 2 hours. As warning times are lower this threshold, the existence of the EAP does not involve variations on potential economic damages.

Table 36. Potential fatalities (households). Structural collapse. Hypothesis H2. NonSt-Case.

Time category	TC1	TC2	TC3	TC4
Category	C4			
Arrival wave time (h)	1.25			
Warning time (h)	1.5	1.25	1.5	1.25
Flood depth (m)	0.76			
Flood severity	Medium			
Fatality rate	0.0002	0.0251	0.0002	0.0251
Number of households	25			
Population at risk	37.5	37.5	12.5	12.5
Number of potential fatalities	0.0	0.9	0.0	0.3

Table 37. Potential fatalities (quarry). Structural collapse. Hypothesis H2. NonSt-Case.

Time category	TC1	TC2	TC3	TC4
Category	C4			
Arrival wave time (h)	1.25			
Warning time (h)	1.5	1.25	1.5	1.25
Flood depth (m)	10.96			
Flood severity	Medium			
Fatality rate	0.0002	0.0251	0.0002	0.0251
Population at risk	6	0	6	0
Number of potential fatalities	0.0	0.0	0.0	0.0

4.11. Overall results and conclusions

Results of the two analyzed situations (Base Case and NonSt-Case) are obtained using the overall model (Figure 23). Therefore, two different F-N and F-D curves are estimated by integrating results from pluvial flooding, river flooding and structural collapse. Figure 30 and Figure 31 show the F-N and F-D curves for the case study of Benaguasil, respectively.

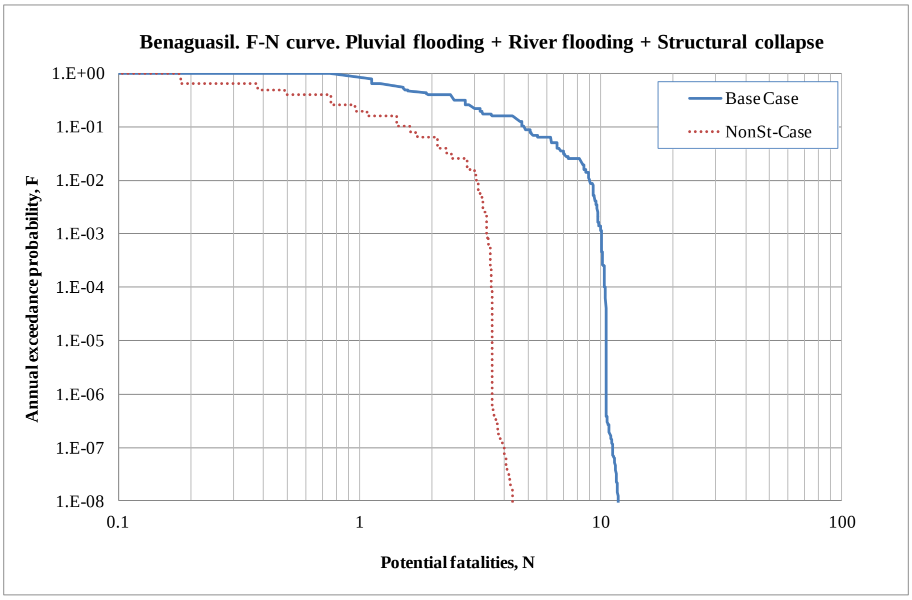


Figure 30. F-N curves integrating pluvial flooding, river flooding and structural collapse. Base Case and NonSt-Case.

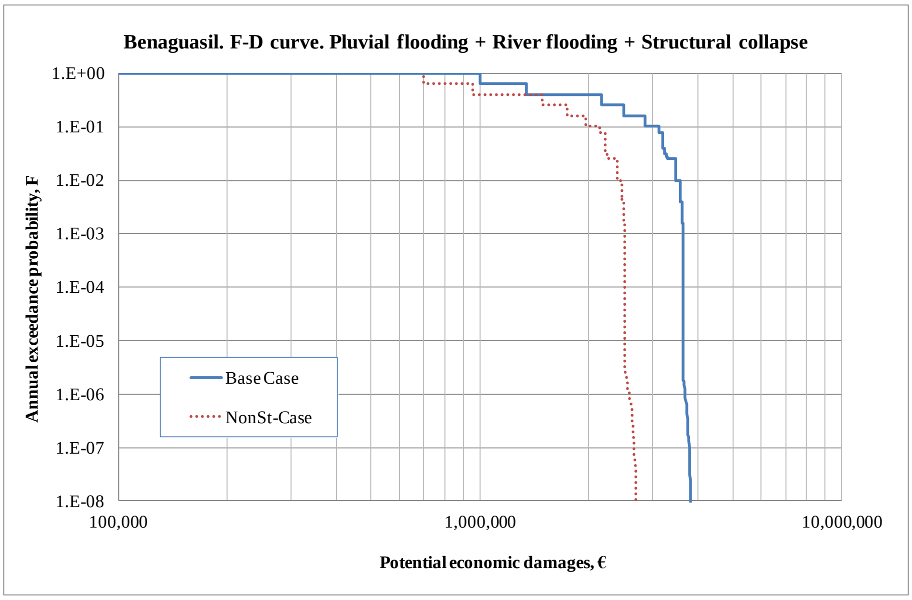


Figure 31. F-D curves integrating pluvial flooding, river flooding and structural collapse. Base Case and NonSt-Case.

In terms of societal risk (Figure 30), 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 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 urban area is located far from flooding due to structural collapse.

Economic risk is represented in Figure 31. 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 outcomes of the analysis for pluvial flooding and river flooding from Castellana and Benaguasil brooks, the local government has decided to develop a Municipal Action Plan against Flood Risk for the city of Benaguasil. The aim of this plan was 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. Communication chains and warning messages are also considered to be activated in case of flood. The implementation of this plan is expected by September-October 2012 (**Annex II** includes Annex VIII of the Municipal Action Plan which contains the description of the flood risk analysis). The implementation of this plan represents a key action towards an improved flood risk management in Benaguasil.

This page intentionally left blank

Chapter 5. CONCLUSIONS AND FURTHER RESEARCH LINES

In this chapter, main conclusions of this thesis are drawn and further research lines are presented. This chapter is divided into three sections: overall remarks, conclusions regarding the case study and further research lines.

5.1. Overall conclusions

- In the first part of this Thesis, main aspects on flood risk analysis, assessment and management have been discussed, including references to existing methods for the estimation of flood risk and its components (probability and consequences).
- Existing methods for flood risk analysis do not take into account the integration of several sources of hazard. Therefore, this thesis has presented a comprehensive methodology to integrate the analysis of pluvial flooding, river flooding and structural collapse into urban flood risk analysis.
- The methodology is mainly focused on the methodological piece developed within the SUFRI project that allows to quantify flood risk in urban areas. The aim of the proposed methodology is to assess existing risk and to support decision making on risk reduction measures.
- The proposed methodology provides a tool that can be applied to inform authorities, local entities and stakeholders on decision making to establish actions for risk reduction.
- The methodology here presented is generally applicable. However, flood risk understanding and risk awareness of population at risk should be addressed for each case study. Hence, integration of social research data may be helpful to characterize consequences (**Annex I**).
- The use of risk models and F-N and F-D curves provides societal and economic risk 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 a helpful and comprehensive tool to represent flood risk.
- In addition, F-N and F-D curves can provide societal and economic flood risk, respectively, in an understandable way. These curves are the basis to illustrate risk quantification and the effect of different measures on flood risk reduction thus providing a guide for planning and managing. Furthermore, F-N and F-D curves 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.
- Uncertainty on results will depend on available data, the level of detail of hydrologic and hydraulic calculations, estimation of system response and potential consequences.

5.2. Conclusions of the case study

- Results of the case study show that the impact of non-structural measures on flood risk can be captured by the presented approach. Outcomes provide new information to support emergency planning.
- The method has been primarily applied for the case study of Benaguasil but it has been developed to be potentially applicable to any urban area affected by several sources of flood hazard.
- Results of the case study indicate that flooding in Benaguasil may result, in general in low fatalities. However, potential economic damages may be frequent and relatively high at the urban area.
- Results of the analysis of non-structural measures have provided that existent risk is sensitive to flood severity understanding of population at risk and the existence of warning systems.
- Based on existent flood risk and the potential of non-structural measures on risk reduction, the local government has decided to develop a Municipal Action Plan against Flood Risk. **Annex II** includes Annex VIII of this Plan, which contains the description of flood risk analysis (not including structural collapse). The full content of this Plan cannot be published as it contains personal data of local authorities and action forces.

5.3. Further research lines

- Pluvial flooding, river flooding from Castellana and Benaguasil brooks, and river flooding from Turia river, including structural collapse of Loriguilla dam, have been modelled independently and results have been further incorporated to an overall model which obtains total flood risk due to the three sources of hazard. The development of a common risk model would require to characterize the existing correlation between rainfall patterns of urban and river catchment areas. The eastern region of Spain is characterized by spatial heterogeneity in terms of monthly rainfall intensity, maximum daily rainfall rates, duration of rainfall episodes, etc. Hence, there would be a need for modelling bivariate rainfall distribution to correlate rainfall data in both catchment areas.
- 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**). It has to be remarked that equity (**Bowles et al., 2005**) is another fundamental principle from which alternatives can be prioritized. It should

be considered that there can be conflict in achieving equity and efficiency (**Munger et al., 2009**). Therefore, the need for reducing flood risk cannot overcome the right of individuals to protect themselves and their interests.

- Regarding tolerability risk guidelines, little research has been conducted to establish standards for flood risk analysis in urban areas. Several individual and societal criteria can be found in the literature for site specific cases, e.g. in The Netherlands (**Vrijling, 2001**). Further investigation should therefore concentrate on the basis and development of a common standard to assess urban flood risk. This standard should include recommendations on how to adapt each case based on local characteristics, public risk awareness, historical data, impact of damages at regional/national/international scale, etc.

Recent research projects (e.g. **Thieken and Beurton, 2012**) have provided new tools such as integrated pluvial and river flood risk analysis (SUFRI project), improved flood risk mapping (RISK-MAP project) or integrative flood risk governance (IMRA project). However, these projects do not provide an integrated framework for comprehensive flood risk management including all flood hazards and potential consequences. Therefore, all sources of flood hazard (seismic, hydrologic, technological, man-made and climate change) have to be integrated into flood risk analysis. Within this framework, further research will be conducted to incorporate human-induced threats into risk models. This work will focus on integrating natural and man-made hazards on quantitative flood risk analysis.

This page intentionally left blank

REFERENCES

ANCOLD (2003): Guidelines on Risk Assessment, Australian National Committee on Large Dams Inc.

Ayyub, B.M. (2001): Elicitation of expert opinions for uncertainty and risks, CRC Press, 2001.

Beven, K.J. (2001) Rainfall-runoff modelling - The Primer, John Wiley and Sons Ltd.

Bowles, D.S., and Aboelata, M. (2007): Evacuation and life-loss estimation model for natural and dam break floods, Extreme Hydrological Events: New Concepts for Security, NATO Science Series Volume 78, 2006, pp. 363-383.

Bowles, D.S., Giuliani, F.L., Hartford, D.N.D., Janssen, J.P.F.M.H, McGrath, S., Poupart, M., Stewart D., and Zielinski. P.A. (2005): ICOLD Bulletin 130 on "Risk Assessment in Dam Safety Management", IPENZ Proceedings of Technical Groups 33/2.

CRUE (2009): Research Funding Initiative, Synthesis Report No I-2009, Addressing the key findings of research: Risk Assessment and Risk Management: Effectiveness and Efficiency of Non-structural Flood Risk Management Measures, Project Contract No: ERAC-CT-2004-515742.

Dawson, W.R. (2003): Generic depth-damage relationships for residential structures with basements, Economic Guidance Memorandum (EGM) 04-01, USACE, 2003.

de Bruijn, K., Klijn, F., Ölfert, A., Penning-Rowsell, E., Simm, J., and Wallis, M. (2009):. Flood risk assessment and flood risk management. An introduction and guidance based on experiences and findings of FLOODsite (an EU-funded Integrated Project). Deltares | Delft Hydraulics, Delft, the Netherlands.

de Membrillera-Ortuño, M.G. (2007): Contribución a la aplicación del análisis y declaración de riesgos en presas españolas, incluyendo priorización de inversiones, Tesis Doctoral, Universitat Politècnica de València, Septiembre 2007 [in Spanish].

DHS (2011): Estimating Economic Consequences for Dam Failure Scenarios, Dams Sector, U.S. Department of Homeland Security, September 2011.

Douben, K.J. (2006): Characteristics of river floods and flooding - A global overview, 1985–2003, Irrigation and Drainage, Vol. 55, p.S9–S21, 2006, D.O.I. 10.10002/ird.239.

EC (2008): Directive 2008/114/EC of the European Parliament and of the Council of 8 December 2008 on the identification and designation of European critical infrastructures and the assessment of the need to improve their protection.

EC (2007): Directive 2007/60/EC of the European Parliament and of the Council of 23 October 2007 on the assessment and management of flood risks.

EC (2000): Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000.

Ekstrand, E.R. (2000): Estimating economic consequences from dam failure in the safety dams program, U.S. Department of the Interior, Bureau of Reclamation, EC-2000-01, 2000.

Elsner, A., Mai, S., Zimmermann, C., and Meyer, V. (2003): Integration of flood risk in coastal hinterland management, In International Conference on CoastGis, Genua, Italy, 2003.

Escuder-Bueno, I., Castillo-Rodríguez, J.T., Zechner, S., Jöbstl, C., Perales-Momparler, S., and Petaccia, G. (2012): A quantitative flood risk analysis methodology for urban areas with integration of social research data, Natural Hazards and Earth System Sciences [accepted for publication].

Escuder-Bueno, I., Castillo-Rodríguez, J., Perales-Momparler, S., and Petaccia, G. (2011c): Application of a complete and quantitative tool for flood risk analysis in urban areas, Proceedings of the Third International Forum on Risk Analysis, Dam Safety, Dam Security, and Critical Infrastructure Management, Escuder-Bueno et al. (eds), Taylor & Francis Group, London, ISBN 978-0-415-62078-9.

Escuder-Bueno, I., Castillo-Rodríguez, J., Perales-Momparler, S., and Morales-Torres, A. (2011b): A complete and quantitative tool for flood risk analysis in urban areas: river and pluvial flooding, Proceedings of the UFRIM symposium, Urban Flood Risk Management: Flood resilient communities, Graz, Austria, September 2011, ISBN 978-3-85125-173-9.

Escuder-Bueno, I., Morales-Torres, A., Castillo-Rodríguez, J., Perales-Momparler, S., Ortner, S., Jöbstl, C., Knoblauch, H., Natale, L., and Petaccia, G. (2011a): SUFRI Methodology for pluvial and river flooding risk assessment in urban areas to inform decision making, WP3 Final Report, SUFRI project, July 2011.

Escuder-Bueno, I., Morales-Torres, A., and Perales-Momparler, S. (2010): Urban Flood Risk Characterization as a tool for planning and managing, Proceedings of the Workshop Exploration of Tolerable Risk Guidelines for the USACE Levee Safety Program, Alexandria, Washington, DC, March 2010, Report 10-R-8.

Frey, H.C., and Patil, S.R. (2002): Identification and review of sensitivity analysis methods. Risk Analysis 2002; 22(3): 553–78.

Gómez, M., and Russo, B. (2009): Criterios de riesgo asociados a escorrentía urbana. Jornadas de Ingeniería del Agua, 2009. [In Spanish].

Gouldby, B. (2007): Uncertainty and sensitivity analysis: Method description, FLOODsite project, Report: T24-10-07, October 2007.

Gouldby, B., and Samuels, P. (2005): Language of risk: Project definitions, FLOODsite project, Report: T32-04-01, March 2005.

Graham, W.J. (1999): A procedure for estimating loss of life caused by dam failure, Sedimentation and River Hydraulics, U.S. Department of Interior, Bureau of Reclamation, DSO-99-06.

Health and Safety Executive (2001): Reducing risks, protecting people - HSE's decision making process.

IEC/FDIS 31010 (2009): International Standard, Risk management – Risk assessment techniques, International Organization for Standardization, IEC/FDIS 31010:2009 (E).

ISO GUIDE 73 (2009): International Standard, Risk management – Vocabulary, International Organization for Standardization, ISO GUIDE 73:2009 (E/F).

Jonkman, S.N. (2003): Global Perspectives on Loss of Human Life Caused by Floods, Nat. Hazards, 34, 151–175, 2003.

Jonkman, S.N. (2008): Loss of life estimation in flood risk assessment. Theory and applications, PhD thesis, Civil Engineering Faculty, Technical University of Delft, 2007.

Jonkman, S.N. (2005): Global Perspectives on Loss of Human Life Caused by Floods, Natural Hazards, Natural Hazards (2005) 34: 151–175, Springer.

Jonkman, S.N., Jongejan, R., and Maaskant, B. (2011): The Use of Individual and Societal Risk Criteria Within the Dutch Flood Safety Policy – Nationwide Estimates of Societal Risk and Policy Applications, Risk Analysis, Vol. 31, No. 2, 2011, DOI: 10.1111/j.1539-6924.2010.01502.x.

Klijn, F., Samuels, P., and van Os, D. (2008): Towards Flood Risk Management in the EU: State of affairs with examples from various European countries, International Journal River Basin Management Vol. 6, No. 4 (2008), pp. 307–321.

Kovacs, P. (2001): The role of insurance in promoting non-structural mitigation of natural disasters, Proceedings of the International Workshop on Non-structural measures for water management problems, London, Ontario, Canada, International Hydrological Programme, p.264–272, October 2001.

Kubal, C., Haase, D., Meyer, V., and Scheuer, S. (2009): Integrated urban flood risk assessment – adapting a multicriteria approach to a city, Natural Hazards and Earth System Sciences, 9, 1881–1895.

Messner, F., Penning-Rowsell, E., Green, C., Meyer, V., Tunstall, S., and van der Veen, A. (2007): FLOODSITE Evaluating flood damages: guidance and recommendations on principles and methods, Report T09-06-01, January 2007.

Merz, B., and Thieken, A. (2009): Flood risk curves and uncertainty bounds, Nat. Hazards, 51, 437-458.

Merz, B., Elmer, F., and Thieken, A. (2009): Significance of “high probability/low damage” versus “low probability/high damage” flood events, Nat. Hazards Earth Syst. Sci., 9, 1033-1046, 2009.

Meyer, V., Kuhlicke, C., Luther, J., Unnerstall, H., Fuchs, S., Priest, S., Pardoe, J., McCarthy, S., Dorner, W., Seidel, J., Serrhini, K., Palka, G., and Scheuer, S. (2011): RISK MAP, Improving Flood Risk Maps as a Means to Foster Public Participation and Raising Flood Risk Awareness: Toward Flood Resilient Communities, Final Report, Sept. 2011.

Ministerio de Fomento (1999): Máximas lluvias diarias en la España peninsular, Ministerio de Fomento, Secretaría de Estado de Infraestructuras y Transportes, Dirección general de Carreteras, 1999 [in Spanish].

Munger, D.F., Bowles, D.S., Boyer, D.D., Davis, D.W., Margo, D.A., Moser, D.A., and Regan, P.J. (2009): Interim tolerable risk guidelines for US Army Corps of Engineers Dams, USSD Conference.

Nanía, L. (2002): Métodos de transformación lluvía-escorrentía y de propagación de caudales. Hidrología superficial y subterránea. Universidad de Granada, 2002. [In Spanish]

Pappenberger, F., Beven, K.J., Ratto, M., and Matgen, P. (2007): Multi-method global sensitivity analysis of flood inundation models, Advances in Water Resources 31 (2008) 1–14, Elsevier.

Parker, D., Tunstall, S., and Wilson, T. (2005): Socio-economic benefits of flood forecasting and warning, Flood Hazard Research Centre, Middlesex University, Queensway, Enfield, EN3 4SF, London, UK.

Pelling, M. (2003): The vulnerability of cities - Natural disasters and social resilience, UK, 2003, ISBN 1-85383-830-6.

Penning-Rowsell, E., Floyd, D., Ramsbottom, P., and Surendran, S. (2005): Estimating injury and loss of life in floods - A deterministic framework, Natural Hazards, Vol.36, pp.43-64.

Penning-Rowsell, E., Chatterton, J.B., and Parker, D. (1978): The Effect of Flood Warnings on Flood Damage Reduction, Middlesex Polytechnic Flood Hazard Research Project, 1978, 102 pages.

Real Decreto 903/2010, de 9 de julio, de evaluación y gestión de riesgos de inundación, Boletín Oficial del Estado, Núm. 171, Sec.I., pág. 61954 [in Spanish].

Reiter, P. (2001): RESCDAM loss of life caused by dam failure, the RESCDAM LOL method and its application to Kyrkosjarvi dam in Seinajoki, Water Consulting Ltd., 2001.

Saltelli, A. (1999): Evaluation of Sensitivity and Uncertainty Analysis Methods in a Quality Assessment Framework with Application to Environmental and Business Statistics, Lot 14 of EUROSTAT SUP COM 1997, JRC reference: Administrative Arrangement 13592-1998-01 A1CA ISP LU.

Scawthorn, C., Flores, P.; Blais, N., Seligson, H., Tate, E., Chang, S., Mifflin, E., Thomas, W., Murphy, J., Jones, C., and Lawrence, M. (2006): HAZUS-MH Flood Loss Estimation Methodology, II: Damage and Loss Assesment, ASCE, 2006.

Schanze, J., Hutter, G., Olfert, A., Penning-Rowsell, E.C., Parker, D., Harries, T., Werritty, A., Nachtnebel, H., Holzmann, H., Neuhold, C., Meyer, V., Kuhlicke, C., Schildt, A., Jessel, B. and Königer, P. (2008): FLOOD-ERA Joint Report, CRUE Research Report No I-1: Systematisation, evaluation and context conditions of structural and non-structural measures for flood risk reduction, Project Contract No: ERAC-CT-2004-515742, 2008.

Schmitt, T.G., Thomas, M., and Ettrich, N. (2004): Analysis and modeling of flooding in urban drainage systems, Journal of Hydrology, 299 (2004) 300–311.

Serrano-Lombillo, A. (2011): Desarrollo de una herramienta completa de análisis y evaluación de riesgos en seguridad de presas, PhD thesis, Universitat Politècnica de València, 2011.

Serrano-Lombillo, A., Escuder-Bueno, I., de Membrillera-Ortuño, M.G., and Altarejos-García, L. (2009): iPresas - Software for risk analysis, 23rd International Congress on Large Dams, Brasilia, 2009.

Srivastava, A., Bowles, D.S. and Chauhan, S.S. (2000): Generalized event tree algorithm and software for dam safety risk assessment.

Témez, J.R. (1991): Extended and Improved Rational method. Highways Administration of Spain, XXIV Congress Madrid Edition [In Spanish]

Thieken, A., and Beurton, S. (2012): Synthesis Report, Addressing the key findings of research related to Flood resilient communities – managing the consequences of flooding, CRUE Flood Risk Management Research Monograph Series.

UFRIM (2011): Proceedings of the UFRIM symposium, Zenz, G. and Hornich, R. (eds), Urban Flood Risk Management: Flood resilient communities, Graz, Austria, 2011, ISBN 978-3-85125-173-9.

USBR (2010): Potential Failure Mode Identification, Description, and Screening, USBR Best Practices, U.S. Bureau of Reclamation, April 2010.

USBR (2001): Risk Based Profiling System, Technical Service Center, U.S. Bureau of Reclamation, January 2001.

Vrijling, J.K. (2001): Probabilistic design of water defence systems in The Netherlands, Reliability engineering and system safety, 74:337–344, 2001.

WHBC (2009): Strategic Flood Risk Assessment, Final Level 1, Final Report, Welwyn Hatfield Borough Council, May 2009.

WNO/GWP (2008): Urban flood risk management, A Tool for Integrated Flood Management, World Meteorological Organization (WNO) / Global Water Partnership (GWP), Associated Programme on Flood Management, March 2008.

APPENDIX

Index

***Municipal Action Plan against Flood Risk**

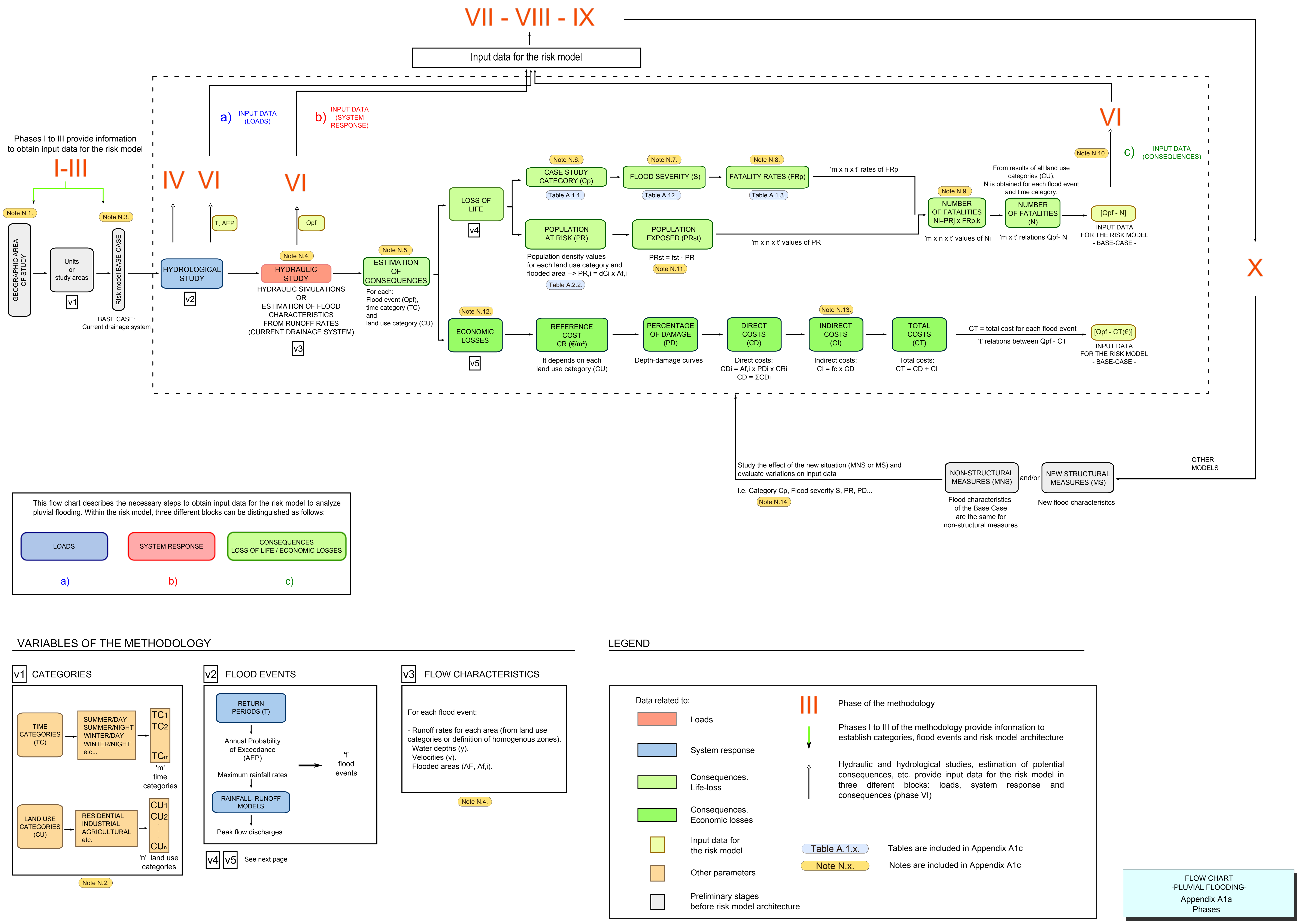
This page intentionally left blank

Appendix A: Schemes to support the application of the methodology

Appendix A1. Pluvial flooding

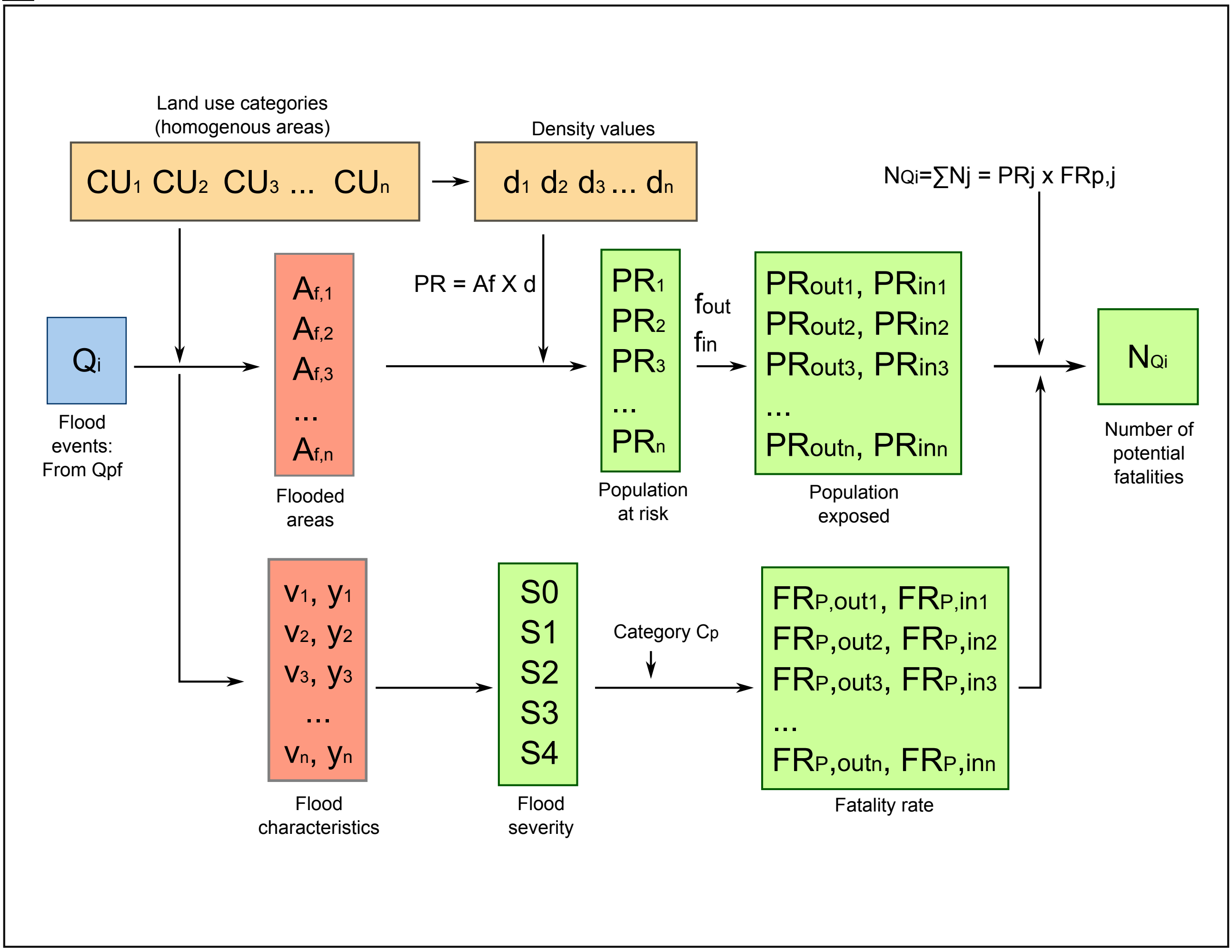
Appendix A2. River flooding (including structural collapse of flood defence infrastructures)

This page intentionally left blank

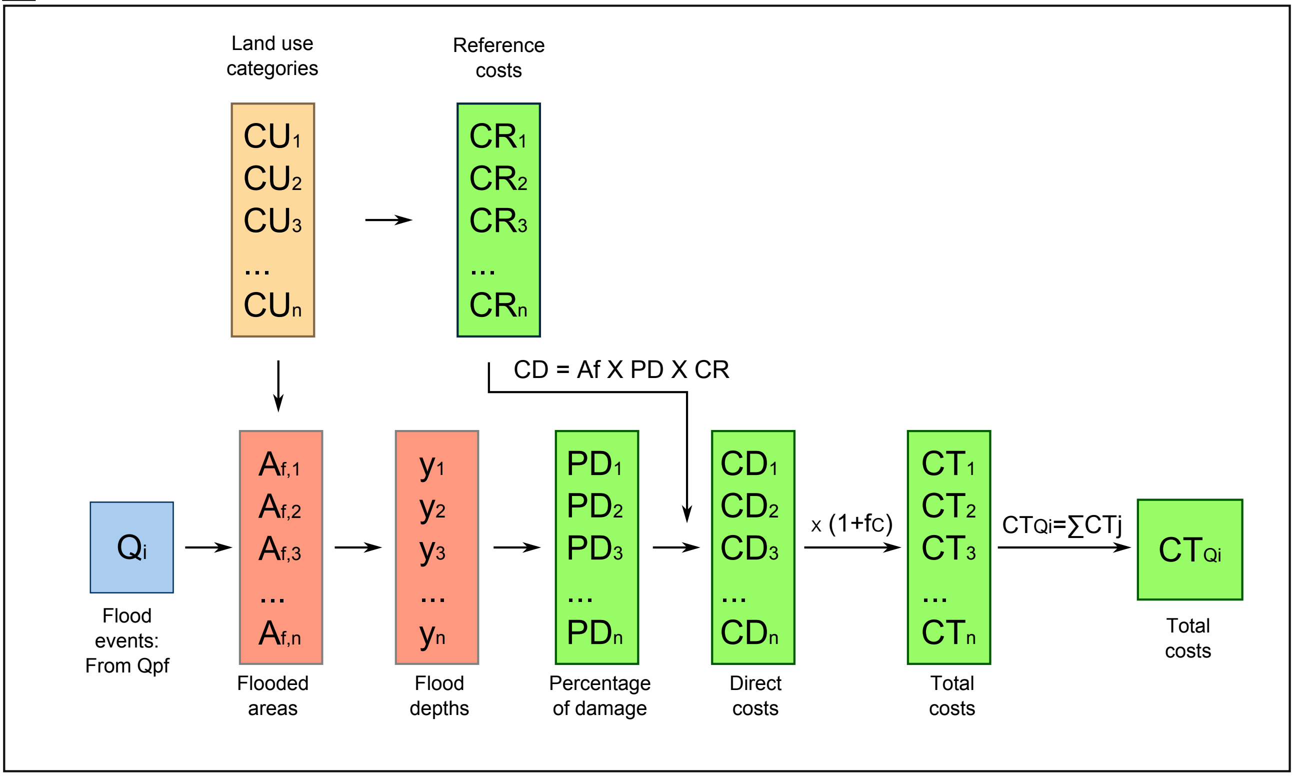


VII - VIII - IX
Input data for the risk model
a) INPUT DATA (LOADS)
b) INPUT DATA (SYSTEM RESPONSE)
c) INPUT DATA (CONSEQUENCES)
Phases I to III provide information to obtain input data for the risk model
I-III
IV
VI
VI
VI
X
Note N.1.
GEOGRAPHIC AREA OF STUDY
Units or study areas
v1
Note N.3.
Risk model BASE-CASE
BASE CASE: Current drainage system
HYDROLOGICAL STUDY
v2
T, AEP
Qpf
Note N.4.
HYDRAULIC STUDY
HYDRAULIC SIMULATIONS OR ESTIMATION OF FLOOD CHARACTERISTICS FROM RUNOFF RATES (CURRENT DRAINAGE SYSTEM)
v3
Note N.5.
ESTIMATION OF CONSEQUENCES
For each: Flood event (Qpf), time category (TC) and land use category (CU)
LOSS OF LIFE
v4
Note N.6.
CASE STUDY CATEGORY (Cp)
Table A.1.1.
Note N.7.
FLOOD SEVERITY (S)
Table A.1.2.
Note N.8.
FATALITY RATES (FRp)
Table A.1.3.
'm x n x t' rates of FRp
POPULATION AT RISK (PR)
Population density values for each land use category and flooded area --> PR,i = dCi x Af,i
Table A.2.2.
POPULATION EXPOSED (PRst)
PRst = fst · PR
Note N.11.
'm x n x t' values of PR
Note N.9.
NUMBER OF FATALITIES Ni=PRj x FRp,k
'm x n x t' values of Ni
NUMBER OF FATALITIES (N)
'm x t' relations Qpf- N
From results of all land use categories (CU), N is obtained for each flood event and time category:
Note N.10.
[Qpf - N]
INPUT DATA FOR THE RISK MODEL - BASE-CASE -
Note N.12.
ECONOMIC LOSSES
v5
REFERENCE COST CR (€/m²)
It depends on each land use category (CU)
PERCENTAGE OF DAMAGE (PD)
Depth-damage curves
DIRECT COSTS (CD)
Direct costs: CDi = Af,i x PDi x CRi
CD = ΣCDi
Note N.13.
INDIRECT COSTS (CI)
Indirect costs: CI = fc x CD
TOTAL COSTS (CT)
Total costs: CT = CD + CI
CT = total cost for each flood event
't' relations between Qpf - CT
[Qpf - CT(€)]
INPUT DATA FOR THE RISK MODEL - BASE-CASE -
OTHER MODELS
Study the effect of the new situation (MNS or MS) and evaluate variations on input data
i.e. Category Cp, Flood severity S, PR, PD...
Note N.14.
NON-STRUCTURAL MEASURES (MNS)
and/or
NEW STRUCTURAL MEASURES (MS)
Flood characteristics of the Base Case are the same for non-structural measures
New flood characterisitcs
This flow chart describes the necessary steps to obtain input data for the risk model to analyze pluvial flooding. Within the risk model, three different blocks can be distinguished as follows:
LOADS
SYSTEM RESPONSE
CONSEQUENCES LOSS OF LIFE / ECONOMIC LOSSES
a)
b)
c)
VARIABLES OF THE METHODOLOGY
v1 CATEGORIES
TIME CATEGORIES (TC)
SUMMER/DAY SUMMER/NIGHT WINTER/DAY WINTER/NIGHT etc...
TC1 TC2 . . TCm
'm' time categories
LAND USE CATEGORIES (CU)
RESIDENTIAL INDUSTRIAL AGRICULTURAL etc.
CU1 CU2 . . CUn
'n' land use categories
Note N.2.
v2 FLOOD EVENTS
RETURN PERIODS (T)
Annual Probability of Exceedance (AEP)
Maximum rainfall rates
RAINFALL- RUNOFF MODELS
Peak flow discharges
't' flood events
v4 v5 See next page
v3 FLOW CHARACTERISTICS
For each flood event:
- Runoff rates for each area (from land use categories or definition of homogenous zones).
- Water depths (y).
- Velocities (v).
- Flooded areas (AF, Af,i).
Note N.4.
LEGEND
Data related to:
Loads
System response
Consequences. Life-loss
Consequences. Economic losses
Input data for the risk model
Other parameters
Preliminary stages before risk model architecture
III Phase of the methodology
Phases I to III of the methodology provide information to establish categories, flood events and risk model architecture
Hydraulic and hydrological studies, estimation of potential consequences, etc. provide input data for the risk model in three diferent blocks: loads, system response and consequences (phase VI)
Table A.1.x. Tables are included in Appendix A1c
Note N.x. Notes are included in Appendix A1c
FLOW CHART -PLUVIAL FLOODING- Appendix A1a Phases

v4 POTENTIAL LOSS OF LIFE



v5 POTENTIAL ECONOMIC LOSSES



ADDITIONAL SCHEMES
-PLUVIAL FLOODING-
Appendix A1b
Variables

TABLE A.1.1. CATEGORY Cp FOR THE CASE STUDY TO OBTAIN FATALITY RATES (Source: SUFRI project)

Category C_p	Definition
C_{p1}	No warning systems
C_{p2}	Existence of warning systems, but not used or protocols are unknown
C_{p3}	Warning systems completely established and proved (drills)

TABLE A.1.2. FLOOD SEVERITY LEVELS (S) (Source: SUFRI project)

Flood severity (S)		Depth y(m)	Velocity v (m/s)	Dragging parameter v·y (m²/s)	Sliding parameter v²·y (m³/s²)
S0	None or low fatalities expected. People expected to survive.	<0.45	<1.50	<0.50	<1.23
S1	*Low severity* People may suffer loss of stability. People in danger.	<0.80	<1.60	<1.00	<1.23
S2	*Medium severity* Significant loss of stability. Cars can lose roadholding. Floating.	<1.00	<1.88	<1.00	<1.23
S3	*High severity* High risk for people outside Low risk for buildings	>1.00	>1.88	>1.00	>1.23
S4	*Extreme severity* Structural damages on buildings	>1.00	>1.88	>3.00	>1.23

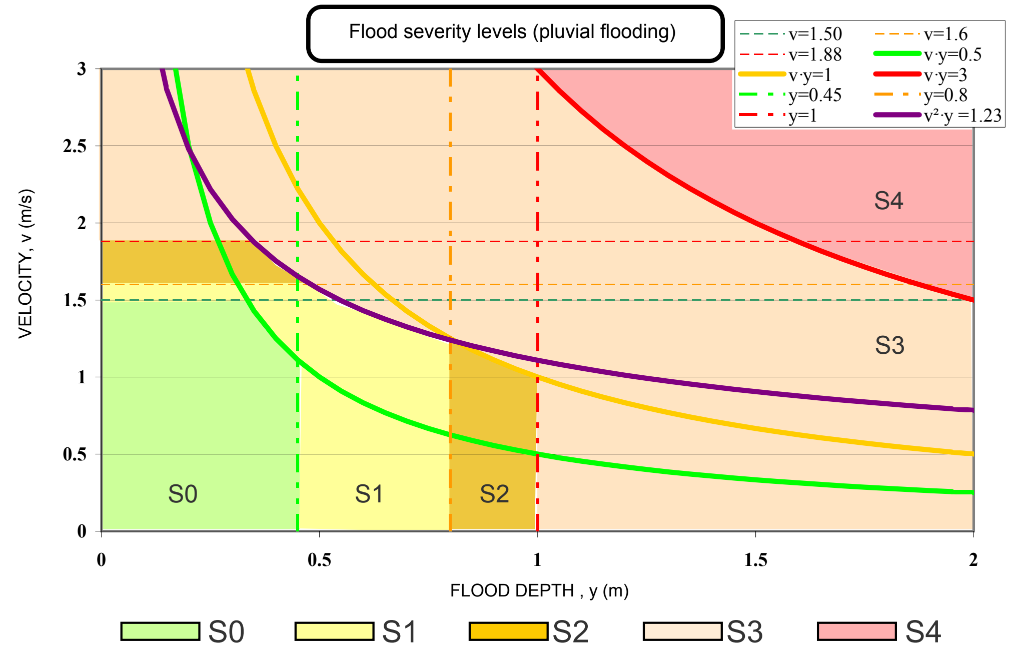
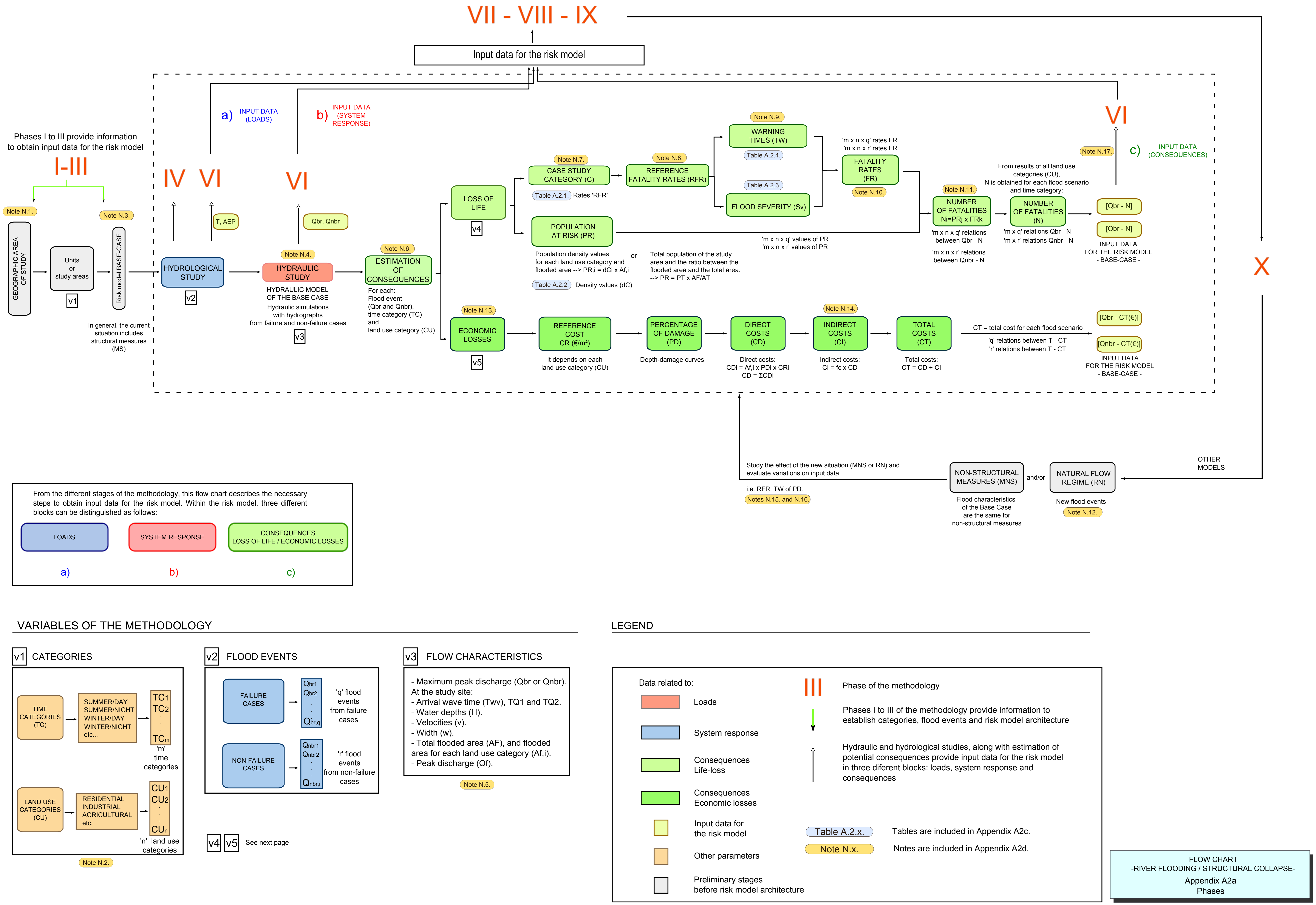


TABLE A.1.3. REFERENCE FATALITY RATES. (Source: SUFRI project, Penning-Rowsell et al., 2005)

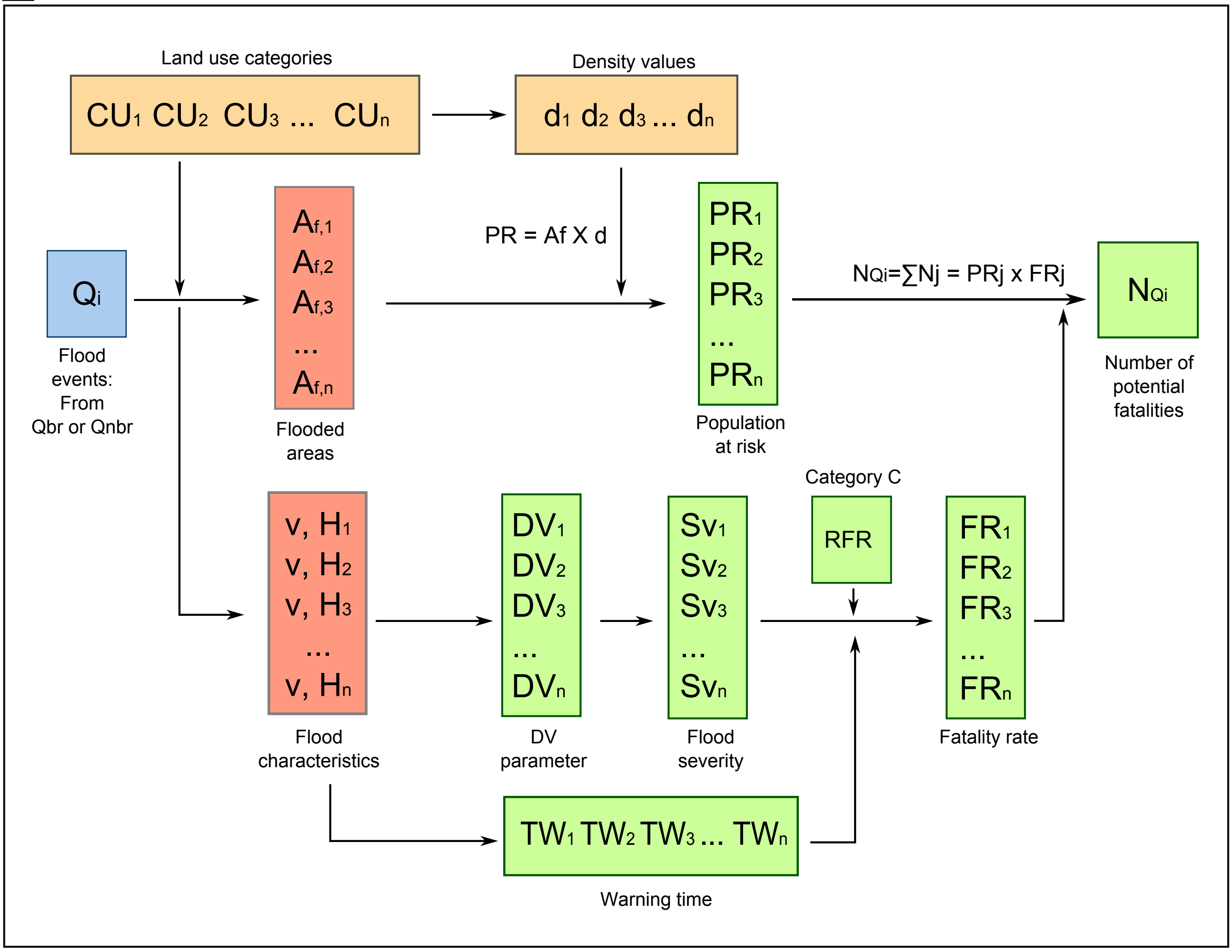
Category C_p	Flood severity S	Fatality rate FRp	Range of values
C_{p1}	S0	0.0003	0.0000 - 0.0009
	S1	0.0021	0.0010 - 0.0030
	S2	0.0038	0.0015 - 0.0045
	S3	0.0105	0.0060 - 0.0400
	S4	0.0448	0.0100 - 0.1100
C_{p2}	S0	0.0003	0.0000 - 0.0008
	S1	0.0018	0.0012 - 0.0024
	S2	0.0033	0.0014 - 0.0037
	S3	0.0090	0.0050 - 0.0350
	S4	0.0384	0.0100 - 0.0950
C_{p3}	S0	0.0002	0.0000 - 0.0007
	S1	0.0015	0.0010 - 0.0020
	S2	0.0027	0.0010 - 0.0030
	S3	0.0075	0.0040 - 0.0280
	S4	0.0320	0.0090 - 0.0800

CODE	NOTE
N.1.	Analysis of the case study: including residential areas, industrial areas and other areas with potential fatalities. Data requirements: demography, land uses, type of buildings, maps, statistics, historical records and information of past events, economic rates, etc.
N.2.	Study of population variability: moment of the day, day of the week, season, special events, etc. In case studies with a high number of population, consequences for two time categories can be obtained and then a factor may be applied to estimate results for other categories (i.e.Nj=Ni x PRj/PRi)
N.3.	A risk model for the Base Case should be developed, including the current drainage system. Then, different situations can be analyzed for studying the effect of other structural or non-structural measures (MS or MNS).
N.4.	Hydraulic modelling or other calculations will provide data for each flood event, defined by a return period. The model/process should represent the characteristics of the current drainage system.
N.5.	Input data for the risk model, related to consequences is divided into two parts: potential loss of life and potential economic damages.
N.6.	The category (Cp) that determines fatality rates (FRp) in case of pluvial flooding, depends on existence of warning systems (Table A.1.1.).
N.7.	Flood severity in pluvial flooding is based on a classification of five levels, from the characteristics of the flood: water depth (y) and velocity (v). These five levels range from S0 to S4.
N.8.	Once the category is established (Cp), fatality rates (FRp) depend on the flood severity level of each flood event (S).
N.9.	The number of potencial fatalities (N) is obtained for each flood event, time category (TC) and land use category (CU) as the product of the fatality rate (FRp) and population at risk (PR): N = PR x FRp. In general, results of potential loss of life lower than 1 may be rounded up to N=1.
N.10.	The risk model uses input data for risk calculation from the list of values Qpf-N obtained from estimations, where T is the return period (flood event) and N is the potential loss of life or number of fatalities for that flood case.
N.11.	People exposed to the flood (PRst) can be estimated as a percentage of the population at risk (PR): number of people within the flooded area.
N.12.	Economic losses of each flood event (direct and indirect costs) are obtained from the estimation of a reference cost (CR) for each land use category (CU). Economic costs depend on the percentage of damages (PD) in each flooded area (depth-damage curves).
N.13.	Indirect costs can be estimated as a percentage of direct costs. A factor, fc, is defined for each case study and it depends on population, infrastructures, economic relevance of the city, etc. i.e. It can range from 0% to 55% (COPUT, 2002).
N.14.	The effect of non-structural measures can be included, for example, as a reduction of the potential economic losses of the flood. A percentage of damage reduction can be estimated from 'warning time-damage reduction' curves (Parker et al., 2005), in flood events with water depths lower than 1.2 m.

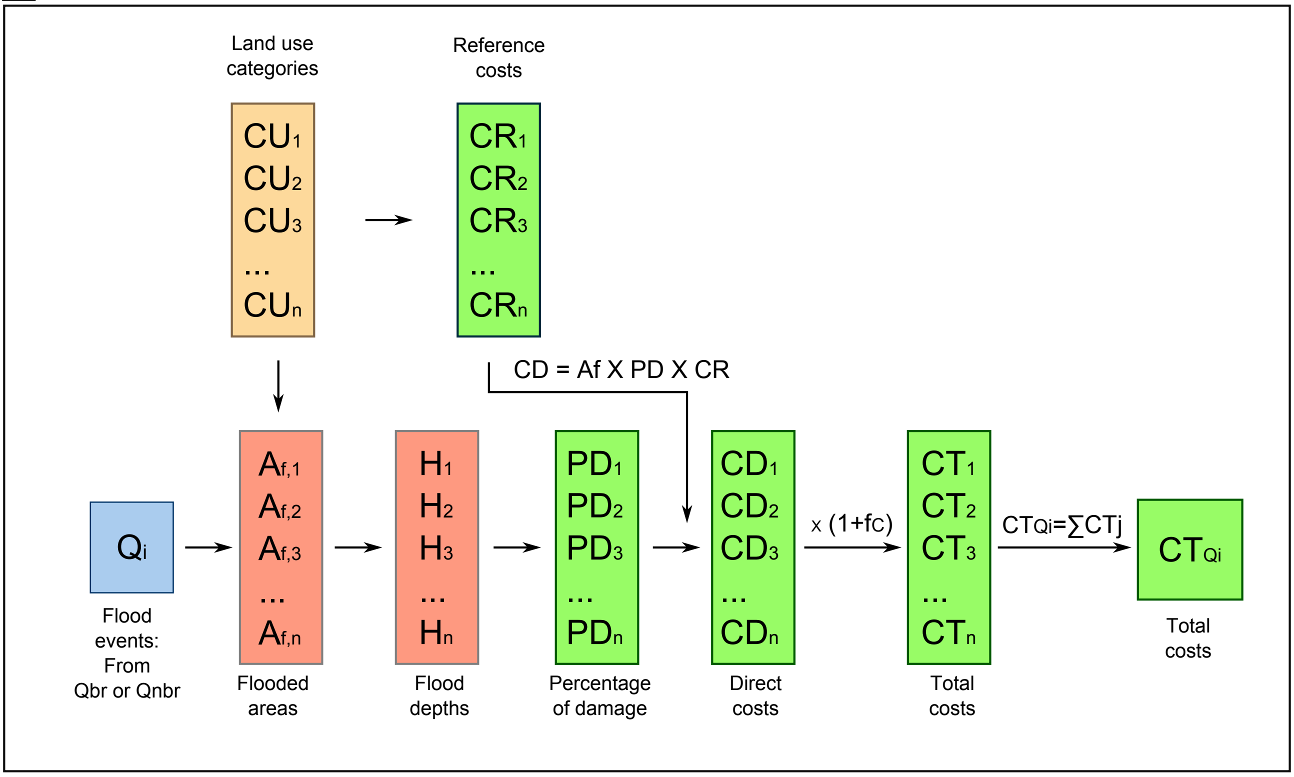


VII - VIII - IX
Input data for the risk model
a) INPUT DATA (LOADS)
b) INPUT DATA (SYSTEM RESPONSE)
Phases I to III provide information to obtain input data for the risk model
I-III
Note N.1.
Note N.3.
GEOGRAPHIC AREA OF STUDY
Units or study areas
v1
Risk model BASE-CASE
In general, the current situation includes structural measures (MS)
IV
VI
T, AEP
HYDROLOGICAL STUDY
v2
VI
Qbr, Qnbr
Note N.4.
HYDRAULIC STUDY
HYDRAULIC MODEL OF THE BASE CASE
Hydraulic simulations with hydrographs from failure and non-failure cases
v3
Note N.6.
ESTIMATION OF CONSEQUENCES
For each: Flood event (Qbr and Qnbr), time category (TC) and land use category (CU)
LOSS OF LIFE
v4
Note N.7.
CASE STUDY CATEGORY (C)
Table A.2.1. Rates 'RFR'
Note N.8.
REFERENCE FATALITY RATES (RFR)
Note N.9.
WARNING TIMES (TW)
Table A.2.4.
Table A.2.3.
FLOOD SEVERITY (Sv)
'm x n x q' rates FR
'm x n x r' rates FR
FATALITY RATES (FR)
Note N.10.
POPULATION AT RISK (PR)
Population density values for each land use category and flooded area --> PR,i = dCi x Af,i
or
Total population of the study area and the ratio between the flooded area and the total area. --> PR = PT x AF/AT
Table A.2.2. Density values (dC)
'm x n x q' values of PR
'm x n x r' values of PR
Note N.11.
NUMBER OF FATALITIES Ni=PRj x FRk
'm x n x q' relations between Qbr - N
'm x n x r' relations between Qnbr - N
From results of all land use categories (CU), N is obtained for each flood scenario and time category:
NUMBER OF FATALITIES (N)
'm x q' relations Qbr - N
'm x r' relations Qnbr - N
Note N.17.
VI
c) INPUT DATA (CONSEQUENCES)
[Qbr - N]
[Qbr - N]
INPUT DATA FOR THE RISK MODEL - BASE-CASE -
Note N.13.
ECONOMIC LOSSES
v5
REFERENCE COST CR (€/m²)
It depends on each land use category (CU)
PERCENTAGE OF DAMAGE (PD)
Depth-damage curves
DIRECT COSTS (CD)
Direct costs: CDi = Af,i x PDi x CRi CD = ΣCDi
Note N.14.
INDIRECT COSTS (CI)
Indirect costs: CI = fc x CD
TOTAL COSTS (CT)
Total costs: CT = CD + CI
CT = total cost for each flood scenario
'q' relations between T - CT
'r' relations between T - CT
[Qbr - CT(€)]
[Qnbr - CT(€)]
INPUT DATA FOR THE RISK MODEL - BASE-CASE -
X
OTHER MODELS
Study the effect of the new situation (MNS or RN) and evaluate variations on input data
i.e. RFR, TW of PD.
Notes N.15. and N.16.
NON-STRUCTURAL MEASURES (MNS)
Flood characteristics of the Base Case are the same for non-structural measures
and/or
NATURAL FLOW REGIME (RN)
New flood events
Note N.12.
From the different stages of the methodology, this flow chart describes the necessary steps to obtain input data for the risk model. Within the risk model, three different blocks can be distinguished as follows:
LOADS
SYSTEM RESPONSE
CONSEQUENCES LOSS OF LIFE / ECONOMIC LOSSES
a)
b)
c)
VARIABLES OF THE METHODOLOGY
v1 CATEGORIES
TIME CATEGORIES (TC)
SUMMER/DAY SUMMER/NIGHT WINTER/DAY WINTER/NIGHT etc...
TC1 TC2 . . TCm
'm' time categories
LAND USE CATEGORIES (CU)
RESIDENTIAL INDUSTRIAL AGRICULTURAL etc.
CU1 CU2 . . CUn
'n' land use categories
Note N.2.
v2 FLOOD EVENTS
FAILURE CASES
Qbr1 Qbr2 . . Qbr,q
'q' flood events from failure cases
NON-FAILURE CASES
Qnbr1 Qnbr2 . . Qnbr,r
'r' flood events from non-failure cases
v3 FLOW CHARACTERISTICS
- Maximum peak discharge (Qbr or Qnbr).
At the study site:
- Arrival wave time (Twv), TQ1 and TQ2.
- Water depths (H).
- Velocities (v).
- Width (w).
- Total flooded area (AF), and flooded area for each land use category (Af,i).
- Peak discharge (Qf).
Note N.5.
v4 v5 See next page
LEGEND
Data related to:
Loads
System response
Consequences Life-loss
Consequences Economic losses
Input data for the risk model
Other parameters
Preliminary stages before risk model architecture
III Phase of the methodology
Phases I to III of the methodology provide information to establish categories, flood events and risk model architecture
Hydraulic and hydrological studies, along with estimation of potential consequences provide input data for the risk model in three diferent blocks: loads, system response and consequences
Table A.2.x. Tables are included in Appendix A2c.
Note N.x. Notes are included in Appendix A2d.
FLOW CHART -RIVER FLOODING / STRUCTURAL COLLAPSE- Appendix A2a Phases

v4 POTENTIAL LOSS OF LIFE



v5 POTENTIAL ECONOMIC DAMAGES



DEFINITION OF THE CASE STUDY CATEGORY TO DETERMINE REFERENCE FATALITY RATES (RFR)

TABLE A.2.1. REFERENCE FATALITY RATES

Category for the case study (C)		Warning time TW (h)	Flood severity (Sv) High (3)	Medium (2)	Low (1)
C1	- There is no public education on flood risk. - No warning systems, no EAP. - There is no coordination between emergency agencies and authorities. - No communication mechanisms to the public.	***0***	0.9	0.3	0.02
		0.25	0.9	0.3	0.02
		0.625	0.7	0.08	0.015
		1	-	0.06	0.0006
		1.5	-	0.0002	0.0002
		24	-	0.0002	0.0001
C2	- There is no public education on flood risk. - There is **no EAP,** but there are other warning systems. - There is no coordination between emergency agencies and authorities. - No communication mechanisms to the public.	***0***	0.9	0.3	0.02
		0.25	0.9	0.3	0.02
		0.625	0.675	0.075	0.014
		1	-	0.055	0.00055
		1.5	-	0.0002	0.0002
		24	-	0.0002	0.0001
C3	- There is no public education on flood risk - There is **EAP,** but it has not been applied yet. - Some **coordination** between emergency agencies and authorities (but protocols are not established). - No communication mechanisms to the public.	***0***	0.9	0.3	0.02
		0.25	0.85	0.2	0.015
		0.625	0.6	0.07	0.012
		1	-	0.05	0.0005
		1.5	-	0.0002	0.0002
		24	-	0.0002	0.0001
C4	- There is no public education on flood risk. - **EAP** is already applied. - Coordination between emergency agencies and authorities (there are **protocols**). - No communication mechanisms to the public.	***0***	0.9	0.3	0.02
		0.25	0.75	0.15	0.01
		0.625	0.5	0.04	0.007
		1	-	0.03	0.0003
		1.5	-	0.0002	0.0002
		24	-	0.0002	0.0001
C5	- There is no public education on flood risk - EAP is already applied. - Coordination between emergency agencies and authorities (there are protocols). - **Communication** mechanisms to the public (not checked yet).	***0***	0.9	0.3	0.02
		0.25	0.75	0.15	0.01
		0.625	0.5	0.0375	0.0065
		1	-	0.0275	0.000275
		1.5	-	0.0002	0.0002
		24	-	0.0002	0.0001
C6	- There is no public education on flood risk - EAP is already applied. - Coordination between emergency agencies and authorities (there are protocols). - Communication mechanisms to the public.	***0***	0.9	0.3	0.02
		0.25	0.75	0.15	0.01
		0.625	0.475	0.035	0.006
		1	-	0.025	0.00025
		1.5	-	0.0002	0.0002
		24	-	0.0002	0.0001
C7*	- **Public education.** - EAP is already applied. - Coordination between emergency agencies and authorities (there are protocols). - Communication mechanisms to the public.	***0***	0.9	0.3	0.02
		0.25	0.65	0.1	0.0075
		0.625	0.4	0.02	0.002
		1	-	0.01	0.0002
		1.5	-	0.0002	0.0002
		24	-	0.0002	0.0001
C8	- Public education - EAP is already applied. It has been proved or used **previously.** - Coordination between emergency agencies and authorities (there are protocols). - Communication mechanisms to the public.	***0***	0.9	0.3	0.02
		0.25	0.55	0.06	0.006
		0.625	0.35	0.01	0.0015
		1	-	0.005	0.00015
		1.5	-	0.0002	0.00015
		24	-	0.0002	0.0001
C9	- Public education. - EAP is already applied. It has been proved or used previously. - **High** coordination between emergency agencies and authorities (there are protocols). - Communication mechanisms to the public.	***0***	0.9	0.3	0.02
		0.25	0.55	0.06	0.006
		0.625	0.35	0.008	0.0015
		1	-	0.004	0.000125
		1.5	-	0.0002	0.0001
		24	-	0.0002	0.0001
C10	- **Regular** activities and plans for public education. - EAP is already applied. It has been proved or used previously. - High coordination between emergency agencies and authorities (there are protocols). - Communication mechanisms to the public.	***0***	0.9	0.3	0.02
		0.25	0.5	0.03	0.005
		0.625	0.3	0.005	0.001
		1	-	0.002	0.0001
		1.5	-	0.0002	0.0001
		24	-	0.0002	0.0001

Natural flow regime (C1) · EAP / No public education (C4) · Dam break / No hydrologic scen. (C7) · Best scenario (C10)

Variation between categories depending on non-structural measures

*(C7 is used for categories 'C8','C9' and 'C10' if the analysis of a flood defence failure in case of non-hydrologic scenario is considered)

REDUCTION ON THE VALUE OF POPULATION DENSITY IN AREAS WITH A HIGH PERCENTAGE OF MULTI-STORY BUILDINGS TO OBTAIN POPULATION AT RISK (PR)

Data requirements:
- Density of population for the study area (d) or total number of citizens within the urban area.
- Average height of buildings (hm) or mean value of number of floors per building (np).
- Water depths due to the flood (H).

This part is considered in urban areas where np>2 or hm>6.6m (urban areas with a high percentage of multi-story buildings).

TABLE A.2.2. Density population for risk calculations (dC)

	Case	dC
Mean value of the number of floors (np)	H < h1p*	dC = d / np
	h1p < H < h2p	dC = d x 2 / np
	H > h2p	dC = d x (H/hn*) / np
Average building heigth (hm)	H < h1p	dC = d x h1p / hm
	h1p < H < h2p	dC = d x h2p / hm
	H > h2p	dC = d x H / hm

*h1p= 3.3m, h2p= 6.6m and hn = height between floors.

(Source: SUFRI project)

NOTE: If there are several urban areas in the case study (several villages, towns, etc. of minor importance or low population), it is recommended to obtain 'np' or 'hm' of three units or cities of differente population (entity) and consider the results as a reference number (p.e. if population=x: x<10,000; 10,000<x<100,000 y x>100,000).

DEFINITION OF FLOOD SEVERITY (Sv)

In general, flood severity of each flood scenario is established from the DV parameter.

$$DV = \frac{Qaf - Q_{2.33}}{w}$$

Data requirements:
- Peak discharge at the study site (Qaf).
- Mean annual discharge of the river at the study site ($Q_{2.33}$).
- Maximum width reached by the flood at the study site (w).

If previous information is not available, then the flood severity category can be determined using flood water depths (H).

TABLE A.2.3. FLOOD SEVERITY (Sv)

		DV	H
Severity for each flood scenario (Sv)	Low (1)	< 4.6 m^2/s	< 3.3 m
	Medium (2)	> 4.6 m^2/s	> 3.3 m
	High (3)	Areas located downstream the dam**	

(Source: Graham, 1999)

**DSO-99-06 procedure does not include recommendations on how to establish the diference between medium and high severity. Therefore, except for specific cases, high flood severity is established in urban areas located close to the dam, where shelter or evacuation are not feasible and total destruction of the area would occur in case of dam break.

WARNING TIME (TW) DEPENDING ON THE ARRIVAL WAVE TIME AND OTHER FACTORS RELATED TO BREACH DEVELOPMENT, FAILURE MODE AND THE EXISTENCE OF AN EMERGENCY ACTION PLAN.

-- WARNING TIME FOR THE NATURAL FLOW REGIME OF THE RIVER (RN) AND STRUCTURAL MEASURES (EXCEPT FOR DAMS)

TW = TD = tQ2 - tQ1

where TD is the diference between the time of the first notice peak discharge at the study site (Q1) and the time of first damages in buildings or households (Q2)

Day: TW = TD = tQ2 - tQ1
Night: TW (h) = TD (h) - 0.25 (TW at night is defined as a time which is 15 minutes lower than TW during the day)

-- WARNING TIMES FOR RISK MODELS WITH DAM UPSTREAM THE STUDY AREA

Breach Development Speed (TBR)

Breach Development	TBR (h)	TBR (min)
Fast	0.25	15
Moderate	0.75	45
Slow	1.25	75

Failure Mode Factor (FMF)

	Average value		Day		Night	
Failure mode	**FMF (h)**	**FMF (min)**	**FMF (h)**	**FMF (min)**	**FMF (h)**	**FMF (min)**
Seismic	0.375	15-30	0.25	15	0.5	30
Internal erosion	0.375	15-30	0.25	15	0.5	30
Hydrologic	0.125	0-30	0	0	0.5	30

(Source: USBR, 2001)

Warting time (TW)*
TW = Wave arrival time (Twv) + Breach Development Speed (TBR) - Failure Mode Factor (FMF) - FPE

*For cases with no dam-break, the warning time is considered as the diference between the peak flow that reaches the first buildings and the first notice flow. This time is denoted by TD
If there is no Emergency Action Plan, a factor FPE equal to 30min should be considered.

p.e. TBR=0.25h y FPE=0.5h. All time values in hours.

	LOAD SCENARIO		Day	Night
NO EMERGENCY ACTION PLAN	Seismic		TW= Twv - 0.5	TW= Twv -0.75
	Internal erosion		""	""
	Hydrologic	No dam-break**	TW= TD	TW= TD - 0.25
		Dam-break	TW= Twv -0.25	TW= Twv -0.5

Warting time (TW)*
TW = Wave arrival time (Twv) + Breach Development Speed (TBR) - Failure Mode Factor (FMF)

**In case of no dam-break, the warning time will be equal to the diference between the first notice peak discharge and the peak flow that reaches the first constructions. This time is denoted by TD.

p.e. TBR=0.25h. All time values in hours.

	LOAD SCENARIO		Day	Night
EMERGENCY ACTION PLAN	Seismic		TW= Twv	TW= Twv - 0.25
	Internal erosion		""	""
	Hydrologic	No dam-break**	TW= TD + 0.5	TW= TD + 0.25
		Dam-break	TW= Twv + 0.25	TW= Twv

(Source: SUFRI project)

CODE	NOTE
N.1.	Analysis of the case study: including residential areas, industrial areas and others with potential fatalities. Data requirements: demography, land uses, type of buildings, maps, statistics, historical records and information of past events, economic rates, etc.
N.2.	Study of population variability: moment of the day, day of the week, season, special events, etc. In case studies with a high number of population, consequences for two time categories can be obtained and a factor is applied to estimate results for other categories (i.e.Nj=Ni x PRj/PRi)
N.3.	A risk model for the Base Case should be implented, including existing flood defence infrastructures (structural measures). In addition, the risk model to study the natural flow regime of the river should be performed for comparison purposes if possible. Other situations can be analyzed for studying the effect of other structural or non-structural measures (MS or MNS).
N.4.	Hydraulic modelling will provide data for each flood event. The model should represent the characteristics of the river. It should be hydraulic, complete and dynamic, enable to obtain results in sub-critical and supercritical flow. Uni-dimensional models are maybe more appropiate than bi-dimensional (as they present low data requirements). Unsteady modelling is necessary in case of structural collapse. Some examples are: MIKE 11(DHI), SOBEK (Deltares) o HEC-RAS (USACE).
N.5.	Q, first notice flow, is the peak discharge at the study site that reaches the capacity of the river bank and it is established as a threshold: population is aware of a potential flood event. First-damage flow, Q2, is the peak discharge at the study site that reaches the first buildings or households.
N.6.	Input data for the risk model, related to consequences is divided into two parts: potential loss of life and potential economic damages.
N.7.	Category of the case study (C) to obtain reference fatality rates (RFR) is defined taking into account: (Table A.2.1.) - Public education. - Communication. - Coordination between emergency agents and authorities. - Existence of Emergency Action Plans.
N.8.	Once the category is defined, there are 15 reference fatality rates for different flood severity levels and warning times, where: - Severity (Sv): High, medium or low. - Warning time (TW): 0 h, 0.25 h, 0.625 h, 1 h, 1.5 h and 24 h.
N.9.	Warning times (TW) vary depending on the Base Case (dams, leeves, dikes, ponds, etc.), also if non-structural measures are applied. If there is a dam usptream the location, warning times depend on breach development, existence of EAP, etc. Warning times are defined differently during the 'day' or at 'night'. (Table A.2.4.)
N.10.	For each flood event, fatality rates (FR) are obtained by interpolating the reference values from warning times obtained from flood characteristics (flood severity and time category). (Table A.2.3.)
N.11.	The number of potencial fatalities (N) is obtained for each flood event, time category (TC) and land use category (CU) as the product of the fatality rate (FR) and population at risk (PR): N = PR x FR. In general, results of potential loss of life lower than 1 may be rounded up to N=1.
N.12.	For risk models of the natural flow regime, input data includes relations Qmax-N, where Qmax is the peak discharge associated with each return period and N is the number of potential fatalities.
N.13.	Economic losses of each flood event (direct and indirect costs) are obtained from the estimation of a reference cost (CR) for each land use category (CU). Economic costs will depend on the percentage of damages (PD) in each flooded area (depth-damage curves).
N.14.	Indirect costs can be estimated as a percentage of direct costs. A factor, fC, is defined for each case study and it will depend on the population, infrastructures, economic relevance of the city, etc. i.e. It will range from 0% to 55% (COPUT, 2002).
N.15.	If dam failure is considered in case of non-hydrological scenario (no rainfall event), then values of the Failure Mode Factor for seismic scenario are used to estimate warning times (FMF, Table A.2.4.).
N.16.	The effect of non-structural measures can be included as a reduction of the potential economic losses of the flood. If the estimation of this reduction can be established, then the percentage of reduction will be estimated from 'warning time-damage reduction' curves (Parker et al., 2005), in flood events with water depths lower than 1.2 m.
N.17.	The risk model will use input data for risk calculations from the list of values Q-N obtained from estimation of potential consequences, where Q is the flow that identifies each flood event (natural flow regime, flood routing or structural collapse) and N is the potential loss of life.

This page intentionally left blank

Appendix B: Additional information

Appendix B1. Jucar River Authority – River basin (Source: CHJ)

Appendix B2. Jucar River Authority – Subcatchment areas (Source: CHJ)

Appendix B3. Jucar River Authority – River gauges (Source: CHJ)

Appendix B4. Municipal term of Benaguasil (Source: PAM Benaguasil)*

Appendix B5. Land uses at the municipal term of Benaguasil (Source: PAM Benaguasil)

Appendix B6. Flooded areas identified in PATRICOVA - Castellana and Benaguasil brooks (Source: PAM Benaguasil)

***Municipal Action Plan against Flood Risk**

NOTE:

Maps included in Appendix B1, B2 and B3 are protected and cannot be included in this document. These maps can be downloaded from the following website:

www.chj.es

Menu:

Confederación Hidrográfica del Júcar > Agua > Sistemas de Información > Cartografía y Datos

Scanned copies are attached.

MINISTERIO
DE MEDIO AMBIENTE,
Y MEDIO RURAL Y MARINO

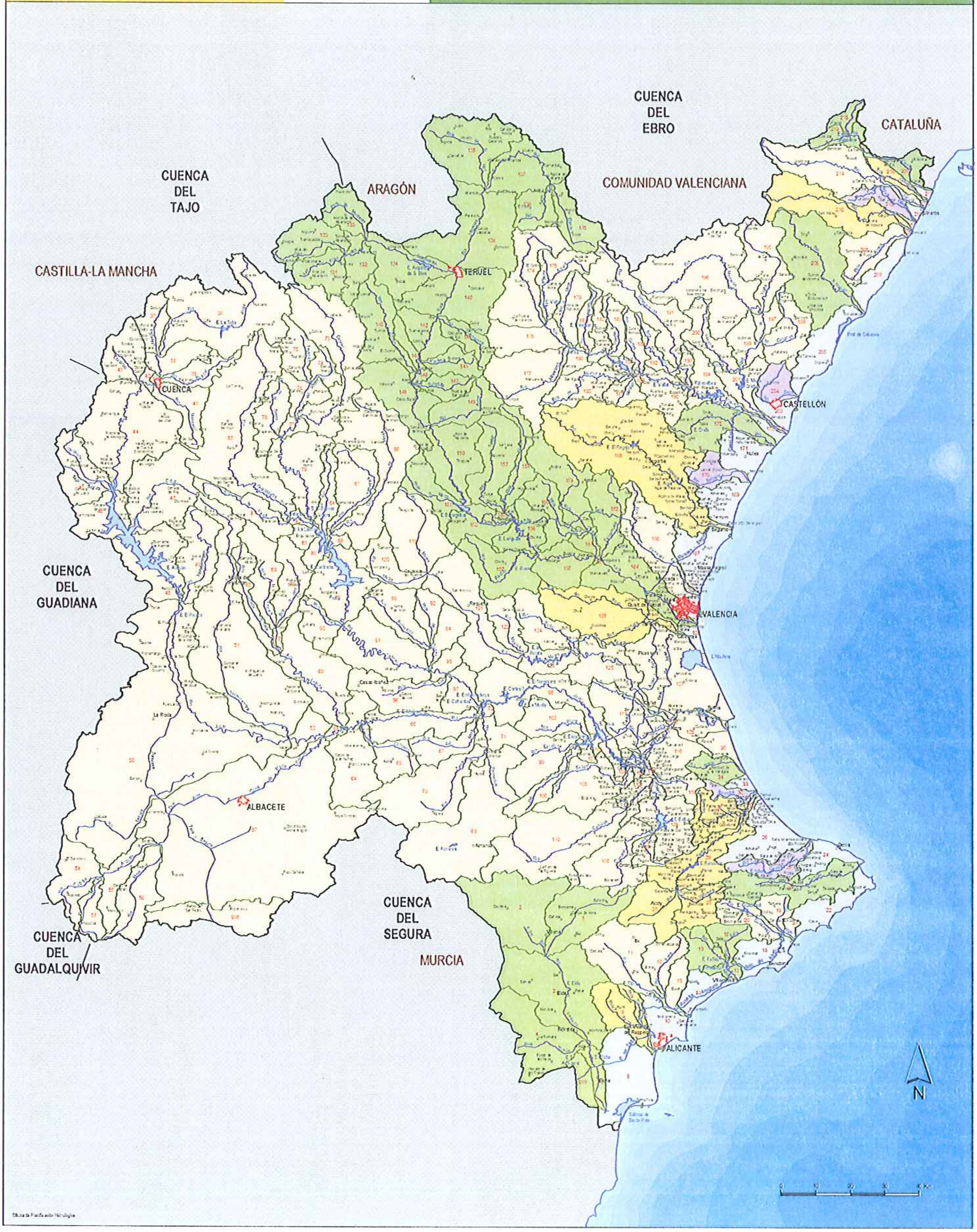
CONFEDERACIÓN
HIDROGRÁFICA
DEL JÚCAR

ÁMBITO TERRITORIAL

MINISTERIO
DE MEDIO AMBIENTE,
Y MEDIO RURAL Y MARINO

CONFEDERACIÓN
HIDROGRÁFICA
DEL JÚCAR

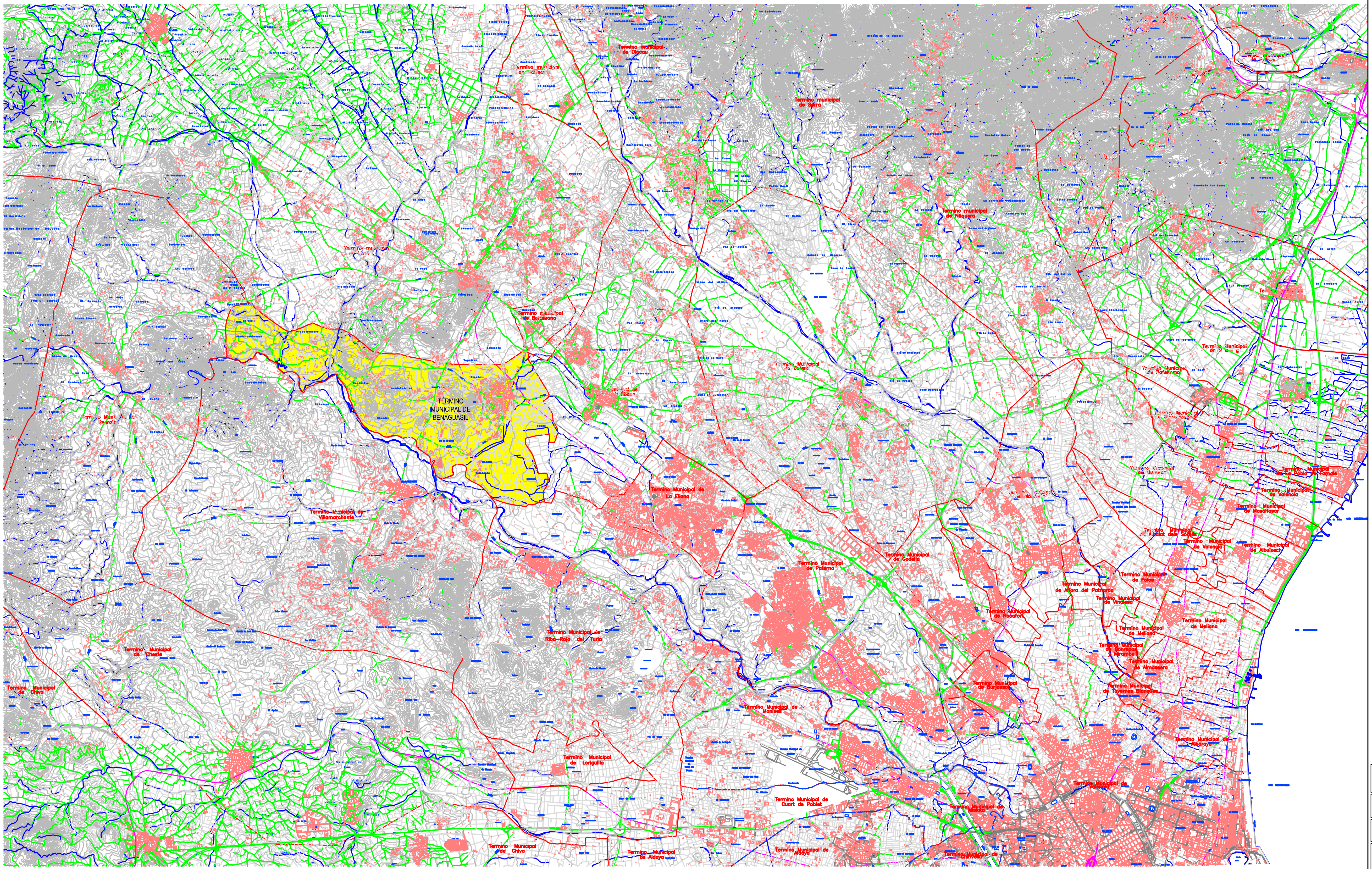
CUENCAS HIDROGRÁFICAS



MINISTERIO DE MEDIO AMBIENTE, Y MEDIO RURAL Y MARINO

CONFEDERACIÓN HIDROGRÁFICA DEL JÚCAR

ESTACIONES DE AFORO

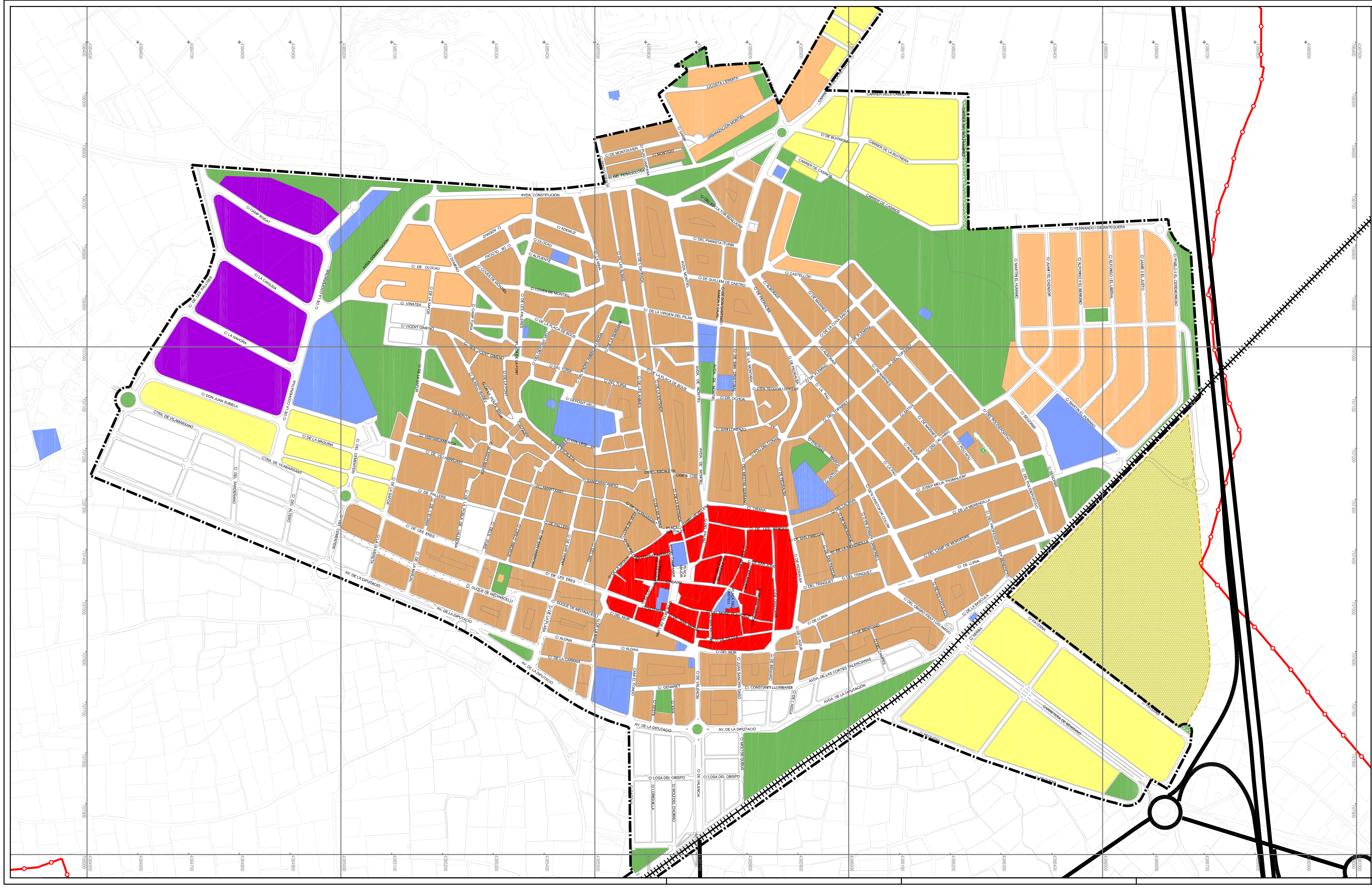


LEGEND

(yellow)	MUNICIPAL TERM

APPENDIX B4

TITLE: MUNICIPAL TERM OF BENAGUASIL	
SOURCE: MUNICIPAL ACTION PLAN - BENAGUASIL	0 400 800 1200 m / N
AUTHOR: Benaguasil — MANUEL JUESAS SIERRA, ARQUITECTO TÉCNICO	1/40.000 — DATE: MAY 2012 — REF: PAM BEN — MAP: 1.1



LAND USES

(red)	RESIDENTIAL - CENTRAL AREA
(brown)	RESIDENTIAL - URBAN EXPANSION AREAS
(light orange)	RESIDENTIAL - ONE-FAMILY HOUSEHOLDS
(yellow)	TERTIARY SECTOR
(purple)	INDUSTRIAL
(blue)	FACILITIES
(green)	GREEN AREAS
(dark yellow)	NON-URBAN AREAS

URBAN LIMIT LINES

(red line)	MUNICIPAL TERM
(dash-dot line)	URBAN AREA

APPENDIX B5

TITLE: LAND USES

SOURCE: MUNICIPAL ACTION PLAN - BENAGUASIL

AUTHOR: Benaguasil — MANUEL JUESAS SIERRA, ARQUITECTO TÉCNICO

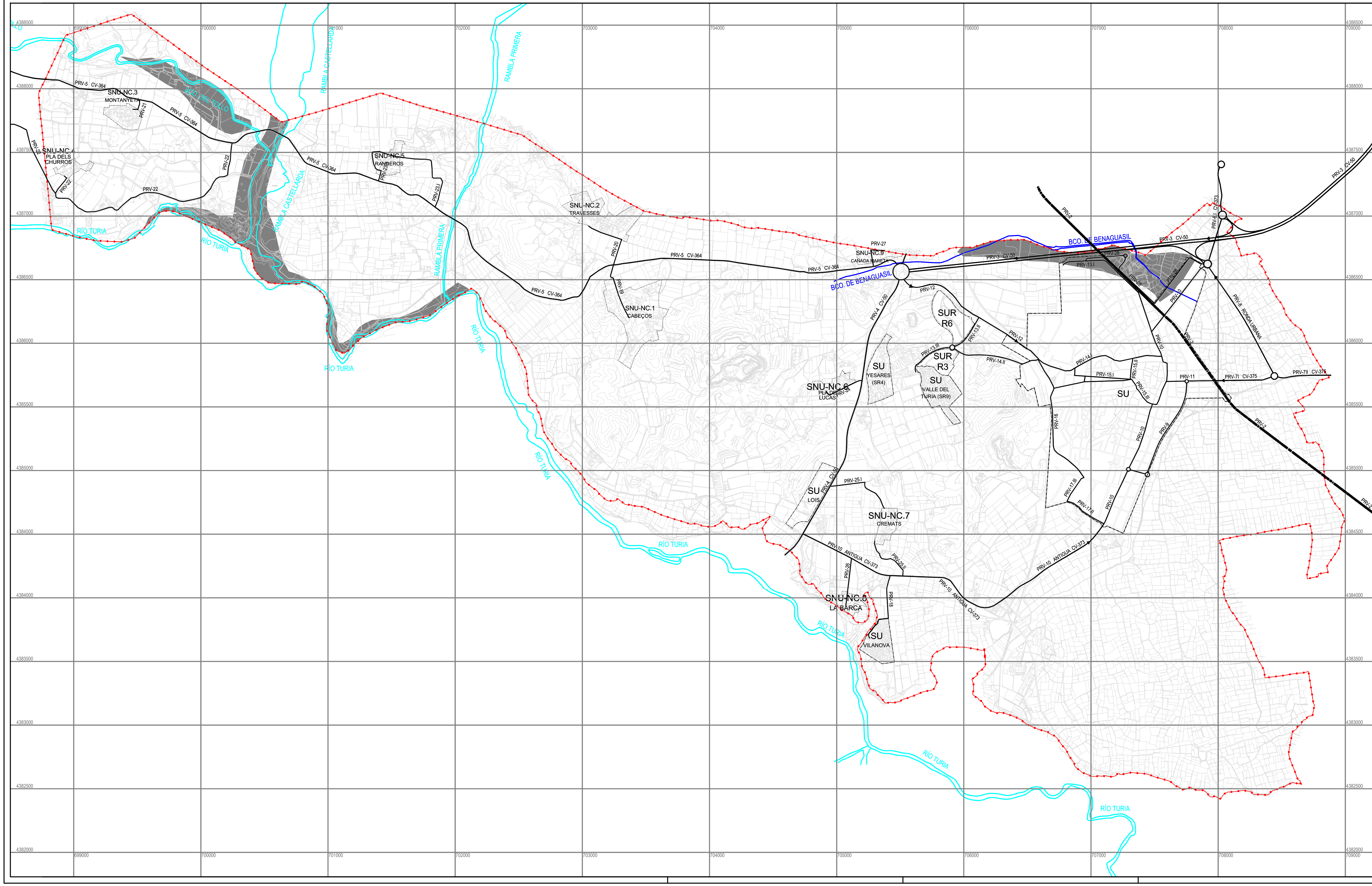
Scale: 0 25 50 75 m — 1/2.500

N

DATE: MAY 2012

REF: PAM BEN

MAP: 1.10 — 1 1



AREAS POTENTIALLY AFFECTED BY FLOODING

RIVER FLOODING FROM CASTELLANA AND BENAGUASIL BROOKS (PATRICOVA, 2002)

BROOKS

CASTELLANA BROOK (*RAMBLA CASTELLANA*)

BENAGUASIL BROOK (*BCO. DE BENAGUASIL*)

URBAN LIMIT LINES

MUNICIPAL TERM

URBAN AREAS

APPENDIX B6

TITLE: AREAS POTENTIALLY AFFECTED BY FLOODING FROM CASTELLANA AND BENAGUASIL BROOKS

SOURCE: MUNICIPAL ACTION PLAN - BENAGUASIL

AUTHOR: Benaguasil

MANUEL JUESAS SIERRA ARQUITECTO TÉCNICO

1/10,000

DATE: MAY 2012

MAP: 8.4

This page intentionally left blank

ANNEX

Index

Annex I. Paper NHESS

[Draft version, August 2012]

Annex II. Municipal Action Plan against Flood Risk of Benaguasil

[*Annex VIII, May 2012*]

This page intentionally left blank

Annex I: Paper NHESS

A quantitative flood risk analysis methodology for urban areas with integration of social research data

Draft version (Aug. 2012).

Received: 12 Dec. 2011 – Revised: 24 July 2012 – Accepted: 30 July 2012.

This page intentionally left blank

Nat. Hazards Earth Syst. Sci., 12, 1–21, 2012
www.nat-hazards-earth-syst-sci.net/12/1/2012/
doi:10.5194/nhess-12-1-2012

Natural Hazards and Earth System Sciences

A quantitative flood risk analysis methodology for urban areas with integration of social research data

I. Escuder-Bueno[1], J. T. Castillo-Rodríguez[1], S. Zechner[2], C. Jöbstl[2], S. Perales-Momparler[3], and G. Petaccia[4]

[1]Universitat Politècnica de València, Research Institute of Water and Environmental Engineering, Valencia, Spain
[2]Graz University of Technology, Institute of Hydraulic Engineering and Water Resources Management, Graz, Austria
[3]PMEnginyeria, Valencia, Spain
[4]University of Pavia, Department of Civil Engineering and Architecture, Pavia, Italy

Correspondence to: J. T. Castillo-Rodríguez (jecasrod@upvnet.upv.es)

Received: 12 December 2011 – Revised: 24 July 2012 – Accepted: 30 July 2012 – Published:

Abstract. Risk analysis has become a top priority for authorities and stakeholders in many European countries, with the aim of reducing flooding risk, considering the population's needs and improving risk awareness. Within this context, two methodological pieces have been developed in the period 2009–2011 within the SUFRI project (Sustainable Strategies of Urban Flood Risk Management with non-structural measures to cope with the residual risk, 2nd ERA-Net CRUE Funding Initiative). First, the "SUFRI Methodology for pluvial and river flooding risk assessment in urban areas to inform decision-making" provides a comprehensive and quantitative tool for flood risk analysis. Second, the "Methodology for investigation of risk awareness of the population concerned" presents the basis to estimate current risk from a social perspective and identify tendencies in the way floods are understood by citizens. Outcomes of both methods are integrated in this paper with the aim of informing decision making on non-structural protection measures. The results of two case studies are shown to illustrate practical applications of this developed approach. The main advantage of applying the methodology herein presented consists in providing a quantitative estimation of flooding risk before and after investing in non-structural risk mitigation measures. It can be of great interest for decision makers as it provides rational and solid information.

1 Introduction

In the recent past, flooding from a wide range of sources (river, pluvial, coastal or maritime flood events) seemed to happen more frequently with snowballing effects for the landscape and society. In fact, one-third of the annual natural disasters and economic losses and more than half of all victims are flood related (Douben, 2006). In the period 1975–2001, floods due to drainage problems, flash floods and river floods accounted for 9 % of all deaths from natural disasters, claiming about 175 000 fatalities worldwide (Jonkman, 2003). Furthermore, present requirements of residential and industrial areas have resulted in new urban developments in flood prone areas, increasing risk to people and assets.

As a result, social demand for higher levels of safety has become a major challenge for the governments of European countries. Though safety is typically linked in engineering to "existing margin to structural collapse", when it comes to flooding, methodologies to support decision making should be based on a much broader concept such as risk (societal, economic, etc.). This allows us to analyze the combined effect of hazard and vulnerability so that the impact on risk of a wide range of options – from an increase of structural safety to a series of non-structural actions such as flood forecasting, warning, emergency management, etc. – can be accounted. The SUFRI project (Sustainable Strategies of Urban Flood Risk Management with non-structural measures to cope with residual risk, 2nd ERA-Net CRUE Funding Initiative) focused on non-structural measures and their impact in risk reduction, including how they enhance social resilience.

Published by Copernicus Publications on behalf of the European Geosciences Union.

However, flood risk cannot be completely eliminated and there will always remain a residual risk.

Additionally, under the EU Floods Directive 2007/60/EC (EC, 2007), a broad basis of knowledge and tools, as well as improved strategies for flood risk management, are being developed. In particular, a key aspect of effective flood risk management is the evaluation of the current situation and the effect of implementing new measures.

In more detail, the need for strategies to improve flood risk management requires the development of advanced warning systems, vulnerability analysis and risk communication to optimize emergency management (Baana and Klijna, 2004; Roos, 2006; Samuels et al., 2006; Sayers et al., 2002; Simonovic, 1999; Graham, 1999).

This submission presents a comprehensive methodology for urban flood risk analysis integrating social research survey data to support the study of non-structural measures. The aim of this approach is to combine both technical and social aspects to inform the decision-making process, showing the impacts of such measures on economic and societal risk.

Two case studies, one focused on an application for a municipality affected by pluvial flooding (Benaguasil, Spain) and a second focused on an urban area (Lodi, Italy) affected by river flooding, are also included to show how the methodology can be applied and used.

2 Overall framework

This section describes the integration of social research data into quantitative flood risk analysis in urban areas with the aim of prioritizing actions for flood risk reduction.

First, Sect. 2.1 summarizes a methodology for pluvial and river flooding risk analysis in urban areas to inform decision making, developed within the SUFRI project and described in detail in its final report (Escuder-Bueno et al., 2011a). Second, Sect. 2.2 summarizes the conceptual basis and a short description of the public opinion poll proposed in the project (Zechner et al., 2011) for estimating public risk awareness and perception of non-structural measures. Next, Sect. 2.3 presents the original approach for the integration of social research data into quantitative flood risk analysis and how the results of opinion polls can be used to incorporate information into the analysis and evaluate the effect of non-structural measures on flood risk reduction.

2.1 Quantitative flood risk assessment in urban areas

The methodology herein presented aims at combining the use of risk models and F–N plus F–D curves to provide a complete and quantitative tool for flood risk estimation (Escuder-Bueno et al., 2011b).

F–N curves are a graphical representation of the probability of events causing a specified level of harm to a specific population (IEC 31010). F–N curves show the cumulative frequency (F) at which N or more members of the population will be affected. Similarly, F–D curves show the cumulative frequency (F) for each level of potential economic damages (D).

This methodology can be applied for analysing any source of flood hazard, but it has been developed in detail for pluvial and river flooding. In addition, the methodology could be applied not only to urban areas but also to flood risk analysis at different scale levels (e.g. a number of municipalities within the flooded area of a river course, regional level, etc.).

2.1.1 Basis

The F–N and F–D curves are quantitative and comprehensive tools for estimating flood risk in a certain area. The F–N curve presents the cumulative annual exceedance probability of the expected estimated level of potential fatalities and the area under the curve corresponds to total societal risk. The F–D curve illustrates the estimated level of economic damages and the area under the curve represents economic risk.

These curves are a useful way of presenting risk information that can be used by managers and system designers to help decision making about risk (IEC 31010), and they are appropriate for comparison of risks from different situations when sufficient data is available, such as the comparison between the situation with and without a number of non-structural measures.

At this point, a short clarification on the definition of non-structural measure is given. In contrast to structural measures, the term "non-structural measure" is not clearly specified and often used ambiguously. The project FLOOD-ERA (1st CRUE ERA-Net Funding Initiative) analyzed and compared existing concepts and proposed a new systematization of structural and non-structural measures (CRUE, 2009; Schanze et al., 2008). Following this systematization, structural measures are considered as any intervention in the flood risk system based on (structural) works of hydraulic engineering. As a result, non-structural measures are all other interventions, mainly focused on acting on potential consequences.

Figure 1 shows the F–D curve for a hypothetic urban area as an example (Escuder-Bueno et al., 2010). This figure depicts the effect of structural and non-structural measures on flooding risk, using typical (but fictitious) values in both axes (annual exceedance probability and estimated economic damages) that have to be properly estimated for each particular case.

Three different curves are presented in Fig. 1: first, the situation without any protection measures (dashed line); second, the situation of the study area with structural measures such as drainage systems, dikes, small and large dams (solid line); and, finally, the situation with both structural and non-structural measures (dotted line).

Depending on what kind of structural measure is considered, the F–N or F–D curve will capture a decrease in the

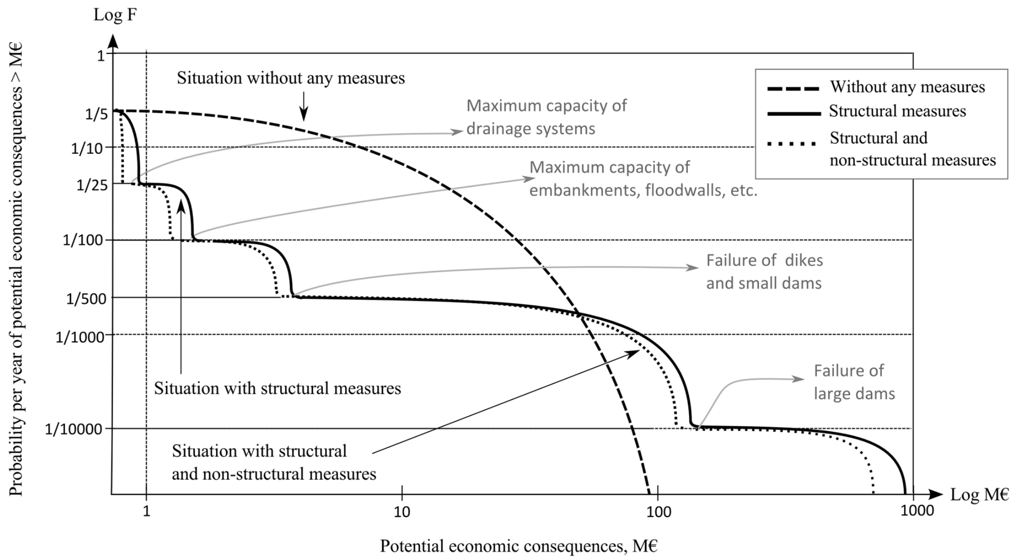


Fig. 1. Effect of structural and non-structural measures on the F–D curve (Escuder-Bueno et al., 2010).

annual probability of exceedance (e.g. drainage systems), an increase in the estimated consequences (e.g. breakage of a large dam or levee), or any other change in the frequency or magnitude of the alternative being analyzed. Moreover, the F–N and F–D curves capture the impact of non-structural measures on flood consequence reduction. Consequently, these curves are the basis of the presented methodology for quantitative flood risk analysis in urban areas.

Based on the definition of the F–N or F–D curves as the representation of the annual cumulative exceedance probability of a certain level of consequences, both societal and economic risk can be represented in terms of potential fatalities or economic damages, respectively.

On the one hand, societal risk can be obtained by estimating potential fatalities based on guidelines found in the literature (e.g. Graham, 1999; DHS, 2011a, b; Penning-Rowsell et al., 2005). In general, these guidelines focus on estimating the population at risk, the population exposed to the flood and fatality rates that are coupled with flooding simulations (peak discharges, arrival wave times, water depths, velocities, flooded areas, etc.).

On the other hand, economic risk can be obtained by estimating potential economic damages from flooded areas, land-use values and depth-damage curves. These curves provide an expected percentage of damages in households, buildings, vehicles, etc. (e.g. COPUT, 2002; Dawson, 2003; Scawthorn et al., 2006) for a certain flood depth. Consequently, extent of flooded areas, reference costs for affected assets and depth-damage curves are used to estimate direct costs. Estimation of indirect costs (e.g. Messner et al., 2007) requires detailed information of the urban area (e.g. loss of production, traffic disruption, costs of emergency services, etc.). In general, indirect costs may be estimated as a percentage of direct costs based on local characteristics. A more

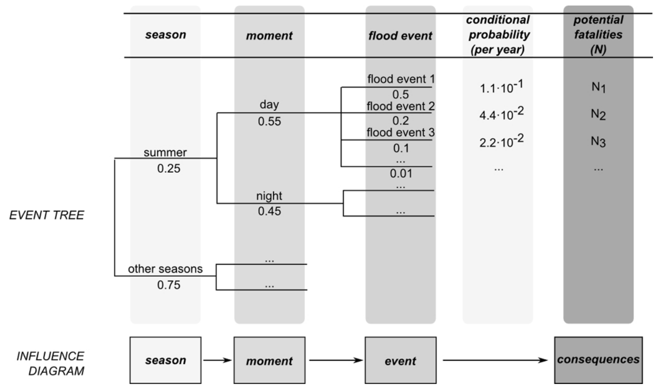


Fig. 2. Generic event tree and compact representation using an influence diagram.

detailed analysis may be necessary, for example, in case of flood events of long duration, existence of hazardous industries or impact in critical infrastructures as defined in EU Directive 2008/114/EC (EC, 2008). With the aim of performing such combinations, this methodology proposes one of the most applicable ways of implementing risk calculations: the use of event trees to compute flood event probabilities and consequences (Serrano-Lombillo et al., 2009).

An event tree is an exhaustive representation of all the 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 (Fig. 2 shows a simplified example).

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.

Consequently, influence diagrams are a compact conceptual representation of the logic of a system. 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.

In particular, the iPresas software (Serrano-Lombillo et al., 2009) has been used to carry out risk calculations. Influence diagrams are built instead of directly using event trees, providing a clear, concise and visual workflow. The software algorithm transforms influence diagrams into event trees and it can be used for any problem that may arise in the field of risk analysis.

The methodology here summarized (presented in Escuder-Bueno et al., 2011b) is flexible enough for performing different risk models as required in any urban area.

2.1.2 Phases to apply the methodology

Phase I – Scope of the case study

This phase consists of properly defining the scope of the study and the required level of detail, with focus on data and time requirements to perform the risk model and calculations.

Phase II – Review of available data

The level of uncertainty in risk estimations will depend on available information (data collection, site visits, etc.). The analysis may include a wide range of studies such as seasonal and daily variations in population, value of assets, land-use distribution, flood prone areas, hydraulic and hydrological studies.

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

Before analysing non-structural measures, it is necessary to study the current situation of the urban area (defined as Base Case). The risk model of the Base Case considers the range of possible flood events due to different load scenarios, including the potential failure of all existent infrastructures (e.g. levees, dikes, dams, drainage system, etc.).

Phase IV – Flood events

Once the proper range of flood events to be considered in the analysis is established, each of these events, characterized by a certain annual probability of exceedance, will be linked to conditional probabilities and potential consequences through the risk model.

Phase V – Risk model architecture

The risk model comprises three generic parts or categories of information: loads, system response and consequences. First, "loads" refers to nodes with information on load scenarios (e.g. if a dam is located upstream of the urban area, it includes data on floods, previous water pool levels, gate reliability and flood routing); next, "system response" includes nodes with information on failure and non-failure cases of flood defence systems; and finally, "consequences" includes potential economic damages and fatalities.

Phase VI – Input data for the risk model

Information from hydrological studies of the catchment area, analyses of system response (failure modes, hydraulic characteristics of the flood, etc.), and estimations of life-loss and economic damages are used as input data to calculate societal and economic risk.

First, life-loss is estimated following different methods for pluvial and river flooding (Escuder-Bueno et al., 2011a), but, in general, the number of potential fatalities is obtained by multiplying population at risk times the fatality rate for each event resulting in flooding. Second, economic losses are assessed by identifying homogenous areas, defining reference costs, and estimating percentages of damage, etc. to calculate direct and indirect costs (e.g. COPUT, 2002).

Phases VII and VIII – Risk calculation and development of F–N curves

All flood events and potential consequences are implemented into the risk model to provide values of societal and economic risk (Phase VII). Then, series of annual probability of exceedance for each value of consequences (loss of life or economic losses) are obtained to represent F–N and F–D curves (Phase VIII). Thus, societal and economic risk can be calculated and represented.

Phase IX – Risk evaluation

Societal and economic risk can be potentially evaluated by comparing results with existing tolerability criteria or standards when available.

Phase X – Study of non-structural measures

Non-structural measures cover a wide spectrum of different actions like, for instance, warning tools, flood proofing and planning instruments (Schanze et al., 2008). In this paper, existing non-structural measures for flood risk reduction are classified into four main groups:

- Public education (denoted as PE),
- Warning systems and emergency management (denoted as EM),
- Coordination between authorities and emergency services (denoted as CO),
- Communication to the public (denoted as CM).

Typically, these measures can have a significant impact on the overall risk by diminishing consequences, both on lives and the economy.

Consequently, the methodology captures the effect of the previously mentioned four groups of non-structural protection measures into existent flood severity understanding and risk awareness of population at risk with the aim of characterizing the expected consequences. Therefore, a review of previous phases is required to estimate new potential consequences and the corresponding F–N or F–D profiles in order to compare the Base Case with the situation after implementing such measures on risk reduction.

2.1.3 Impact of non-structural measures on potential consequences

This section summarizes how potential consequences are estimated in pluvial and river flooding, including the impact of non-structural measures on this stage of the flood risk analysis.

Pluvial flooding

In pluvial flooding, potential consequences in terms of loss of life can be estimated as the combination of population exposed to the flood and fatality rates related to the characteristics of the flood. With that purpose, a classification of five flood severity levels (from S0, where low levels of victims are expected, to S4, extreme severity) was established, based on a set of data collected from literature review (Gómez and Russo, 2009; Reiter, 2001; Nanía, 2002; Témez, 1991) including theoretical studies and experimental data. After representing all the available data together, five flood severity levels were defined by the combination of different hydraulic parameters such as flood depth, velocity, dragging and sliding parameters (Table 1 and Fig. 3).

Once each flood severity level had been defined based on hydraulic characteristics, fatality rates were obtained based on the method proposed by Penning-Rowsell et al. (2005). This method focuses on the estimation of the total number of people located in flood-prone areas, the proportion of those people who are likely to be exposed to it, and those who may be injured or killed.

With the aim of providing different fatality rates based on the existence of warning systems and their impact on potential loss of life, three different levels of flood warning are considered. These levels are based on the three factors proposed by Penning-Rowsell et al. (2005) to characterize area vulnerability (flood warning, speed of onset and nature of area). Flood warning is captured by the FW parameter. This factor score ranged from 1 to 3 depending on available warning systems, which are characterized in terms of emergency planning, awareness and preparedness of the affected population, and preparing and issuing flood warnings. Consequently, any urban area can be classified in one of the three categories shown in Table 2 and linked to one of the three values of FW.

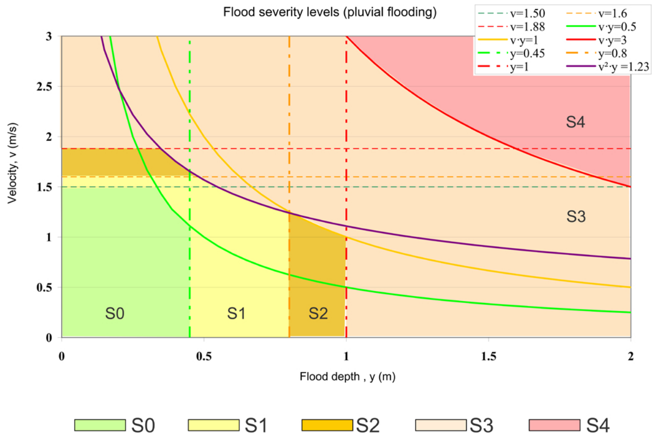


Fig. 3. Flood severity levels for estimating consequences in pluvial flooding (Escuder-Bueno et al., 2011a).

Table 2 lists the established categories concerning the existence of flood warning systems: first, urban areas where no warning systems are available; second, areas where warning systems do exist, but their effectiveness cannot be ensured; and finally, areas with verified or advanced warning systems. Consequently, any urban area can be classified in one of these three different situations as shown in Table 2.

For each category (C_{p1} to C_{p3}) and flood severity level ($S0$ to $S4$), fatality rates are estimated using mean values for building typology, people vulnerability and the so-called area vulnerability factors (except for the FW parameter, Table 2). If other characteristics of the population are considered, fatality rates should be corrected following the guidelines given in Penning-Rowsell et al. (2005). In addition, mean values of water depth and velocity were used for each flood severity level to provide a reference value for each category, C_p, and flood severity level, S. Consequently, fifteen fatality rates have been proposed as shown in Fig. 4.

River flooding

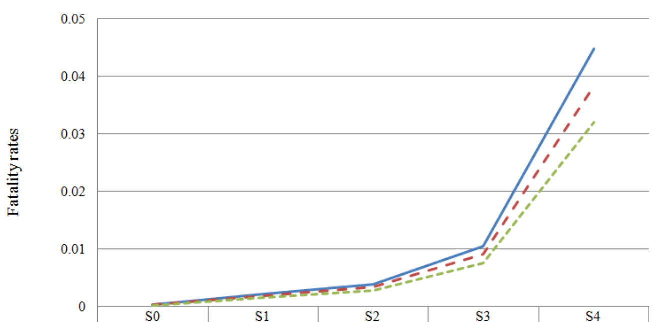
Flood hydraulic characteristics (e.g. water depths, velocities, rise-rate, flood areas, etc.) in river flooding differ from pluvial flooding. As a result, different methods should be applied to estimate potential consequences. Ten categories were established (Escuder-Bueno et al., 2011a) to assess potential

Table 1. Flood severity levels for estimating consequences in pluvial flooding (Escuder-Bueno et al., 2011a).

ID	Flood severity levels (S)	Depth y (m)	Velocity v (m s^{-1})	Dragging parameter vy (m^2 s^{-1})	Sliding parameter v^2y (m^3 s^{-2})
S0	No victims are expected. People expected to survive.	< 0.45	< 1.50	< 0.50	< 1.23
S1	Low severity Pedestrians may suffer loss of stability. People in danger.	< 0.80	< 1.60	< 1.00	< 1.23
S2	Medium severity Significant loss of stability. Cars can lose road holding. Floating.	< 1.00	< 1.88	< 1.00	< 1.23
S3	High severity High risk for people outside. Low risk for buildings.	> 1.00	> 1.88	> 1.00	> 1.23
S4	Extreme severity Structural damages on buildings.	> 1.00	> 1.88	> 3.00	> 1.23

Table 2. Categories for defining fatality rates in pluvial flooding (Escuder-Bueno et al., 2011a).

ID	Category	FW parameter Penning-Rowsell et al. (2005)
C_{p1}	No warning systems are available	3
C_{p2}	Warning systems do exist but not used	2
C_{p3}	Verified and advanced warning systems	1



	S0	S1	S2	S3	S4
CP1	0.0003	0.0021	0.0038	0.0105	0.0448
CP2	0.0003	0.0018	0.0033	0.009	0.0384
CP3	0.0002	0.0015	0.0027	0.0075	0.032

Fig. 4. Fatality rates for pluvial flooding for each category and flood severity level.

loss of life in urban areas in case of river flooding. This classification of ten categories ($C1$ to $C10$) has been developed depending on the existence of public education on flood risk, warning systems, risk communication, and coordination between emergency agencies and authorities. It defines a certain level of flood severity understanding for each category, linked to fatality rates based on a compilation of historical data and existing reference values on loss of life (Graham, 1999; USBR, 2001). Consequently, different fatality rates are considered for each category ($C1$ to $C10$) depending on available warning times (from 0 to 24 h) and three flood severity levels (Table 3). These three severity levels depend on characteristics of river flooding such as the peak discharge in the flooded area, mean annual peak discharge and extent of the flood (Graham, 1999). Thus, once the existing public education, emergency management, communication and coordination systems are evaluated for the urban area, a certain category is used to associate fatality rates with the analyzed flood events. Accordingly, the analysis of a non-structural measure (e.g. implementation of an Emergency Action Plan for Dams) will potentially result in a new category with respect to the Base Case.

2.2 Social research to investigate population risk awareness

2.2.1 Basis

Different groups are involved in the flood risk management process. Alongside the task forces, the affected population is asked to act in a proper way to reduce possible consequences of flooding. In this context, effective risk communication plays a major role to initiate, support, maintain and keep up the knowledge about flood reducing measures and adequate behaviour. To be able to design an effective communication plan for a crisis, the following factors must be taken into consideration: people's behaviours, as well as their

Table 3. Fatality rates in case of river flooding (Escuder-Bueno et al., 2011a).

ID	Category for the case study (C)	Warning time TW (h)	Flood severity (Sv)		
			High (3)	Medium (2)	Low (1)
$C1$	– There is no public education on flood risk terms. – No warning systems, no EAP (Emergency Action Plan). – There is no coordination between emergency agencies and authorities. – No communication mechanisms to the public.	0	0.9	0.3	0.02
		0.25	0.9	0.3	0.02
		0.625	0.7	0.08	0.015
		1	–	0.06	0.0006
		1.5	–	0.0002	0.0002
		24	–	0.0002	0.0001
$C2$	– There is no public education on flood risk terms. – There is no EAP, but there are other warning systems. – There is no coordination between emergency agencies and authorities. – No communication mechanisms to the public.	0	0.9	0.3	0.02
		0.25	0.9	0.3	0.02
		0.625	0.675	0.075	0.014
		1	–	0.055	0.00055
		1.5	–	0.0002	0.0002
		24	–	0.0002	0.0001
$C3$	– There is no public education on flood risk terms. – There is EAP, but it has not been applied yet. – Some coordination between emergency agencies and authorities (but protocols are not established). – No communication mechanisms to the public.	0	0.9	0.3	0.02
		0.25	0.85	0.2	0.015
		0.625	0.6	0.07	0.012
		1	–	0.05	0.0005
		1.5	–	0.0002	0.0002
		24	–	0.0002	0.0001
$C4$	– There is no public education on flood risk terms. – EAP is already applied. – Coordination between emergency agencies and authorities (there are protocols). – No communication mechanisms to the public.	0	0.9	0.3	0.02
		0.25	0.75	0.15	0.01
		0.625	0.5	0.04	0.007
		1	–	0.03	0.0003
		1.5	–	0.0002	0.0002
		24	–	0.0002	0.0001
$C5$	– There is no public education on flood risk terms. – EAP is already applied. – Coordination between emergency agencies and authorities (there are protocols). – Communication mechanisms to the public (not checked yet).	0	0.9	0.3	0.02
		0.25	0.75	0.15	0.01
		0.625	0.5	0.0375	0.0065
		1	–	0.0275	0.000275
		1.5	–	0.0002	0.0002
		24	–	0.0002	0.0001
$C6$	– There is no public education on flood risk terms. – EAP is already applied. – Coordination between emergency agencies and authorities (there are protocols). – Communication mechanisms to the public.	0	0.9	0.3	0.02
		0.25	0.75	0.15	0.01
		0.625	0.475	0.035	0.006
		1	–	0.025	0.00025
		1.5	–	0.0002	0.0002
		24	–	0.0002	0.0001
$C7$	– Public education. – EAP is already applied. – Coordination between emergency agencies and authorities (there are protocols). – Communication mechanisms to the public.	0	0.9	0.3	0.02
		0.25	0.65	0.1	0.0075
		0.625	0.4	0.02	0.002
		1	–	0.01	0.0002
		1.5	–	0.0002	0.0002
		24	–	0.0002	0.0001
$C8$	– Public education. – EAP is already applied. It has been proved or used previously. – Coordination between emergency agencies and authorities (there are protocols). – Communication mechanisms to the public.	0	0.9	0.3	0.02
		0.25	0.55	0.06	0.006
		0.625	0.35	0.01	0.0015
		1	–	0.005	0.00015
		1.5	–	0.0002	0.00015
		24	–	0.0002	0.0001
$C9$	– Public education. – EAP is already applied. It has been proved or used previously. – High coordination between emergency agencies and authorities (there are protocols). – Communication mechanisms to the public.	0	0.9	0.3	0.02
		0.25	0.55	0.06	0.006
		0.625	0.35	0.008	0.0015
		1	–	0.004	0.000125
		1.5	–	0.0002	0.0001
		24	–	0.0002	0.0001
$C10$	– Regular activities and plans for public education. – EAP is already applied. It has been proved or used previously. – High coordination between emergency agencies and authorities (there are protocols). – Communication mechanisms to the public.	0	0.9	0.3	0.02
		0.25	0.5	0.03	0.005
		0.625	0.3	0.005	0.001
		1	–	0.002	0.0001
		1.5	–	0.0002	0.0001
		24	–	0.0002	0.0001

Note: Category $C7$ also used for case studies which correspond to categories $C8$, $C9$ or $C10$ if dam break occurs with no-hydrologic scenario.

needs. In this respect, science currently provides us with limited empirical data. Therefore, the questionnaire developed within the SUFRI project, as part of the “Methodology for investigation of risk awareness of the population concerned” (Zechner et al., 2011), provides empirical data on the subjective view of the citizens regarding flooding. Particular attention is paid to the desired communication and information before, during and after a flood (Grossmann and Seiser, 2011).

With the standardized questionnaire, an appropriate instrument is available to investigate the risk awareness of the population. For the survey, a written questionnaire in combination with a personal hand-out and collection has been chosen. The written questionnaire provides the possibility to obtain a wide range of answers; it allows a higher level of sensitive questions due to the higher anonymity, which fosters the honesty of answers, the respondent has more flexibility to fill-out the questionnaire (e.g. time, reconsideration), and external effects through interviewer’s attitude and interpretation do not occur. The standardization of the questions and the possibilities for answering facilitate the analysis and evaluation of the level of flood risk awareness for a particular region by using relevant survey practices. Since this method is less time consuming, the costs are lower.

The personal contact at the beginning improves the understanding of the research request and leads to an increase of the return rate, as well as the arrangement of a collection time and date, even if this is at the expense of a high degree of anonymity.

The opinion poll consists of 69 questions and an additional field where the respondent has the chance to give further comments (Grossmann and Seiser, 2011). To counteract the limited answer possibilities, supplementary open questions were added into the questionnaire. Questions are related to natural hazards and floods, consequences of flood events (physical, mental and financial), communication and information, as well as self-protection and individual precautions. In addition, aspects of the current warning situation and emergency management, along with level of information, are included.

However, it is important to keep in mind that the level of awareness changes with the participation of people in the opinion poll.

2.2.2 Description

The methodology consists of four different phases:

Phase I – Preparation

Good preparation on defining the study area is the basis for the success of the opinion poll. For example, the physical measurement parameter for defining the number of households can be related to a potential flood event, at least in the range of the 100-yr flood (this means that all the households taken into consideration for the random sampling are situated in the respective area of a 100-yr flood). A detailed demographic survey of the study area is necessary, i.e. socio-economic data collection, number of people to investigate, period of time for the survey, etc.

Besides the determination of these “hard facts”, consideration of “soft factors” is also important. Therefore, it is necessary to make a survey of existing associations, citizens’ initiatives, non-governmental organizations (NGOs), or other groups who may be working in this field. Depending on the local circumstances, an involvement of these groups can be considered, or at least information about the scheduled opinion poll may be provided. To guarantee the success of the opinion poll and further use of the results, the local government has to be involved too.

The opinion poll is implemented at the scale of communities (cities or villages) or counties to get a clear picture of the current risk perception, population requirements and their cooperativeness regarding flood protection measures.

Phase II – Procedure

Phase II consists of two main steps.

– Distribution: Questionnaires will be handed out face-to-face. The presentations of the questionnaire are conducted along a street or a certain area at different times.

– Collection: The type of collection of the questionnaires is selected depending on local circumstances (e.g. face-to-face, by mail, e-mail or fax).

Phase III – Analysis

The opinion poll is analyzed using a data base of all questions and corresponding answers, including answers to open and closed questions which can be statistically or qualitatively analyzed, respectively.

In this paper, the analysis has been qualitative. In future works, research on which statistical tools are more suitable to validate and extend the scope of the results should be undertaken.

In addition, hypothesis and connectivity testing of predefined questions for the following subjects has to be done (an example is given for each subject):

– Risk awareness, self-protection and individual precaution (17 hypotheses);
  Hypothesis 1: The more knowledge people have about floods, the higher the awareness about the residual risk and the willingness to take self-protection measures in the future.

– Communication and information (9 hypotheses);
  Hypothesis 26: The younger the persons are, the more they would like to retrieve (obtain) information from the internet.

– Economic consequences of flood events/insurances (3 hypotheses);
  Hypothesis 28: Those previously affected differ from those previously unaffected in their willingness to insure themselves against potential damages from catastrophes in the future.

Consequently, a series of 29 hypotheses was developed in the project. These 29 hypotheses allow detailed analyses concerning correlations between different factors, which means between two or more different questions, e.g. gender and knowledge concerning floods. These hypotheses are generally applicable, depending on results of questions (e.g. if there are enough answers for each correlated question). Also, these hypotheses should be statistically tested when data from future surveys are available.

Phase IV – Follow-up activities

It is essential to present the results for those who supported and took part in the opinion poll in Phase I (e.g. local government, emergency services, citizens, citizens' initiatives or NGOs). Thus, a positive effect can be obtained, and the public feels that their opinions are taken into account, which could lead to new approaches in flood risk management. Depending on local circumstances and target groups, different forms of communication can be used, e.g. assemblies, newspaper reports or presentations.

2.3 Integrating social research into quantitative urban flood risk analysis

2.3.1 Basis

The existing risk awareness has to be analyzed to define the Base Case, not only with the aim of estimating current flood vulnerability of the urban area, but also to establish the basis for analyzing how each non-structural measure will influence potential consequences.

Thus, results of the proposed opinion poll in the previous section will provide information to estimate current flood vulnerability and new case scenarios with non-structural measures. These new case scenarios will be compared with the Base Case to inform decision makers when prioritizing flood risk reduction actions.

For the integration of social research data into the methodology for quantitative flood risk analysis described in Sect. 2.1, questions of the opinion poll are assigned to the four main groups of non-structural protection measures defined in Sect. 2.1.2 or to an extra group which collects general information (e.g. age, gender, etc.). These groups are:

– General information (GO),

– Public education (PE),

– Warning systems and emergency management (EM),

– Coordination between authorities and emergency services (CO), and

– Communication to the public (CM).

Table 4 classifies all questions (from Q1 to Q69) into the aforementioned five groups and checkmarks the identified connections between them and parameters defined within the overall methodology for estimating potential consequences.

In pluvial flooding, loss of life depends on population at risk (PAR) and the estimated fatality rates, based not only on the existence of warning systems, flood severity, area and people vulnerability, but also on the percentage of people exposed to the flood (f). Hence, results of the survey will support the estimation of factors shown in Table 4. In addition, the opinion poll provides information on current potential economic costs (e.g. land-use values, indirect costs and the expected reduction of damages by self-protection measures).

In river flooding, results of the opinion poll support the category selected from the classification described in Sect. 2.1.4 ($C1$ to $C10$) related to different levels of flood severity understanding depending on the four groups shown in Table 4 (public education, warning systems and emergency management, coordination between actors (e.g. authorities, emergency services, etc.) and communication to the public).

2.3.2 Evaluation of non-structural measures

The abovementioned four groups of non-structural protection measures are included in this section to describe how to integrate new information into the risk model (in Phase X). At this point, results of social research will provide information to incorporate the change in risk awareness into the model with the aim of assessing the impact on flood risk reduction.

– Public education (PE):

  Public education programmes can reduce flood risk considerably. A better knowledge of the existing risk, emergency management practices, sources of risk, protective measures and procedures in case of flooding can reduce potential flood consequences. An increase in public awareness can be either considered in the analysis as a better flood severity understanding, that is, as a higher category ($C1$–$C10$) for estimating potential fatalities in river flooding, or as a reduction on population at risk or the percentage of people exposed to the flood due to a more effective response and more rapid evacuation processes.

– Warning systems and emergency management (EM):

  The purpose of a flood system is to provide warning on impending flooding and help flood management agencies and the members of flood-prone communities to understand the nature of developing floods so that they can take action to mitigate the flood's effects. A flood warning system is made up of a number of components

Table 4. Integration of social research into quantitative flood risk analysis.

			SOCIAL RESEARCH				
RISK ANALYSIS		Questions	Q1-4, Q10-21, Q40-41, Q43-44, Q51-58, Q60-69	Q5-9, Q25, Q36-38, Q59	Q28-31, Q35 , Q39-50	Q22, Q28-31, Q35	Q22-24, Q26-34
		Inputs \ Groups	GO	PE	EM	CO	CM
PLUVIAL FLOODING	LOSS OF LIFE	Population at risk (PAR)	✓	–	–	–	–
		People exposed to the flood (f)	✓	✓	✓	✓	✓
		Category (C_p)	✓	–	✓	✓	✓
	ECONOMIC DAMAGES	Percentage of damages (PD)	–	✓	✓	✓	✓
		Indirect costs (CI)	✓	✓	✓	✓	✓
RIVER FLOODING	LOSS OF LIFE	Population at risk (PAR)	✓	–	–	–	–
		Warning Times (WT)	✓	–	✓	✓	✓
		Category (C)	✓	✓	✓	✓	✓
	ECONOMIC DAMAGES	Percentage of damages (PD)	–	✓	✓	✓	✓
		Indirect costs (CI)	✓	✓	✓	✓	✓

Note: Q = question of the opinion poll, PAR = population at risk, f = percentage of people exposed to the flood, C_p = category for defining the range of fatality rates in pluvial flooding, PD = percentage of damages in assets, CI = indirect costs, WT = warning time; C = category for defining the range of fatality rates in river flooding, GO = General information; PE = Public education; EM = Warning systems and emergency management; CO = Coordination, and CM = Communication to the public.

which must be integrated. These components include (AEMS, 2009):

- monitoring of rainfall and river flows that may lead to flooding,
- prediction of flood severity and the time of onset,
- interpretation of the prediction to determine flood impacts,
- construction of warning messages describing what is happening and will happen, the expected impact and what actions should be taken,
- dissemination of warning messages,
- response to the warnings by involved agencies and community members, and
- review of the warning system after flood events.

The improvement of the effectiveness of existent warning systems or the implementation of advance systems can increase the available warning time and the percentage of people who receive the message during the flood event. In addition, the improvement of emergency management plans can reduce considerably potential consequences. In pluvial flooding, this can be assessed by using a higher category C_p related to the existence of a warning system, and in river flooding by means of a higher category C.

- Coordination between emergency agencies and authorities (CO):

  A high level of coordination between emergency agencies and authorities will increase the effectiveness of flood emergency management. This will result in prompt responses, larger warning times and efficient evacuating procedures providing shelter and assistance.

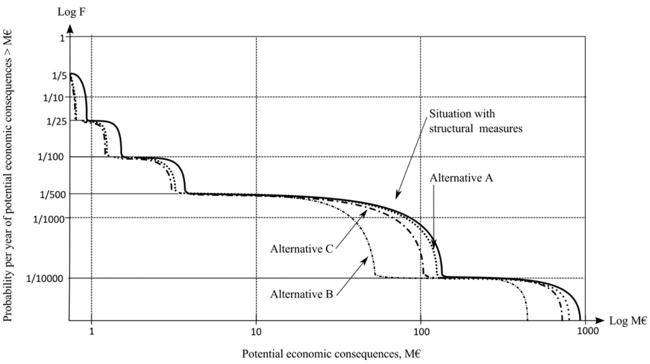


Fig. 5. Example of risk information based on comparison of F–D curves obtained by integrating social research data into quantitative flood risk assessment.

– Communication to the public (CM):

  Risk communication is the basis for an effective flood risk management. The combination of public education and risk communication will provide information to the public, increasing risk awareness and decreasing vulnerability.

Survey data can be considered for estimating potential consequences for the current situation or the impact of a non-structural measure (or set of measures) based on the relations shown in Table 4. As an example, Fig. 5 shows the F–D curves of a hypothetical analysis including four alternatives (the situation with only structural measures, and alternatives A, B, and C).

Results of the opinion poll can be used to estimate potential consequences for each alternative. For example, if Alternative A includes the existence of an advanced warning system which increases the available warning time from 1 to 2 h and the results of the survey show that citizens need less than 1.5 h to take self-protection measures (such as waterstops, flood defence barriers, etc.), then the expected damages to households should be adapted to an evaluation of Alternative A; consequently, F–D curves will differ from the case with only structural measures to this alternative. Other outcomes of the survey, such as the confidence of people in local authorities, can be included in the estimation of potential consequences of other alternatives such as new emergency procedures or planning policies.

In conclusion, after evaluating the effect of a non-structural measure (or set of measures) on the estimation of potential consequences by including the evaluation of outcomes of a social research survey to characterize public risk awareness, the flood risk can be quantified to represent F–N and F–D curves. These curves can be used to analyze the impact of different measures on the magnitude and frequency of consequences. Conclusions of this comparison will support decision making in developing a proposal of non-structural protection measures.

3 Case studies: Benaguasil and Lodi

The integration of social research data into flood risk analysis has been applied to two case studies (Fig. 6), Benaguasil (Spain) and Lodi (Italy), as examples of pluvial and river flooding, respectively. This section includes a short description of both urban areas (Sect. 3.1), outlines results of the public opinion poll (Sect. 3.2) and their integration into risk analysis (Sect. 3.3), and further, outlines conclusions to support decision making on non-structural protection measures (Sect. 3.4).

3.1 Description

Benaguasil is located in the east of Spain, 20 km inland from the city of Valencia, placed in the catchment area of the Turia River. The town is not affected by river floods as it is located far from the river bed. Thus, flood risk is mainly due to pluvial flooding as a result of the low capacity of the drainage system that reaches its maximum capacity with precipitation rates higher than 20 mm in a few minutes, flooding garages, ground floors, houses and roads.

The exceedance of the capacity of the drainage system produces flooding of basements and ground floors of many houses every year and, consequently, significant economic damages. Furthermore, new residential areas have been connected directly to the existing drainage system. Consequently, flooding problems have increased in the last years.

Lodi is located in the north of Italy, crossed by the Adda River with a dam located at Olginate 75 km upstream of the town. The city of Lodi has been flooded during the last century 30 times (ten of these were caused by the main tributaries of Adda River, Brembo and Serio, in the 60's). The most recent flood event occurred in November 2002, with a peak discharge around 1800 $m^3 s^{-1}$ with an estimated return period of 100 yr.

In both cases, flood risk has been analyzed in two situations: first, the current situation of the urban area, and second, the situation with the implementation of non-structural measures concerning public education and improved warning systems.

3.2 Social research

In Benaguasil, 201 households with approximately 800 residents are located within the potential flooded area related to the 100-yr rainfall event. In June 2010, these households were considered for the survey. Interviews were carried out personally with a high return rate of 32 % (Zechner et al., 2011).

More women (64 %) than men (36 %) took part in the opinion poll (with a total of 33 interviewees). With an average age of 40 yr in this urban area, 92 % of the respondents were older than 30 yr, with a percentage of 21 % older than 60 yr. There is a wide distribution of the highest

Table 5. Excerpt of questions (Q) and hypotheses (H) chosen for the analysis of Benaguasil and Lodi case studies referring to two groups of non-structural measures: public education (PE) and communication to the public (CM).

ID	Question/Hypothesis	PE	CM
Q5	How would you rate your personal knowledge about floods and their causes?	✓	
Q22	How much time do you need to prepare sufficiently for a flood?		✓
Q24	How would you like to obtain information in case of a flood event?		✓
Q25	Rate the following statements: I can assess flood risk well; Due to a lack of information, the feeling of insecurity may arise; . . .	✓	
Q26	How reasonable are the following means of communication to keep oneself informed on a regular basis about flood issues: . . .		✓
Q28	How well informed did you feel during the last flood event?		✓
Q29	How long did it take between the first warnings and the onset of the flood?		✓
Q30	This time span was . . .		✓
Q36	Do you know concrete measures to protect yourself in case of flood?	✓	
Q38	Where have you learned about these measures?	✓	
H6	The estimated meaningfulness of self-protection measures and the willingness to take self-protection measures in the future depend on information access.	✓	
H19	Dependent on the level of education, the need for information differs in case of floods.	✓	
H26	The greater the knowledge of a person with regard to floods, the shorter the necessary time span in order to be prepared sufficiently for floods.		✓

educational achievement, with 36 % finishing compulsory education, 21 % professional training, 14 % upper secondary school, and 21 % university.

In Lodi, 3000 residents are living in the area of the 100-yr flood (750 households). Within this group, every 3rd household was interviewed in October and November 2010 personally, resulting in a high return rate of 64 %.

More men (62 %) than women (38 %) took part in the opinion poll (with a total amount of 188 questionnaires). In this case, 98 % of the respondents were older than 30 yr, with a percentage of 43 % older than 60 yr. The highest educational achievement in Lodi differs from those in Benaguasil, with 28 % of the interviewees of the former having finished compulsory education, 8 % professional training, 44 % upper secondary school, and 14 % university.

With the aim of providing information for flood risk analysis and capturing the influence of the non-structural measures regarding public education and improved warning systems, a set of questions of the opinion poll have been selected concerning two of the four groups identified in Sect. 2.1.2 (public education (PE) and communication to the public (CM)).

Table 5 shows selected questions and hypotheses regarding Benaguasil and Lodi case studies from Jöbstl et al. (2011). These questions have been related in this paper to the aforementioned groups: public education (PE) and communication to the public (CM). The three hypotheses listed in Table 5 were obtained from data analysis of surveys.

Questions shown in Table 5 are then classified following the aforementioned two groups: public education (PE) and communication to the public (CM). Two examples of results of the opinion poll are also given in this section (Figs. 7 and 8).

3.2.1 Public education (PE)

Question Q5 shows current risk perception and knowledge of the interviewed inhabitants of Benaguasil and Lodi. In both cases, more than 65 % rate their knowledge about floods very good, mostly good or somewhat good.

The general knowledge about flood risk and the individual perception of the risk was analyzed through the answers to question Q25 (Fig. 7).

The individual knowledge of floods and the associated risk presented differences between both cases: whereas in Benaguasil the majority (69 %) can evaluate flood risk well; in Lodi, only 7 % agree with this. In addition, 68 % feel uncomfortable because of missing information.

However, results of questions Q36 and Q38 (Table 5) show the knowledge about self-protection measures differs in these two case studies; in Benaguasil, 73 % of the respondents know such measures (83 % gain their knowledge from friends and relatives), as opposed to 38 % in Lodi (where only 34 % obtained information from relatives, as most of the people in Lodi stated to have other information sources). Results in Benaguasil show that measures are

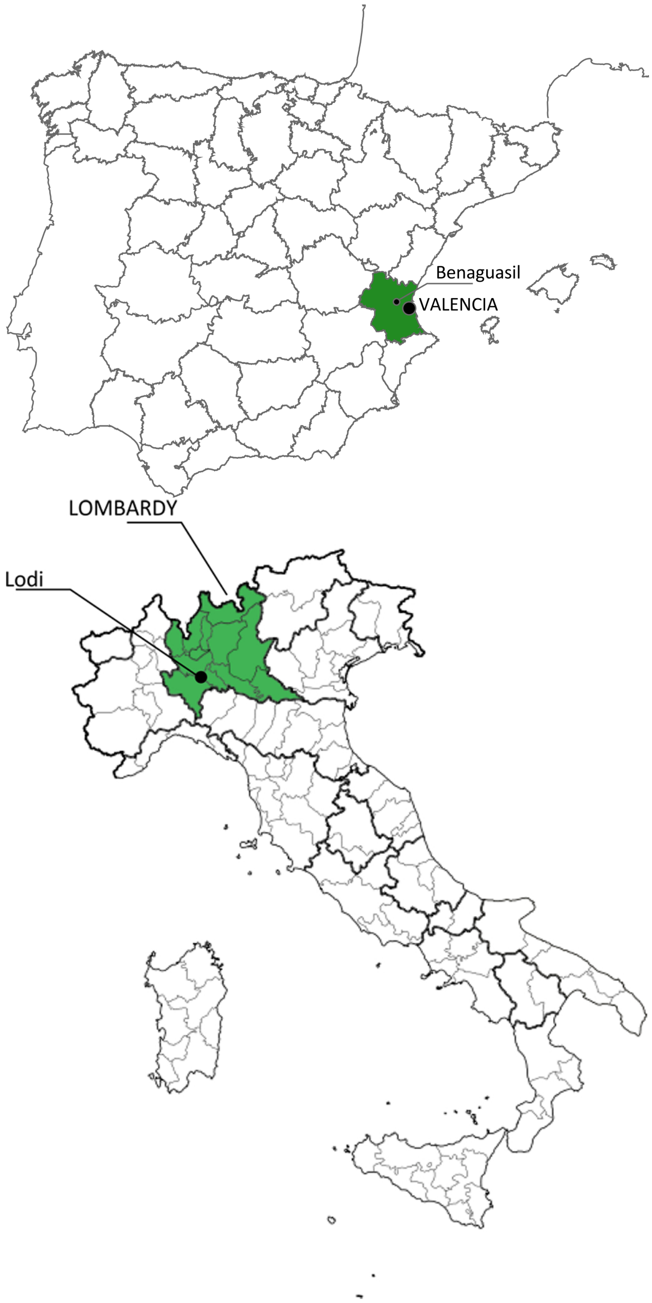


Fig. 6. Location of Benaguasil in Valencia (Spain) and Lodi in Lombardy (Italy).

estimated effective or very effective by 62 % of the respondents. Only a few think that these measures are little or not effective (13.8 %). However, most of respondents are not willing to take self-protection measures in the future. On the contrary, in Lodi self-protection measures are estimated not, little or partially effective by approximately 62 % of the respondents. Only a few think that these measures are very effective (24.5 %), but despite this low rate, approximately 80 % of those interviewed intend to take self-protection measures in the future. These results show that the estimated meaningfulness of self-protection measures may vary depending on the case study and the willingness to take these measures in the future will depend on the information access (hypothesis H6, Table 5), risk perception and also on public education.

In addition to the aforementioned results, no difference regarding the level of risk awareness had been found depending on gender or level of education. However, the preferred means to obtain information depended on the level of education (hypothesis H19, Table 5).

3.2.2 Communication to the public (CM)

Due to the influence of warning systems on potential consequences, it is important to know, for example, public perception of the required warning time to prepare self-protection measures.

In Benaguasil, 89 % of interviewees considered that they would need less than 2 h to prepare themselves sufficiently for a flood (questions Q22, Q29 and Q30, Fig. 8). However, in Lodi this only applies for 7 %. Nearly half of Lodi's inhabitants believe they would need more than 6 h, but 53 % of them had only up to 0.5 h during the last flood, and 16 % between 0.5 and 2 h. The available time between the first warning and the onset of the flood was far too short for 82 % of all interviewed people.

From results of these questions, it was concluded in both cases that the greater the knowledge of a person with regard to floods, the shorter the time span needed to be prepared sufficiently is (H26, Table 5).

Regarding the influence of communication and warning systems on risk reduction, it has to be considered which types of communication are preferred by the public in order to develop adequate communication strategies. On this point, there are significant differences between both cases (Table 5, question Q24); in Lodi, information by emergency services (85 %) and community or local councils (67 %) are preferred, but in Benaguasil most prefer to get information by the media (62 %) or Internet (31 %).

In Benaguasil, advertisements in the media (71 %) and on-site information centres (50 %) as well as websites on the Internet (46 %) are the preferred communication means to keep oneself informed on a regular basis (see Table 5, question Q26). In Lodi, the analysis has not shown such a clear picture, but on-site information centres (40 %) and advertisements in the media (37 %) are also preferred.

In addition, regarding the information provided to people during last flood events, most of the interviewees felt very badly informed (Table 5, question Q28), Lodi with 85 % and Benaguasil with 68 %.

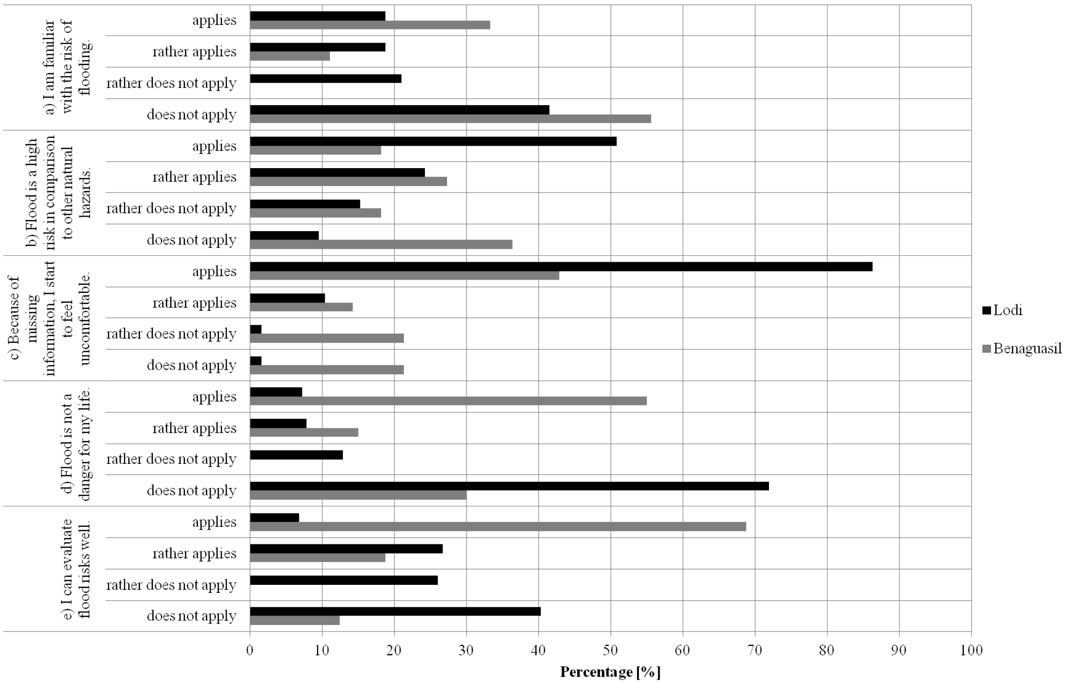


Fig. 7. General knowledge about flood risk. Note: **(a)** I am familiar with the risk of flooding (Lodi $n = 176$, Benaguasil $n = 9$); **(b)** flood is a high risk in comparison to other natural hazards (Lodi $n = 177$, Benaguasil $n = 11$); **(c)** because of missing information, I start to feel uncomfortable (Lodi $n = 182$, Benaguasil $n = 14$); **(d)** flood is not a danger for my life (Lodi $n = 178$, Benaguasil $n = 20$); **(e)** I can evaluate flood risks well (Lodi $n = 176$, Benaguasil $n = 16$).

3.3 Flood risk analysis

3.3.1 Benaguasil

Risk due to pluvial flooding has been assessed for Benaguasil by defining two analyses: first, the study of the current situation (denoted as Base Case), and second, the effect of non-structural measures regarding a public education program on flood risk and the existence of warning systems (denoted as PFR+WS-Case).

On one hand, the public education program would include the following aspects:

- Annual information campaigns and workshops for action forces and the public;
- Design of a website with updated information and advice to the public;
- Regular publications in the local bulletin; and
- An information desk at the Town Council.

On the other hand, the components of the warning system are:

- Daily reports at a specific information desk;
- Information on prediction or monitoring of rainfall events provided by Civil Protection, the Spanish Agency of Meteorology or local services of the City Council;
- Interpretation of the prediction (identification of the corresponding level of meteorological risk alarm, vulnerable areas, and expected hydraulic characteristics);
- Specific warning messages describing what is happening, the expected impact and what actions should be taken depending on the level of meteorological risk alarm;
- Dissemination of warning messages, transmitted by means of loudspeakers located at the urban area; and
- Annual drills and tests to verify efficiency of warning messages.

Based on the connections provided in Sect. 2.3 to integrate social research data into flood risk analysis (Table 4) with the aim of evaluating the current situation (Base Case) and the effect of non-structural measures (PFR+WS-Case), Table 6 shows the impact of results of social research data on the estimation of potential fatalities for the case study of Benaguasil.

Main aspects of the analysis are summarized:

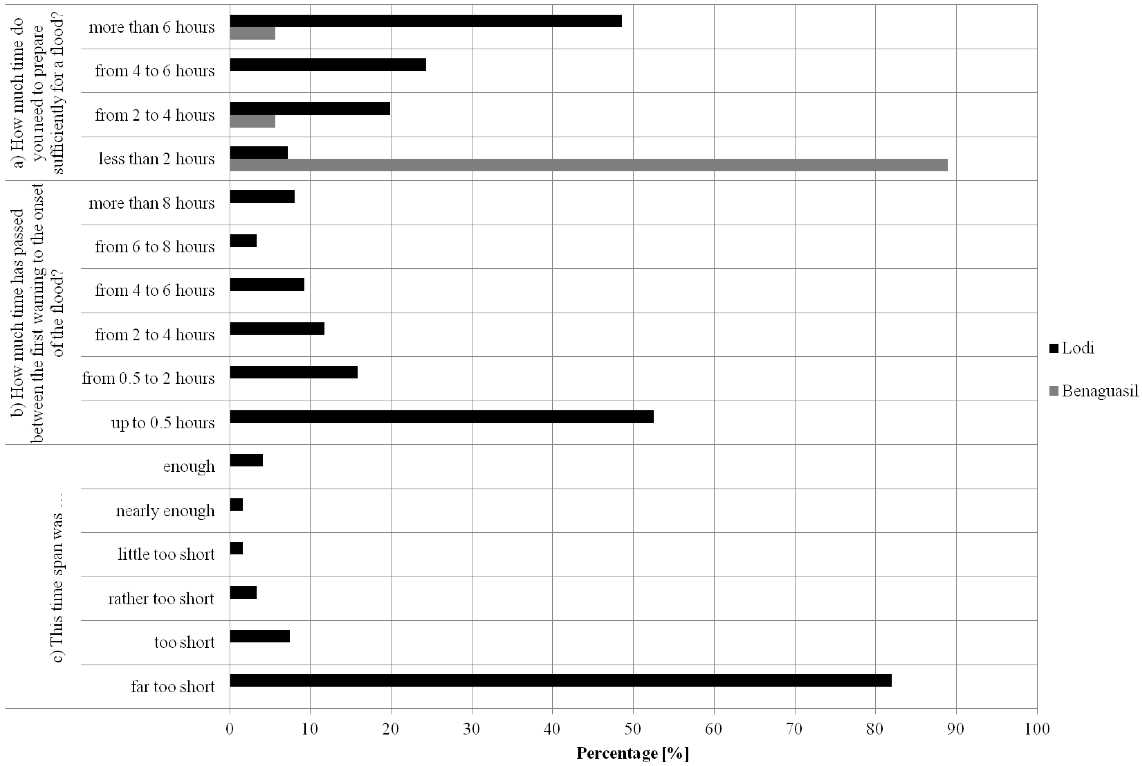


Fig. 8. (a) Time to prepare for a flood; **(b)** time passed between warning and onset of flood, and **(c)** evaluation of the time span. Note: **(a)** Lodi $n = 181$, Benaguasil $n = 18$; **(b)** Lodi $n = 120$, Benaguasil $n = -$, and, **(c)** Lodi $n = 122$, Benaguasil $n = -$.

Table 6. Integration of social research data into flood risk analysis to estimate potential consequences for the case study of Benaguasil.

	BENAGUASIL					
	Inputs for risk analysis		Public education (PE)	Communication to the public (CM)	Base Case (current situation)	PFR+WS-Case (including non-structural measures)
PLUVIAL FLOODING	LOSS OF LIFE	Population at risk (PAR)	–	–	–	–
		People exposed to the flood (f)	✓	✓	People exposed to the flood $f = P\text{exp}/\text{PAR}$	People exposed to the flood $0.5 \times f$
		Category (C_p)	–	✓	$C_{\text{p}1}$	$C_{\text{p}3}$
	ECONOMIC DAMAGES	Percentage of damages (PD)	✓	✓	PD depends on water depth	Reduction of PD based on water depth and waterstops ($y < 1.2$ m)
		Indirect costs (CI)	✓	✓	27 %	27 %*

* Although public education and improved warning systems would in some cases reduce indirect costs, no differences are considered for the Benaguasil case.
Note: PAR = population at risk; f = percentage of people exposed to the flood with respect to population at risk; $C_{\text{p}1}$ = category for defining fatality rates for the Base Case; $C_{\text{p}3}$ = category for defining fatality rates for the PFR+WS-Case; PD = percentage of damages to assets which depends on water depth and the effect of waterstops as self-protection measures; and CI = indirect costs as a percentage of direct costs.

- The population of Benaguasil is estimated to be 11 144 inhabitants (2010). Combining daily and seasonal variations (approx. 200 people), four time categories are established to estimate the population at risk.
- Seven flood events are defined, relating to maximum daily rainfall rates and annual probabilities of exceedance ranging from 2 to 100-yr return periods.
- Benaguasil is mainly divided into residential zones, except for an industrial area located in the south. Three land uses are identified and related to different reference costs to estimate economic damages.
- Runoff rates have been obtained for each flood event based on the Rational Method (Témez, 1991) adapted to urban catchments. Six catchments areas have been identified, obtaining flooded areas and runoff coefficients based on land-use characteristics and the capacity of the existing drainage network. Flood hydraulic characteristics are estimated to obtain flood severity levels and fatality rates, as well as the percentage of damages based on depth-damage curves (COPUT, 2002).
- The effect of a public education programme on flood risk and the existence of warning systems is analyzed based on social research data as described in Table 6, defining the category C_{p3} (as a result of the existence of warning systems), a reduction on the percentage of people exposed to the flood (due to an improved flood severity understanding), and establishing a reduction of the percentage of damages to households (i.e. a better knowledge of self-protection measures and higher warning times will reduce economic damages, as it was obtained from social research that citizens need approximately 2 h to prepare sufficiently for a flood).

As it has been described in Sect. 2.1, the required information for characterizing all possible flood events and potential consequences can be incorporated into a risk model. The information needed to feed the model, given in Table 7, is related to rainfall events, hydraulic characteristics of the flood, potential consequences in terms of loss of life and economic damages, etc. Table 7 describes the categories of the information used for the case study of Benaguasil. Risk results are compared and represented in Figs. 9 and 10.

As potential fatalities in the case of river flooding are usually higher than in pluvial flooding, in Benaguasil economic risk has more significance than societal risk. However, there is no doubt that public education and warning systems have an effect on risk reduction in both F–N and F–D graphs.

3.3.2 Lodi

River flooding has been assessed for the Lodi case. Two analyses are defined: first, the study of the current situation with structural measures (levees nearby the urban area, without considering Olginate dam), denoted as Base Case, and second, the situation after the application of public education and warning systems, denoted as PFR+WS-Case.

On one hand, the public education program, set by Civil Protection, would include the following aspects:

- Annual information campaigns at schools;
- Guidelines, updates and training courses for public administration workers and volunteers;
- Practical exercises to test the response of action forces; and
- Organization and coordination of volunteers groups.

On the other hand, specific procedures for communication and warning would be applied, such as:

- Identification of potential flooded areas based on the "Program of the Hydrogeological Assessment (PAI)" of Po River and all its tributaries, by the Po River Agency in 2001;
- Definition of the "alarm" if the Po level reaches a specified water level;
- Specific messages to be transmitted by fax to local authorities;
- Specific messages to the population to be displayed on specific notice boards; and
- Specific messages to the population to be announced by sirens.

As it has been described for Benaguasil and based on the connections provided in Sect. 2.3 to integrate social research data into flood risk analysis (Table 4), Table 8 shows the impact of results of social research data on the estimation of potential fatalities for the Lodi case.

Social research results revealed a medium–high level of risk awareness, but no public education campaigns have been performed yet. In addition, the available warning times in past flood events were too short, and, consequently, category C5 for estimating potential loss of life has been considered for the Base Case.

Main aspects of the analysis for Lodi are summarized below:

- Daily and seasonal variability of the population in Lodi (42 737 inhabitants).
- Eight flood events for return periods from 2 to 500 yr were used, based on flow measures recorded at four stations in the basin to estimate flood wave characteristics (discharge vs. duration) and using the Gumbel and GEV (Generalized Extreme Value) probability distributions to evaluate the discharges for an assigned return period.

Table 7. Categories of information for the case study of Benaguasil.

Category	Content
General	To incorporate daily variability of population: includes probabilities of flood occuring during the day or at night.
General	To incorporate seasonal variability of population: includes probabilities of flood occuring in summer or winter. Four time categories are defined (TC1: summer/day, TC2: summer/night, TC3: winter/day, and TC4: winter-night).
Loads	To incorporate rainfall events which result in pluvial flooding in the urban area; includes probabilities of occurrence in terms of return periods (T) and annual exceedance probabilities.
System response	To incorporate hydraulic characteristics of the flood for each rainfall event; includes peak runoff rates (Q), water depths, velocities, and flooded areas.
Consequences	To incorporate consequences in terms of potential loss of life depending on flood hydraulic characteristics, flood severity levels, people exposed to the flood, and fatality rates. Relates number of potential fatalities (N) to flood characteristics (Q) and time categories (TC).
Consequences	To incorporate consequences in terms of potential economic damages depending on flood hydraulic characteristics, depth-damage curves, and land uses. Relates potential economic costs (CT) to flood characteristics (Q) and time categories (TC).

Table 8. Integration of social research data into flood risk analysis to estimate potential consequences in Lodi.

LODI						
Inputs for risk analysis			Public education (PE)	Communication to the public (CM)	Base Case (current situation)	PFR+WS-Case (including non-structural measures)
RIVER FLOODING	LOSS OF LIFE	Population at risk (PAR)	–	–	–	–
		Warning Times (WT)	✓	✓	Values from hydraulic studies	Values from hydraulic studies*
		Category (C)	–	✓	$C5$	$C9$
	ECONOMIC DAMAGES	Percentage of damages (PD)	✓	✓	PD depends on water depth	Reduction of PD based on water depth and waterstops ($y < 1.2$ m)
		Indirect costs (CI)	✓	✓	20 %	10 %

* Despite the expected increase in warning times, no differences are considered for Lodi case due to the complexity of estimating its estimation for this case study.
Note: $C5$ = category for defining fatality rates for the Base Case (see Table 3); $C9$ = category for defining fatality rates for the PFR+WS-Case; PD = percentage of damages in assets which depends on water depth and the effect of waterstops as self-protection measures (Parker et al., 2005); and CI = indirect costs as a percentage of direct costs.

– Flooded areas were computed by a 2-D-model based on shallow water equations written in conservative form (Cunge et al., 1990).

– Two land-use categories are considered: residential and agricultural areas.

– Population at risk was decreased by a factor of 2.53 by taking into account building typologies in Lodi.

– Economic losses were estimated by multiplying a reference cost with the percentage of damages from ad hoc depth-damage curves based on data of the 2002 flood.

Input data needed to feed the risk model was related to rainfall events, peak discharges at the river, hydraulic characteristics of the flood, potential consequences in terms of loss of life and economic damages, etc. The main differences with the case study of Benaguasil concern the nature of the system response, in particular to the hydraulic characteristics of the

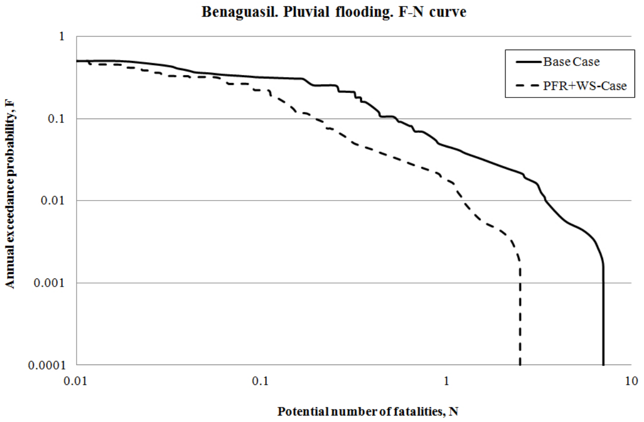


Fig. 9. F–N curve for Benaguasil: pluvial flooding. Base Case and PFR+WS-Case.

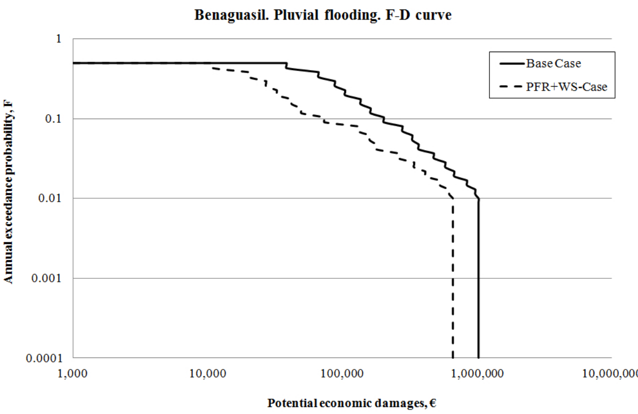


Fig. 10. F–D curve for Benaguasil: pluvial flooding. Base Case and PFR+WS-Case.

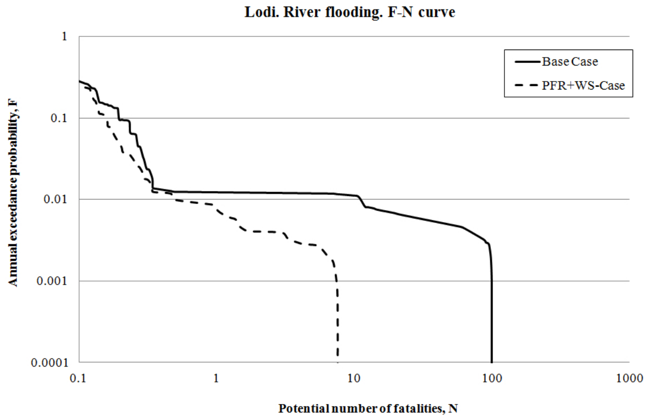


Fig. 11. F–N curve for Lodi: river flooding. Base Case and PFR+WS-Case.

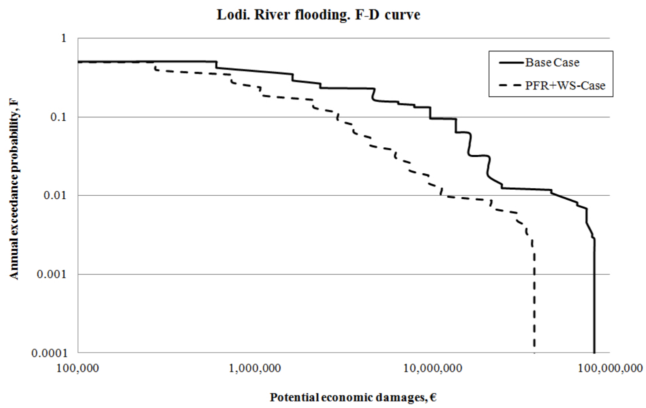


Fig. 12. F–D curve for Lodi: river flooding. Base Case and PFR+WS-Case.

flood due to river flooding, including water depths, velocities, flooded areas and peak discharges at the river. Results are compared and represented in the F–N and F–D curves shown in Figs. 11 and 12.

Figure 11 shows that the F–N curve for the PFR+WS-Case captures the effect on flood risk of the existence of a public education programme and warning system. During the 2002 flood, having an estimated return period of 100 yr, the existence of these non-structural measures would have reduced flood risk to one tenth.

Data from the Lodi Town Council stated that there were 15 949 800 € of damages during the 2002 flood. Figure 12 illustrates that the F–D curve for the current situation shows a similar level of potential economic damages for the same probability of occurrence, and economic costs would be reduced by implementing non-structural measures of public education and warning (resulting in higher levels of self-protection and lower damages).

3.4 Decision making on non-structural protection measures

The obtained results illustrate, in both case studies, the impact on risk reduction of the implementation of non-structural measures concerning public education and warning systems.

Results of social research have supported the estimation of inputs for the analysis, and help to identify the population's needs and preferred communication means in order to develop adequate communication strategies and campaigns providing information to select adequate procedures and increase risk awareness.

In addition, social research supports the estimations carried out to perform alternative analyses by evaluating the existing public awareness and the expected effect of public education campaigns on flood severity understanding. Thus, the preferred communication means can be identified as provided in Table 9 for the Benaguasil and Lodi cases.

Table 9. Preferred communication types in Benaguasil and Lodi case studies.

	Benaguasil	Lodi
Preferred information source in case of flooding	Advertisement in the media Sites on the Internet	Emergency Services Community/Local councils
Preferred communication to keep oneself informed on a regular basis about flood issues	Advertisement in the media On-site information centres Sites on the Internet	Community/Local councils Emergency services

Once social research results have been used to characterize preferred means of information or communication to the public or other aspects of public risk awareness, different non-structural measures, strategies or alternatives for risk reduction can be assessed by using the methodology described in Sect. 2.1 and the resulting F–N and F–D curves.

At this point, it has to be remarked that probability estimates for different alternatives should be assigned by an expert group/consultation based on results of social research and the analysis of the current situation. Whether resources are available for that or if it has to be done through a smaller group, detailed justification of the reason for such elicitation should be clearly provided (Ayyub, 2001).

When quantitative risk results through alternative analysis are displayed using F–N and F–D curves, it is possible to see the noticeable impacts of the structural and non-structural measures as compared to the current risk. This display of information can help to support decisions regarding the definition of information campaigns, warnings, and communication procedures, etc.

As an example, in the Lodi case, further analyses have shown that there is no significant relation between the knowledge of a person with regard to flood and the necessary time span in order to be prepared sufficiently for floods. Therefore, reducing the flood risk only by setting public education measures may not have a direct impact on the necessary warning time (i.e. although people know about the risk and the possibility of self-protection measures, it does not reduce the necessary time for preparation). Increase of the warning time also must be a part of emergency management (not only to know about the existence of measures, but also to know how to use them efficiently).

For further detail of justification of prioritization among different alternatives, proper indicators should be developed, e.g. following dam safety examples (Bowles, 2004; Munger et al., 2009). This cost-effective approach will require a detailed budget of any alternative and the achieved risk reduction. The annual economic risk reduction can be subtracted from the annual cost of the measure and then divided by the societal risk reduction, which is beyond the scope of this paper (more case studies and measures would be needed), before a formal proposal on a cost-effective post-processing analysis can be validated.

4 Conclusions and further research

This paper has presented an approach to integrate social research data into flood risk analysis with the aim of supporting decision making on non-structural protection measures.

This approach is mainly focused on the application of two methodological pieces developed within the SUFRI project that allow qualification of flood risk in urban areas, evaluating different case scenarios in order to compare them with the current situation and the impact of non-structural measures on risk reduction.

Social research data analysis revealed the importance of communication and information strategies as well as self-precaution and warning systems from the point of view of affected people. The development of public education, coordination, communication and emergency management strategies can be reinforced by the outcomes of opinion polls.

Furthermore, common tendencies in the individual flood risk understanding between case studies have been analyzed (a data set of five case studies has been developed within the SUFRI project). However, some differences have been found, and this confirms clearly the need for a survey based on the specific characteristics of the urban area, defining a special strategy for each case study. Though the scope of this work has been limited to qualitative analysis of the survey data, emphasis should be given to statistical tools in the future so that their validity can be tested and the scope of the results broadened.

The relevance of quantitative flood risk analysis in urban areas is supported by results, indicating that F–N and F–D curves are a helpful and comprehensive tool to represent flood risk.

Results of both case studies show that the impact of non-structural measures on flood risk can be addressed by the presented approach. Outcomes obtained by flood risk analyses provide new information to support emergency planning. Hence, results and conclusions of the flood risk analysis in Benaguasil are now being used to develop the Municipal Action Plan against Floods, which will include organization and communication schemes, content and planning of information campaigns, procedures in case of emergency, and recommendations for an improved flood risk management. In the Lodi case, results will support information campaigns and emergency management plans.

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. Thus, it is important to measure not only the impact but also the efficiency of different non-structural protection measures. Further research could be conducted to evaluate the efficiency of these measures by defining indicators, such as those found in the literature for dam safety management (ANCOLD, 2003).

In addition, it has to be remarked that equity is another fundamental principle from which alternatives can be prioritized and tolerability of risk guidelines are derived (ICOLD, 2005). It should be considered that there can be conflict in achieving equity and efficiency (Munger et al., 2009). Thus, the need for society to reduce flood risk cannot overcome the rights of individuals to protect themselves and their interests.

Regarding those tolerability risk guidelines, due to different characteristics of each investigation area, little research has been conducted to establish standards for flood risk assessment in urban areas. Several individual and societal criteria can be found in the literature (Vrijling, 2001), but tolerability guidelines on urban flood risk still need to be developed. Further investigation should therefore concentrate on the basis and development of a common standard to assess urban flood risk, but also include recommendations on how to adapt each particular case based on various aspects including location, public risk awareness, historical data, and impact of flood damages at regional/national/international scale, etc.

Acknowledgements. The work described in this paper was supported by the 2nd ERA-Net CRUE Funding Initiative, particularly funded by the Ministry of Science and Innovation of Spain and the Federal Ministry of Agriculture, Forestry, Environment and Water Management of Austria (Department 19B of the Government of Styria, Torrent and Avalanche control).

Authors would like to express their gratitude to the City Council of Benaguasil and the town of Lodi for their help and willingness to collaborate on this work.

Edited by: A. Thieken
Reviewed by: W. Lehman and three anonymous referees

References

AEMS: Commonwealth of Australia, Flood Warning, Manual 21, Australian Emergency Manuals Series, ISBN 978-1-921152-17-7, 2009.

Australian National Committee on Large Dams (ANCOLD): Incorporated Guidelines on Risk Assessment, October 2003.

Ayyub, B. M.: Elicitation of expert opinions for uncertainty and risks, CRC Press, 2001.

Baana, P. J. and Klijna, F.: Flood risk perception and implications for flood risk management in the Netherlands, Int. J. River Basin Manage., 2, 113–122, 2004.

Bowles, D. S.: ALARP Evaluation-Using Cost Effectiveness and Disproportionality to Justify Risk Reduction, Australian National Commission on Large Dams (ANCOLD) – Bulletin, 127, 89–106, August 2004.

Conselleria d'Obres Públiques, Urbanisme i Territori (COPUT): Plan de Acción Territorial de Carácter Sectorial sobre Prevención de Riesgo de Inundación en la Comunidad Valenciana (PATRICOVA), 2002 (in Spanish).

CRUE Research Funding Initiative: Synthesis Report No I-2009, Addressing the key findings of research, Risk Assessment and Risk Management: Effectiveness and Efficiency of Non-structural Flood Risk Management Measures, Project Contract No: ERAC-CT-2004-515742, 2009.

Cunge, J. A., Holly, F. M., and Vervey, A.: Practical aspects of Computational River Hydraulics, Pitman Publ. Inc, London, 1990.

Dawson, W. R.: Generic depth-damage relationships for residential structures with basements, Economic Guidance Memorandum (EGM) 04-01, USACE, 2003.

DHS: Estimating Economic Consequences for Dam Failure Scenarios, Dams Sector, US Department of Homeland Security, September 2011, 2011a.

DHS: Estimating Loss of Life for Dam Failure Scenarios, Dams Sector, US Department of Homeland Security, September 2011, 2011b.

Douben, K. J.: Characteristics of river floods and flooding: a global overview, 1985–2003, Irrigation Drainage, 55, S9–S21, 2006.

EC: Directive 2007/60/EC of the European Parliament and of the Council of 23 October 2007 on the assessment and management of flood risks, 2007.

EC: Directive 2008/114/EC of the European Parliament and of the Council of 8 December 2008 on the identification and designation of European critical infrastructures and the assessment of the need to improve their protection, 2008.

Escuder-Bueno, I., Morales-Torres, A., and Perales-Momparler, S.: Urban Flood Risk Characterization as a tool for planning and managing. Workshop Alexandria, March 2010: Exploration of Tolerable Risk Guidelines for Levee Systems, Washington DC (USA), available at: www.ipresas.upv.es, www.sufri.tugraz.at, 2010.

Escuder-Bueno, I., Castillo-Rodríguez, J. T., Perales-Momparler, S., and Morales-Torres, A.: SUFRI methodology for pluvial and river flooding risk assessment in urban areas to inform decision-making, SUFRI project, WP3, final report, July 2011, available at: www.sufri.tugraz.at, 2011a.

Escuder-Bueno, I., Castillo-Rodríguez, J. T., Perales-Momparler, S., and Morales-Torres, A.: A complete and quantitative tool for flood risk analysis in urban areas: river and pluvial flooding, Proceedings UFRIM Conference, Graz (Austria), September 2011, 2011b.

Gómez, M. and Russo, B.: Criterios de riesgo asociados a escorrentía urbana, Jornadas de Ingeniería del Agua, 2009 (in Spanish).

Graham, W. J.: A procedure for estimating loss of life caused by dam failure, DSO-99-06, US Department of Interior, Bureau of Reclamation, 1999.

Grossmann, G. and Seiser, T.: Final Report – Survey about risk awareness – SUFRI project, 2011 (unpublished report).
IEC/FDIS 31010, ISO International Standard: Risk management – Risk assessment techniques, IEC/FDIS 31010:2009 (E), 2009.
International Commission on Large Dams (ICOLD): Risk Assessment in Dam Safety Management: A Reconnaissance of Benefits, Methods and Current Applications, Bulletin130, 2005.
Jöbstl, C., Zechner, S., Knoblauch, H., Pohl, R., Bornschein, A., Natale, L., Petaccia, G., Escuder-Bueno, I., Castillo-Rodríguez, J. T., Perales-Momparler, S., Morales-Torres, A., Bateman, A., Medina, V., Díaz, A., Grossmann, G., Kulmhofer, A., and Seiser, T.: SUFRI – Sustainable Strategies of Urban Flood Risk Management with non-structural measures to cope with the residual risk, Final Report, Graz 2011, available at: www.sufri.tugraz.at, 2011.
Jonkman, S. N.: Global Perspectives on Loss of Human Life Caused by Floods, Nat. Hazards, 34, 151–175, 2003.
Messner, F., Penning-Rowsell, E., Green, C., Meyer, V., Tunstall, S., and van der Veen, A.: FLOODSITE Evaluating flood damages: guidance and recommendations on principles and methods, Report T09-06-01, January 2007.
Munger, D. F., Bowles, D. S., Boyer, D. B., Davis, D. W., Margo, D. A., Moser, D. A., Regan, P. J., and Snorteland, N.: Interim tolerable risk guidelines for US Army Corps of Engineers dams. In USSD Workshop on the future of dam safety decision making: combining standards and risk, April 2009.
Nanía, L.: Métodos de transformación lluvía-escorrentía y de propagación de caudales, Hidrología superficial y subterránea, Universidad de Granada, 2002 (in Spanish).
Parker, D., Tunstall, S., and Wilson, T.: Socio-economic benefits of flood forecasting and warning, Flood Hazard Research Centre, Middlesex University, Queensway, Enfield, EN3 4SF, London, UK, 2005.
Penning-Rowsell, E., Floyd, D., Ramsbottom, P., and Surendran, S.: Estimating injury and loss of life in floods: A deterministic framework, Nat. Hazards, 36, 43–64, 2005.
Reiter, P.: RESCDAM – Loss of life caused by dam failure, the RESCDAM LOL method and its application to Kyrkosjarvi dam in Seinajoki, Water Consulting Ltd., 2001.
Roos, M.: Flood management practice in northern California, Irrigation Drainage, 55, 93–99, 2006.
Samuels, P., Klijn, F., and Dijkman J.: An analysis of the current practice of policies on river flood risk management in different countries, Irrigation Drainage, 55, 141–150, 2006.
Sayers, P. B., Hall, J. W., and Meadowcroft, I. C.: Towards risk-based flood hazard management in the UK, Proceedings of ICE-Civil Engineering 150 May 2002, 36–42, Paper 12803, 2002.
Scawthorn, C., Flores, P.; Blais, N., Seligson, H., Tate, E., Chang, S., Mifflin, E., Thomas, W., Murphy, J., Jones, C., and Lawrence, M.: HAZUS-MH flood loss estimation methodology, II: Damage and Loss Assessment, Nat. Hazards Rev., 7, 72–81, 2006.
Schanze, J., Hutter, G., Olfert, A., Penning-Rowsell, E.C., Parker, D., Harries, T., Werritty, A., Nachtnebel, H., Holzmann, H., Neuhold, C., Meyer, V., Kuhlicke, C., Schildt, A., Jessel, B., and Königer, P.: FLOOD-ERA Joint Report, CRUE Research Report No I-1: Systematisation, evaluation and context conditions of structural and non-structural measures for flood risk reduction, Project Contract No: ERAC-CT-2004-515742, 2008.
Serrano-Lombillo, A., Escuder-Bueno, I., de Membrillera-Ortuño, M. G., and Altarejos-García, L.: iPresas – Software for risk analysis, 23rd International Congress on Large Dams, Brasilia, 2009.
Simonovic, S. P.: Social criteria for evaluation of flood control measures – Winnipeg case study, Urban Water, 1, 167–175, 1999.
Témez, J. R.: Extended and Improved Rational method, Highways Administration of Spain, XXIV Congress Madrid Edition, 1991 (in Spanish).
US Bureau of Reclamation (USBR): Risk Based Profiling System, Technical Service Center, 2001.
Vrijling, J. K.: Probabilistic design of water defence systems in The Netherlands, Reliab. Eng. Syst. Safe., 74, 337–344, 2001.
Zechner, S., Jöbstl, C., and Knoblauch, H.: SUFRI Methodology for investigation of risk awareness of the population concerned, SUFRI project, WP4, final report, December 2011.

This page intentionally left blank

Annex II: Municipal Action Plan against Flood Risk of Benaguasil

Annex VIII (May 2012)

This page intentionally left blank

Fecha Revisión Anexo VIII
23-05-2012

Anexo VIII

Descripción del análisis del riesgo por inundación en el municipio de Benaguasil

8.1. INTRODUCCIÓN

8.2. INUNDACIONES HISTÓRICAS

8.3. ANÁLISIS DEL RIESGO

8.4. ESTIMACIÓN CUALITATIVA DEL RIESGO

8.5. ESTIMACIÓN CUANTITATIVA DEL RIESGO

8.6. EFECTO DE MEDIDAS NO ESTRUCTURALES

Plano 8.1. **Identificación de zonas afectadas en eventos históricos.**
Plano 8.2. **Área urbana y subcuencas.**
Plano 8.3. **Identificación de zonas afectadas por inundación por precipitación «in situ» y por escorrentía, avenida o desbordamiento de cauces - Casco Urbano.**
Plano 8.4. **Identificación de zonas afectadas por inundación por escorrentía, avenida o desbordamiento de cauces según PATRICOVA - Término municipal.**

Página en blanco

Acrónimos

BNGx	Zonas identificadas en el casco urbano para la estimación del caudal de escorrentía
CD	Costes directos causados por la inundación (en euros)
CI	Costes indirectos causados por la inundación (en euros)
Cp	Categoría para el establecimiento de tasas de mortalidad asociadas a inundación por precipitación in situ (varía desde C_{p1} a C_{p3})
CT	Costes totales (en euros)
Cx	Categoría para el establecimiento de tasas de mortalidad asociadas a inundación por escorrentía, avenida o desbordamiento de cauces (varía desde C1 a C10)
d	Distancia igual a la mitad del ancho promedio de un bloque de viviendas en el municipio (aprox. 18 metros).
D	Diámetro (m)
f_C	Factor para el cálculo de costes totales por la inundación (en euros) en función de la relación entre costes directos e indirectos (igual a 1+CI/CD).
F	Probabilidad anual acumulada de excedencia de un determinado nivel de consecuencias por inundación
F-D	Acrónimo empleado para definir a las curvas que representan la probabilidad anual acumulada de excedencia, F, de un valor estimado de costes económicos por inundación, D (*damage*).
F-N	Acrónimo empleado para definir a las curvas que representan la probabilidad anual acumulada de excedencia, F, de un nivel de pérdida potencial estimada de vidas por inundación, N.
H	(*High*) Área de baja densidad de población
I	Intensidad de lluvia (mm/hora)
IDF	Intensidad-Duración-Frecuencia
L	(*Low*) Área de baja densidad de población
L	Longitud de calle considerada para el cálculo de costes económicos por inundación en los tramos de estudio
n	Coeficiente de rugosidad de Manning
N	Pérdida potencial estimada de vidas
PAM	Plan de Actuación Municipal
PATRICOVA	Plan de Acción Territorial de carácter sectorial frente al riesgo de inundación en la Comunitat Valenciana
P_d	Precipitación máxima en 24 horas
PD	Porcentaje de daños causado por la inundación
Q	Caudal (m^3/s)
S	Nivel de severidad de la inundación (desde S0 a S4)
SUFRI	*Sustainable Strategies for Urban Flood Risk management with non-structural measure to cope with the residual risk (2nd CRUE ERA-Net funding initiative)*
t	Tiempo
T	Periodo de retorno (en años)
T1	Primer escenario de inundación (periodo de retorno igual a 2 años)
T7	Séptimo escenario de inundación (periodo de retorno igual a 100 años)
U	(*Upstream*) Área situada en zonas no urbanizadas
v	Velocidad (m/s)
v_{100}	Velocidad del agua en un colector a sección llena (m/s)
w	Ancho de la calle
y	Calado o nivel alcanzado por el agua (m).

Página en blanco

8.1. Introducción

En este anexo se describe en detalle el análisis del riesgo por inundación efectuado para la elaboración del **Plan de Actuación Municipal (PAM)** del municipio de **Benaguasil**.

Este anexo incluye una descripción más amplia de los eventos de inundación registrados en el municipio y descritos de forma resumida en la memoria del presente PAM (apartado 2.2.2). Posteriormente, se describe el análisis del riesgo de inundación efectuado *ad hoc* como complemento a los estudios existentes, considerando tanto caracterización de avenidas como respuesta del sistema y potenciales consecuencias de la inundación.

Tal y como se indica en la memoria del PAM (apartado 2.2.1), la Directriz Básica de Planificación de Protección Civil ante el Riesgo de Inundaciones advierte la necesidad de considerar todas aquellas inundaciones que representen un riesgo, distinguiendo tres tipos de inundación:

a) por precipitación «in situ».
b) por escorrentía, avenida o desbordamiento de cauces.
c) por rotura o la operación incorrecta de obras de infraestructura hidráulica.

En el momento de redacción del presente PAM no es posible analizar el tercer tipo de inundación, pues el Plan de Emergencia de la Presa de Loriguilla, que es la primera presa que se encuentra aguas arriba del municipio (a una distancia aproximada de 50 km), está en trámites de aprobación. Cuando se incluya en el Plan Especial ante el Riesgo de Inundaciones de la Comunitat Valenciana, éste definirá qué municipios deben elaborar un procedimiento de actuación, en base a la normativa vigente. En ese momento, el presente PAM se actualizará en consecuencia.
Por tanto, se analizan los dos primeros tipos: el riesgo de inundación por precipitación «in situ» y por escorrentía, avenida o desbordamiento de cauces.

Atendiendo al segundo tipo de inundación, en el año 2002 se publicó y aprobó el Plan de Acción Territorial de Carácter sectorial sobre prevención del Riesgo de Inundación de la Comunitat Valenciana (PATRICOVA), incluyendo el análisis del riesgo de inundación por escorrentía, avenida o desbordamiento de cauces. Este estudio previo a la redacción del PAM se ha complementado con el análisis efectuado *ad hoc*, resumido en los apartados 2.2.2 a 2.2.5 de la memoria y detallado en este Anexo.

8.2. Inundaciones históricas

Inundación por precipitación «in situ»

El **Plano 8.1** recoge las áreas afectadas por eventos históricos de inundación por precipitación «in situ», identificadas por el Ayuntamiento de Benaguasil.

A partir de los datos de pluviometría disponibles, artículos de prensa local, fotografías e información aportada por el Ayuntamiento se ha elaborado la Tabla 8.1 que resume los eventos de precipitación más intensa de los últimos años en el municipio, a partir de los registros efectuados por la Confederación Hidrográfica del Júcar (CHJ) y una estación pluviométrica situada en el Ayuntamiento. Además, se recogen extractos de noticias de prensa y fotografías.

		PRECIPITACIÓN (mm) POR DÍA			
MES	**FECHA**	**RAMBLA CASTELLARDA**	**VILAMARXANT**	**AYTO.***	**IMAGEN/ NOTA DE PRENSA**
AGO. 2003	16/08/2003	2,9	0,2	71,0	Las Provincias 18/08/2003: *"…En Benaguasil, los vecinos se esforzaban durante toda la mañana por eliminar el agua que se había introducido en sus viviendas…"*
	17/08/2003	35,5	95,3	4,9	
OCT. 2006	16/10/2006	0,5	0,0	0,0	Diario crítico de la Comunidad Valenciana 18/10/2006: *"El temporal provoca un tornado, accidentes e inundaciones en Valencia. Una breve pero intensa tromba de agua y granizo afectó este miércoles a las comarcas de L'Horta, el Camp del Turia y la Plana Baja causando numerosos problemas….Las precipitaciones provocaron la inundación de algunas viviendas, campos y bajos en la Pobla de Vallbona, Llíria y Benaguasil. Las inundaciones registradas se han producido porque el sistema de alcantarillado no podía absorber el agua debido a la rapidez con la que se han producido las tormentas."*
	17/10/2006	0,2	0,0	0,0	
	18/10/2006	23,3	31,0	28,9	
MAY. 2008	31/05/2008	10,6	16,6	32,0	Benaguasil, 31 de mayo de 2008 (Figura 8.1)
OCT. 2008	09/10/2008	29,0	32,6	68	Benaguasil, 12 de octubre de 2008 (Figura 8.2)
	11/10/2008	0,2	0,2	36,8	
	12/10/2008	14,6	36,7	4,0	
	13/10/2008	35,0	24,5	26,0	
SEPT. 2009	10/09/2009	Sin dato		0,0	Benaguasil, 14 de septiembre de 2009 (Figura 8.3)
	11/09/2009			0,0	
	12/09/2009			3,5	
	13/09/2009			24,6	
	14/09/2009			18,3	
	15/09/2009			1	
	16/09/2009			1,8	
	17/09/2009			24,8	
	22/09/2009	1,0	0,5	1,1	
	23/09/2009	28,6	40,3	32,6	
	28/09/2009	13,7	13,7	0,0	
	29/09/2009	49,0	56,9	43,0	
	30/09/2009	5,5	15,6	0,0	

*De 7am del día de la fecha a 7am del día siguiente.

Tabla 8.1. Eventos históricos de inundación.

Figura 8.1. Ctra. de Vilamarxant, Benaguasil, el 31 de mayo de 2008. Fuente: Policía Local de Benaguasil.

Figura 8.2. Calle Pilota, Benaguasil, tras las lluvias ocurridas el 12 de octubre de 2008. Fuente: Policía Local de Benaguasil.

Figura 8.3.Plaza Major de la Vila, Benaguasil, durante las lluvias ocurridas el 14 de septiembre de 2009. Fuente: Ayuntamiento de Benaguasil.

Al analizar en detalle los registros de las estaciones Rambla Castellarda y Vilamarxant (CHJ) para los eventos del 31 de mayo de 2008 y el 12 de octubre de 2008, se observan intensidades máximas de 124 y 92 mm/h respectivamente (ambas en la estación de Vilamarxant), con volúmenes de precipitación de 15,1 mm en 20 minutos el 31 de mayo de 2008 y de 27,1 mm en media hora el 12 de octubre de 2008 (Tabla 8.2 y Tabla 8.3).

HORA	R. CASTELLARDA (mm)	VILAMARXANT (mm)
31/05/2008 17:55	1,68	0
31/05/2008 18:00	2,64	0,48
31/05/2008 18:05	4,32	2,64
31/05/2008 18:10	0,48	10,32
31/05/2008 18:15	0	1,68

Tabla 8.2. Registro en las estaciones *Rambla Castellarda* y *Vilamarxant*: 31 de mayo de 2008.

HORA	R. CASTELLARDA (mm)	VILAMARXANT (mm)
12-10-08 6:50	0,0	0,2
12-10-08 6:55	0,0	0,0
12-10-08 7:00	0,0	0,2
12-10-08 7:05	0,2	0,0
12-10-08 7:10	0,5	0,2
12-10-08 7:15	0,7	0,2
12-10-08 7:20	1,0	0,7
12-10-08 7:25	0,5	1,0
12-10-08 7:30	0,0	3,4
12-10-08 7:35	0,2	0,7
12-10-08 7:40	0,2	5,5
12-10-08 7:45	0,7	6,2
12-10-08 7:50	2,4	3,6
12-10-08 7:55	1,2	7,7

Tabla 8.3. Registro en las estaciones Rambla Castellarda y Vilamarxant: 12 de octubre de 2008.

Inundación por escorrentía, avenida o desbordamiento de cauces

Tal y como se describe en la memoria del PAM, no se dispone de información detallada sobre eventos históricos de inundación por escorrentía, avenida o desbordamiento de cauces.

8.3. Análisis del riesgo

8.3.1. Caracterización de avenidas

Inundación por precipitación «in situ»

Los escenarios de precipitación a considerar deben atender a los umbrales de aviso definidos por la Agencia Estatal de Meteorología (AEMET) para el establecimiento de los niveles de riesgo meteorológico (por precipitación, tormentas o temporal costero, según se detalla en el apartado 4.1.3 de la memoria del PAM). De este modo, los resultados obtenidos del rango de eventos de precipitación analizado pueden emplearse para la definición de las características de la inundación para cada nivel de riesgo meteorológico.

Para el municipio de Benaguasil, se definen **tres umbrales de aviso de referencia,** por considerarse los más significativos para el municipio de Benaguasil (Tabla 8.4):

- Umbral de aviso de nivel amarillo de riesgo meteorológico por lluvias
- Umbral de aviso de nivel naranja de riesgo meteorológico por lluvias
- Umbral de aviso de nivel rojo de riesgo meteorológico por tormentas (por presentar un valor de 60 mm en una hora, inferior al umbral de precipitación de 90 mm en una hora asociado al nivel rojo por lluvias, y, por tanto, más restrictivo que éste último).

Nivel	Umbral	Descripción
	20 mm en una hora	Umbral de aviso para el nivel **amarillo** de riesgo meteorológico por lluvias
	40 mm en una hora	Umbral de aviso para el nivel **naranja** de riesgo meteorológico por lluvias
	60 mm en una hora	Umbral de aviso para el nivel **rojo** de riesgo meteorológico por tormentas

Tabla 8.4. Umbrales de aviso de referencia.

Una vez definidos los umbrales de referencia, en el caso de Benaguasil se han estimado los valores de precipitación máxima en 24 horas (P_d) esperados para un rango de periodos de retorno (T) de 2 a 100 años (Tabla 8.5) con el fin de identificar el rango de eventos de precipitación a analizar. Una vez conocidos estos datos, se obtienen los valores de intensidad de precipitación asociados a una lluvia de 30 minutos de duración (Tabla 8.6) a partir de las curvas Intensidad-Duración-Frecuencia (IDF).

T (años)	2	5	10	15	25	50	100
P_d (mm)	53	79	98	110	125	146	170

Tabla 8.5. Precipitación máxima en 24 horas según periodo de retorno.

T (años)	2	5	10	15	25	50	100
Intensidad (mm/hora) para una lluvia de duración t=30 min	38	56	70	79	89	104	122

Tabla 8.6. Intensidad de precipitación en mm/hora para una lluvia de 30 minutos de duración.

Los tres umbrales seleccionados (correspondientes a eventos de precipitación de 20, 40 y 60 mm en una hora) equivalen a intensidades máximas de 40, 80 y 120 mm/hora si se considera un episodio de lluvias de 30 minutos de duración. Comparando estos valores con la Tabla 8.6 se establece que los eventos de precipitación asociados a dichos umbrales equivalen, aproximadamente, a eventos con periodos de retorno de 2, 15 y 100 años (pues presentan valores de 38, 79 y 122 mm/hora, próximos a 40, 80 y 120).

Por ello, un rango de 2 a 100 años es adecuado para el análisis de la respuesta del sistema y de las potenciales consecuencias de inundación en el municipio, ya que abarca los tres umbrales de referencia establecidos y para los cuales se elaborarán posteriormente los mapas de riesgo y procedimientos de actuación.

Por tanto, en el caso de Benaguasil se analizan *siete escenarios de precipitación* correspondientes a periodos de retorno de 2, 5, 10, 15, 25, 50 y 100 años, respectivamente. Para cada escenario de precipitación se evalúa la respuesta de la red de alcantarillado y las características hidráulicas de la inundación (extensión, velocidad y calado) en las zonas afectadas por la escorrentía superficial generada.

Inundación por escorrentía, avenida o desbordamiento de cauces

En base al análisis efectuado en el PATRICOVA para la zona del término municipal de Benaguasil, se consideran tres categorías de frecuencia de inundación según la siguiente clasificación (descrita en el PATRICOVA, así como en la Directriz Básica y en el Plan Especial):

- <u>Zonas de inundación frecuente</u>: zonas sometidas a inundaciones de periodo de retorno inferior a 50 años, o lo que es lo mismo, probabilidad de sufrir una inundación un año cualquiera igual o superior al 2%.
- <u>Zonas de inundación ocasional</u>: zonas que sufren inundaciones entre 50 y 100 años de periodo de retorno, es decir, probabilidad de inundación entre el 2% y el 1%.
- <u>Zonas de inundación excepcional</u>: zonas inundadas con crecidas de 100 hasta 500 años de periodo de retorno, con probabilidades de inundación entre el 1% y 0,2%.

A partir de estas tres categorías de frecuencia, el PATRICOVA define las áreas de afección por inundación por escorrentía, avenida o desbordamiento de cauces en el término municipal de Benaguasil (apartado 8.4, **Plano 8.4**).

8.3.2. Respuesta del sistema

Inundación por precipitación «in situ»

En este apartado se describen las características de la cuenca urbana, red de alcantarillado, puntos críticos, así como el análisis de la respuesta del sistema (cuenca-red), la escorrentía generada y las características de la inundación para los siete escenarios de precipitación.

Características de la cuenca urbana

El análisis de inundación por precipitación «in situ» requiere de la transformación de la lluvia caída sobre la cuenca, para cada escenario de precipitación, en la escorrentía generada, y posterior propagación del caudal, que puede ser captado por la red de alcantarillado o circular en superficie.

El área correspondiente a la cuenca urbana del municipio de Benaguasil se encuentra grafiada en el **Plano 8.2**. El área se ha dividido en seis subcuencas (Tabla 8.7) definidas en el **Plano 8.2**.

Sub-cuenca	Superficie (m²)
ÁREA 1	423.932
ÁREA 2	233.496
ÁREA 3	396.014
ÁREA 4	323.195
AREA 5	235.894
ÁREA 6	255.590

Tabla 8.7. Subcuencas en el área urbana de Benaguasil.

Dentro del casco urbano se han definido ocho zonas (identificadas con el prefijo BNG) en función de la subcuenca o subcuencas de aportación (por ejemplo, la zona *BNG1* del casco urbano corresponde al área afectada por la escorrentía generada por la precipitación caída en la subcuenca *Área 1*). La Tabla 8.8 muestra las subcuencas de aportación a cada una de las ocho zonas.

Zona	Sub-cuenca de aportación
BNG1	ÁREA 1
BNG2	ÁREA 2
BNG126	ÁREAS 1,2 y 6
BNG4	ÁREA 4
BNG45	AREAS 4 y 5
BNG3	ÁREA 3
BNG345	ÁREAS 3,4 y 5
BNG0	ÁREAS 1 a 6

Tabla 8.8. Zonas definidas en el casco urbano según sub-cuenca de aportación.

Para cada escenario de precipitación y zona se han obtenido los caudales de escorrentía aplicando el Método de Témez. Para ello, se ha empleado un factor de torrencialidad igual a 11,4 y un coeficiente de uniformidad temporal igual a 1.

Se distinguen tres tipos de superficie atendiendo a las características del suelo en relación a la propagación de escorrentía. Los tres tipos considerados son: suelo no urbanizado (U), urbano de baja densidad (L) y urbano de alta densidad (H), con valores del umbral de escorrentía de 23, 8 y 5 mm, respectivamente. Estas tres tipologías corresponden a valores del coeficiente de escorrentía (C) de 0,40, 0,75 y 0,85, para un periodo de retorno de 10 años, aproximadamente.

Los caudales de escorrentía obtenidos (en m^3/s) se muestran en la Tabla 8.9.

	Periodo de retorno (años)						
Zona	**2**	**5**	**10**	**15**	**25**	**50**	**100**
BNG1	2,90	5,26	7,08	8,26	9,74	11,85	14,27
BNG2	1,38	2,68	3,73	4,42	5,31	6,58	8,07
BNG126	4,22	7,71	10,42	12,18	14,40	17,55	21,19
BNG4	1,50	3,04	4,30	5,14	6,23	7,80	9,64
BNG45	2,83	5,31	7,27	8,55	10,17	12,49	15,18
BNG3	3,36	6,07	8,15	9,49	11,19	13,59	16,35
BNG345	4,99	9,18	12,44	14,56	17,24	21,06	25,47
BNG0	9,04	16,63	22,56	26,40	31,27	38,19	46,20

Tabla 8.9. Caudales de escorrentía en función del escenario de precipitación y zona.

Red de Alcantarillado y Capacidad de la red

La red de alcantarillado del municipio se ha descrito en el apartado 2.1.10 *Servicios Básicos* de la memoria. En los **Planos 1.7 y 1.8** del Anexo 4.1 pueden distinguirse las principales canalizaciones.

Una vez conocidos los caudales de escorrentía se ha procedido a la comprobación de la capacidad de la red de colectores del casco urbano. Para ello, se han seleccionado 13 tramos de la red, cuyas principales características se muestran en la Tabla 8.10.

Zona	Subzona del tramo de colector	Diámetro (m)	Coeficiente de rugosidad de Manning (n)	Velocidad a sección llena v (m/s)	Capacidad Q (m^3/s)
BNG1	L1a	0,40	0,011	4,53	0,57
BNG1	L1b	1,00	0,014	1,76	1,38
BNG1	H1	1,00	0,014	2,59	2,03
BNG2	L2	1,00	0,014	5,35	4,20
BNG2	H2	1,00	0,014	4,70	3,69
BNG3	L3	0,50	0,011	4,10	0,80
BNG3	H3	1,00	0,014	5,49	4,31
BNG4	L4	0,40	0,011	5,23	0,66
BNG5	L5	0,50	0,011	1,56	0,31
BNG5	H5	0,50	0,011	1,59	0,31
BNG126	L6	1,00	0,014	0,99	0,78
BNG345	H345	0,30	0,011	1,77	0,13
BNG0	U7	1,00	0,014	3,86	3,03

Tabla 8.10. Características de los principales tramos de la red de alcantarillado.

Comparando la capacidad de los colectores (Tabla 8.10) con los caudales de escorrentía obtenidos (Tabla 8.9) se comprueba que la red es incapaz de gestionar la escorrentía generada en la mayoría de escenarios de precipitación, a excepción de los tres primeros en la zona BNG2 (con una capacidad de 4,2 m^3/s).

Por tanto, los resultados muestran que la sobrecarga de la red es significativa para escenarios de muy bajo periodo de retorno y, por ello, se ha analizado en mayor detalle la inundación producida por precipitación «in situ» en diferentes zonas del casco urbano.

Identificación de puntos críticos

El **Plano 8.1** recoge las áreas afectadas por eventos históricos de inundación por precipitación «in situ», identificadas por el Ayuntamiento. A partir de la información proporcionada y las características de cada una de las ocho zonas, se han identificado 21 tramos de estudio en el municipio atendiendo a puntos de especial interés (áreas afectadas en eventos anteriores, estrechamientos o confluencia de calles con escorrentía procedente de diversas subcuencas).

La Tabla 8.11 muestra cada uno de los tramos de estudio, identificados en base a los puntos de la red de alcantarillado grafiados en los **Planos 1.7 y 1.8** del **Anexo 4.1**(como ejemplo, el tramo 1 equivale al tramo de calle que discurre sobre los puntos 849A a 840 de la red de alcantarillado).

Zona	Tramo	ID Tramo
BNG1	849A-840	1
BNG1	840-77	2
BNG1	73B-73E	2b
BNG1	77-65	3
BNG1	514-65	3b
BNG1	33-25	4
BNG1	33-73	4b
BNG2	11-14	5
BNG2	14-19	6
BNG2	19-25	7
BNG6	34-35	8
BNG23	438-442	8b
BNG3	172-178	9
BNG3	178-147	10
BNG3	125-122	11
BNG3	116-113	12
BNG7	86-49	13
BNG4	112-111	14
BNG5	111-109	14b
BNG5	105-103	15
BNG5	102-99	16

Tabla 8.11. Tramos de estudio.

Análisis de la escorrentía superficial y características hidráulicas de la inundación

Para cada uno de los 21 tramos se estiman los caudales máximos de escorrentía para cada escenario de precipitación y se obtienen los valores previstos de calado y velocidad del agua.

Para ello, se definen las diferentes subcuencas de aportación para cada tramo, incluyendo la diferenciación de las tres tipologías de uso del suelo (U, L y H) en función del coeficiente de escorrentía.

Las **Tabla 8.12** y **Tabla 8.13** muestran los valores de calado y velocidad obtenidos para cada tramo y periodo de retorno. En gris se muestran los casos en los que no se produce escorrentía superficial.

Calado, y (m)			Escenario de precipitación - Periodo de retorno (años)						
Zona	*Tramo*		2	5	10	15	25	50	100
BNG1	1	849A-840	0,00	0,00	0,03	0,04	0,06	0,08	0,10
BNG1	2	840-77	0,00	0,23	0,32	0,37	0,43	0,51	0,60
BNG1	2b	73B-73E	0,21	0,35	0,43	0,47	0,53	0,61	0,69
BNG1	3	77-65	0,00	0,06	0,09	0,11	0,13	0,16	0,19
BNG1	3b	514-65	0,06	0,11	0,14	0,16	0,17	0,20	0,23
BNG1	4	33-25	0,11	0,17	0,21	0,23	0,26	0,29	0,32
BNG1	4b	33-73	0,14	0,24	0,29	0,32	0,36	0,41	0,46
BNG2	5	11-14	0,00	0,00	0,00	0,00	0,00	0,07	0,14
BNG2	6	14-19	0,00	0,04	0,15	0,20	0,26	0,32	0,39
BNG2	7	19-25	0,00	0,09	0,18	0,23	0,28	0,34	0,41
BNG6	8	34-35	0,26	0,39	0,47	0,52	0,58	0,66	0,74
BNG23	8b	438-442	0,22	0,33	0,40	0,45	0,50	0,57	0,65
BNG3	9	172-178	0,06	0,14	0,18	0,21	0,24	0,29	0,33
BNG3	10	178-147	0,00	0,03	0,13	0,17	0,21	0,27	0,33
BNG3	11	125-122	0,00	0,12	0,21	0,26	0,31	0,38	0,44
BNG3	12	116-113	0,37	0,54	0,65	0,72	0,80	0,91	1,02
BNG7	13	86-49	0,18	0,36	0,49	0,57	0,66	0,77	0,90
BNG4	14	112-111	0,13	0,24	0,30	0,34	0,39	0,46	0,52
BNG5	14b	111-109	0,14	0,25	0,32	0,37	0,42	0,48	0,55
BNG5	15	105-103	0,19	0,26	0,32	0,36	0,40	0,46	0,52
BNG5	16	102-99	0,19	0,28	0,34	0,38	0,42	0,48	0,54

Tabla 8.12. Calado de inundación (y) para cada tramo de estudio.

Velocidad, v (m/s)			Escenario de precipitación - Periodo de retorno (años)						
Zona	*Tramo*		2	5	10	15	25	50	100
BNG1	1	849A-840	0,00	0,00	0,53	0,69	0,84	1,02	1,18
BNG1	2	840-77	0,00	0,59	0,73	0,80	0,88	0,97	1,06
BNG1	2b	73B-73E	0,63	0,85	0,97	1,03	1,11	1,20	1,30
BNG1	3	77-65	0,00	0,16	0,34	0,39	0,44	0,50	0,56
BNG1	3b	514-65	0,77	1,15	1,34	1,44	1,56	1,70	1,84
BNG1	4	33-25	0,55	0,72	0,81	0,87	0,92	1,00	1,07
BNG1	4b	33-73	0,47	0,65	0,74	0,79	0,85	0,92	0,99
BNG2	5	11-14	0,00	0,00	0,00	0,00	0,00	0,77	1,16
BNG2	6	14-19	0,00	0,37	0,94	1,13	1,32	1,53	1,72
BNG2	7	19-25	0,00	0,85	1,32	1,52	1,72	1,96	2,19
BNG6	8	34-35	0,78	0,99	1,12	1,18	1,26	1,36	1,46
BNG23	8b	438-442	0,27	0,35	0,39	0,42	0,44	0,47	0,51
BNG3	9	172-178	0,53	0,95	1,16	1,26	1,38	1,53	1,68
BNG3	10	178-147	0,00	0,48	1,25	1,50	1,75	2,02	2,28
BNG3	11	125-122	0,00	1,06	1,53	1,74	1,96	2,21	2,45
BNG3	12	116-113	1,32	1,65	1,84	1,94	2,06	2,20	2,35
BNG7	13	86-49	1,25	1,65	1,80	1,88	1,98	2,11	2,25
BNG4	14	112-111	0,57	0,84	0,99	1,07	1,16	1,27	1,38
BNG5	14b	111-109	0,40	0,43	0,47	0,49	0,52	0,56	0,59
BNG5	15	105-103	0,37	0,46	0,52	0,56	0,61	0,66	0,72
BNG5	16	102-99	0,42	0,54	0,61	0,65	0,70	0,76	0,82

Tabla 8.13. Velocidad del agua (v) para cada tramo de estudio.

Identificación de zonas afectadas

El **Plano 8.3** recoge las áreas afectadas por inundación por precipitación «in situ» a partir del análisis realizado de la respuesta del sistema.

La definición de las zonas afectadas se efectúa en base a tres rangos del calado de inundación:

- Calado inferior a 0,15 m: El área de afección considerada se corresponde con la superficie del tramo o tramos de calle inundados. No se consideran afecciones a viviendas.
- Calado entre 0,15 y 0,45 m: Se considera la afección a viviendas situadas a lo largo del tramo de estudio afectado.
- Calado superior a 0,45 m: Se considera la afección a viviendas situadas no solo a lo largo del tramo de estudio sino también a edificios o viviendas situados en las proximidades.

Inundación por escorrentía, avenida o desbordamiento de cauces

Características de la cuenca

Las características de la cuenca a considerar se describen en el apartado *2.1.2 Localización en la cuenca. Red Hidrográfica* de la memoria del PAM, grafiadas en los **Planos 1.1, 1.2 y 1.3** del **Anexo 4.1.**

Características hidráulicas de la inundación

Según los criterios del PATRICOVA, el riesgo de inundación por escorrentía, avenida o desbordamiento en cauces se clasifica atendiendo a la combinación de tres niveles de frecuencia (apartado 8.3.1) y dos niveles de calados de inundación, distinguiendo:

- Calados bajos: en general, el nivel de agua esperado en la zona de inundación es inferior a 80 centímetros. Aunque se pueden producir vías preferentes de flujo con fuertes daños, en general las pérdidas económicas son limitadas y las medidas a adoptar para disminuirlas serán sencillas.
- Calados altos: el nivel esperado es superior a los 80 centímetros. En este caso los daños comienzan a ser muy importantes.

Identificación de zonas afectadas

Los estudios del PATRICOVA identifican, según se recoge en los **Planos 8.3 y 8.4**, dos zonas de inundación por desbordamiento de cauces en el término municipal de Benaguasil que son:

• Zona A: corresponde a la zona de influencia del cauce del río Turia y de sus ramblas. Esta zona se encuentra alejada del casco urbano. El área afectada corresponde a una zona predominante agraria con presencia de viviendas aisladas y una cantera situada junto a la confluencia de la Rambla Castellarda con el río Turia.

• Zona B: abarca el área del Barranco de Benaguasil (conocido en el municipio como Barranquet), en su discurrir por el norte-noreste del casco urbano. El área afectada correspondería al complejo polideportivo municipal, piscina cubierta y viviendas del sector residencial de la C/ Pablo II el Ceremonioso, según **Plano 8.3**.

Esta zona corresponde con el área potencialmente inundable por un pequeño barranco que discurre por el norte del término municipal (con tramos en el término de Llíria), cuyo trazado y características se han visto modificados por la construcción de la variante de Benaguasil (autovía CV-50). Actualmente puede considerarse que comienza como una cuneta de dicha autovía, y discurre por el norte de la misma hasta que la cruza a la altura del polideportivo municipal. A partir de dicho cruce, es conducido por un pequeño canal abierto que discurre por el sur del campo de fútbol, y desemboca en un terreno de cultivo al norte del polígono industrial que hay en esa zona.

El área afectada para las zonas A y B se muestra en la tabla siguiente.

Zona	Subzona	Descripción	Uso	Superficie (m²)
A	A1	Zona Bco. del Tollo	Varios	184.278
A	A2	Zona Cauce y Rambla Castellana	Varios	369.361
A	A3	Tras Rambla Escarihuela	Varios	1.000.094
B	B1	Barranco Benaguasil Viviendas	Residencial	28.633
B	B2	Barranco Benaguasil Polig. Ind.	Industrial	19.424
B	B3	Barranco Benaguasil Polideportivo	Equipamientos	30.074

Tabla 8.14. Zonas afectadas identificadas en el PATRICOVA.

8.3.3. Consecuencias

En este apartado se describe la estimación de consecuencias de inundación por precipitación «in situ» y escorrentía, avenida o desbordamiento de cauces, como parte del análisis del riesgo de inundación en Benaguasil.

Cabe mencionar que para la estimación de daños se ha tenido en cuenta el Catálogo de Bienes y Espacios Protegidos presentado en el Plan General de Ordenación Urbana de Benaguasil, considerándose que éstos no se verían afectados de forma considerable por la inundación.

Inundación por precipitación «in situ»

Resumen de la metodología de estimación de consecuencias

El análisis de consecuencias de inundación por precipitación «in situ» se basa en la metodología propuesta a tal efecto en el proyecto SUFRI[1] (*Sustainable Strategies of Urban*

[1] SUFRI Project. Escuder-Bueno *et al*, 2011. WP3 Final Report. (www.sufri.tugraz.at)

Flood Risk Management with non-structural measures to cope with the residual risk), proyecto europeo desarrollado entre 2009 y 2011, cuyo principal objetivo es mejorar la gestión de riesgos de inundación mediante la utilización de medidas no estructurales. Este proyecto describe la metodología a desarrollar para el cálculo del riesgo de inundación tanto por escorrentía, avenida o desbordamiento de cauces como por precipitación «in situ».

En el caso del análisis del riesgo de inundación por precipitación «in situ», para la estimación de la *pérdida potencial de vidas* asociada a la inundación, la metodología propone una clasificación de cinco niveles de severidad de la inundación en función de las características de calado y velocidad, así como tres categorías para el municipio de estudio en base a la existencia de sistemas de aviso a la población. Cada una de estas categorías se asocia a valores diferentes de *tasas de mortalidad* en función del grado de *severidad de la inundación* obteniendo la pérdida potencial estimada de vidas como el producto de la población expuesta a la inundación y la tasa de mortalidad asociada. Por otra parte, los *costes económicos* pueden estimarse a partir de valores de referencia en función del uso del suelo y del grado de destrucción a partir de curvas calado-daños.

Pérdida potencial estimada de vidas

Niveles de severidad de la inundación

La definición de la severidad de la inundación por precipitación «in situ» se basa en una clasificación que atiende a cuatro variables: calado de inundación (y), velocidad del flujo (v), y a dos parámetros adicionales, siendo éstos el producto "velocidad·calado" y el producto "velocidad^2·calado" según la Tabla 8.15.

	Nivel de severidad (S0-S4)	***Calado y(m)***	***Velocidad v(m/s)***	***Parámetro Vuelco v·y (m²/s)***	***Parámetro Deslizamiento v²·y (m³/s²)***
S0	No se esperan víctimas	<0,45	<1,50	<0,50	<1,23
S1	*Severidad leve.* Peatones pueden sufrir pérdida de estabilidad y dificultades para caminar.	<0,80	<1,60	<1,00	<1,23
S2	*Severidad media.* Significativas pérdidas de estabilidad. Vehículos pierden adherencia.	<1,00	<1,88	<1,00	<1,23
S3	*Severidad elevada.* Alto riesgo para personas situadas en el exterior. Arrastre de vehículos.	>1,00	>1,88	>1,00	>1,23
S4	*Severidad extrema.* Daños estructurales a edificios.	>1,00	>1,88	>3,00	>1,23

Tabla 8.15. Niveles de severidad de la inundación por precipitación «in situ» (proyecto SUFRI).

El establecimiento de los cinco niveles de severidad (S0 a S4) se basa en criterios existentes en la literatura, entre los que destaca el que depende de las condiciones de estabilidad de personas expuestas al flujo del agua en términos de deslizamiento, arrastre y vuelco[2]. La Figura 8.4 muestra la distribución del nivel de severidad de la inundación por precipitación «in situ» en función del calado y velocidad.

[2] Gómez y Russo, 2009.

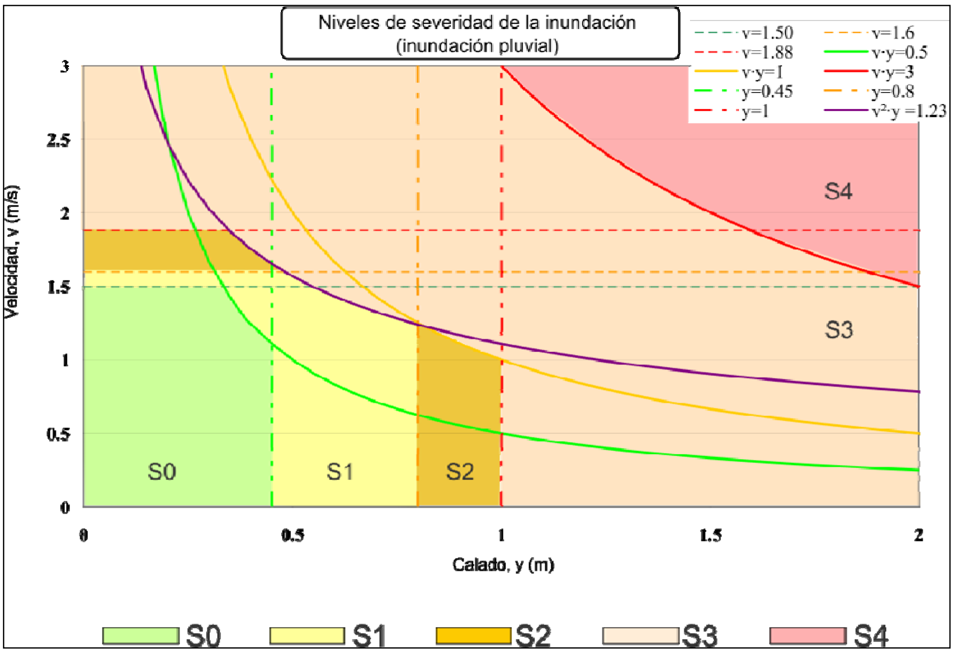


Figura 8.4. Niveles de severidad de inundación por precipitación «in situ» (proyecto SUFRI).

Siguiendo esta clasificación pueden identificarse los niveles de severidad esperados para cada uno de los 21 tramos de estudio en cada escenario de precipitación.
A continuación se muestran los resultados obtenidos de calado y velocidad del agua para cada tramo y escenario de precipitación representados en combinación con los criterios de la Figura 8.4.

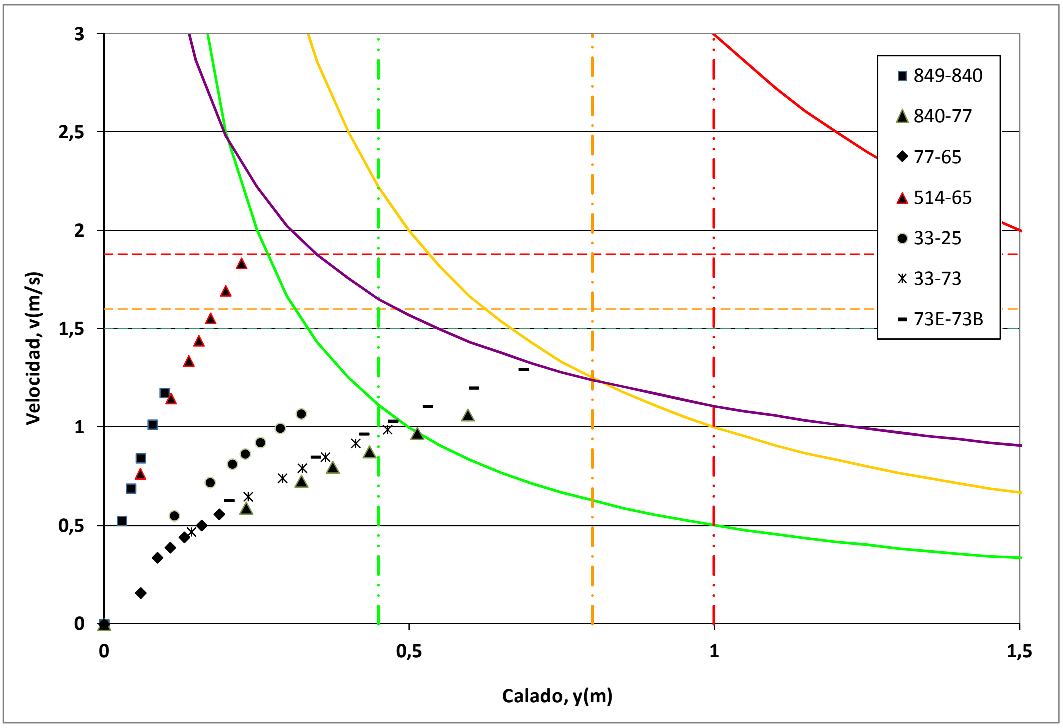


Figura 8.5. Calado y velocidad para cada escenario de precipitación para los tramos 1 a 4b.

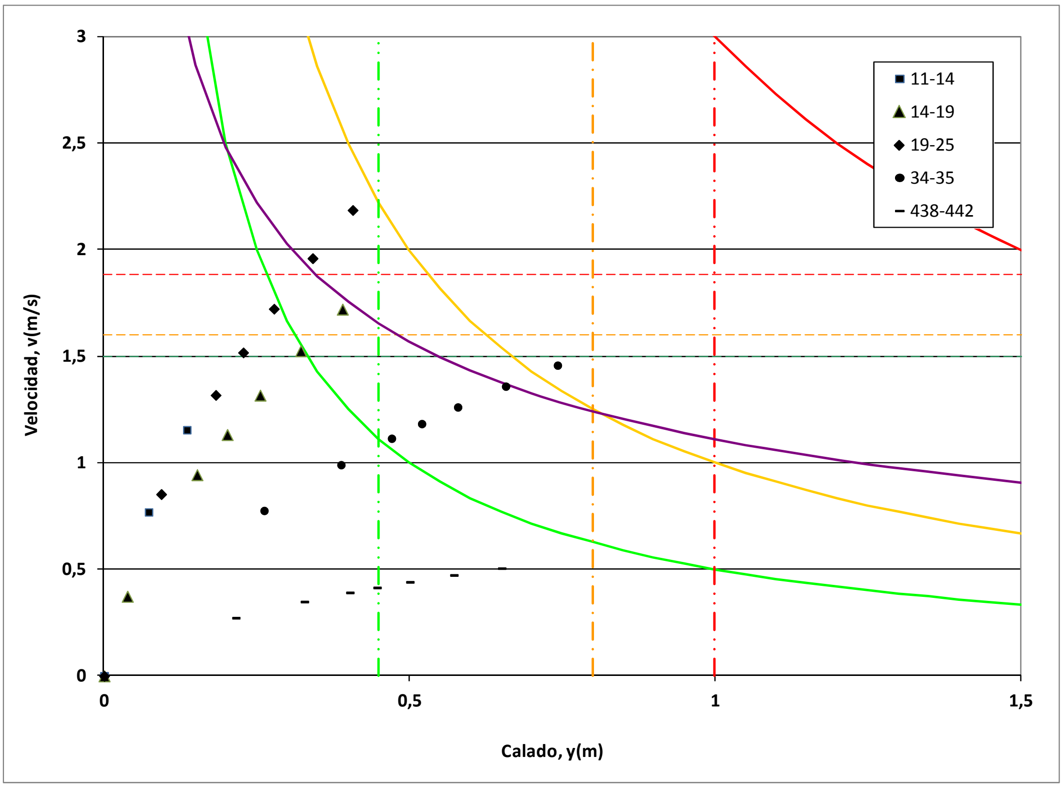


Figura 8.6. Calado y velocidad para cada escenario de precipitación para los tramos 5 a 8b.

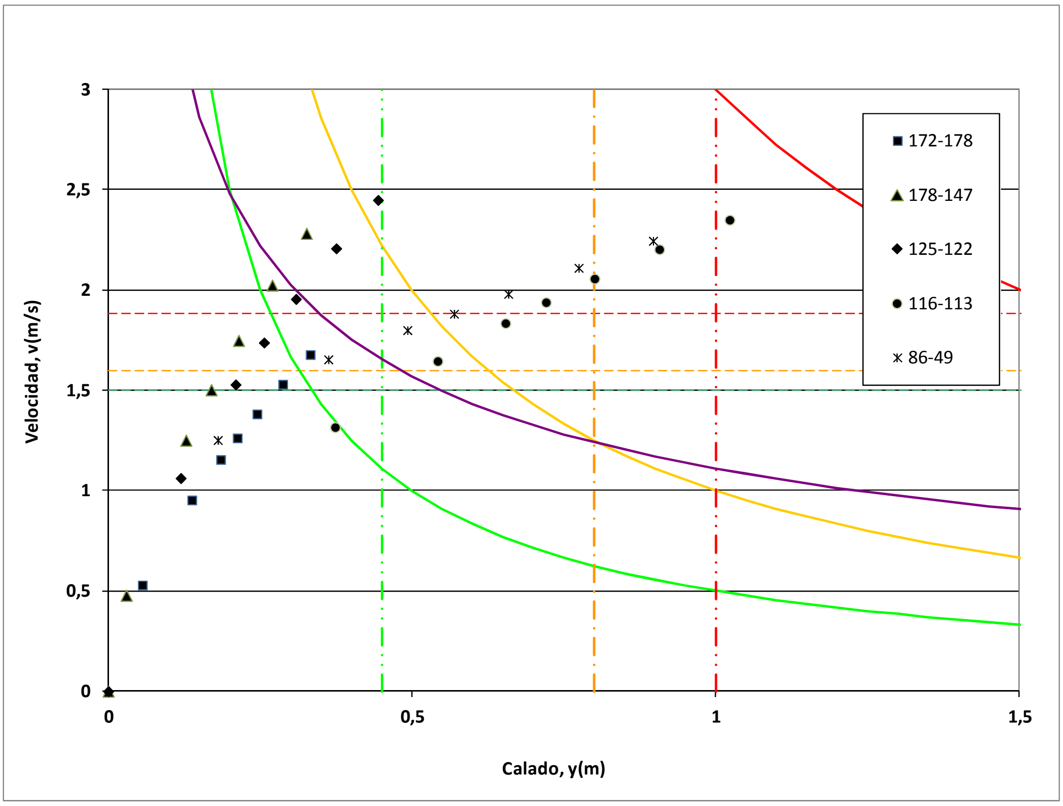


Figura 8.7. Calado y velocidad para cada escenario de precipitación para los tramos 9 a 13.

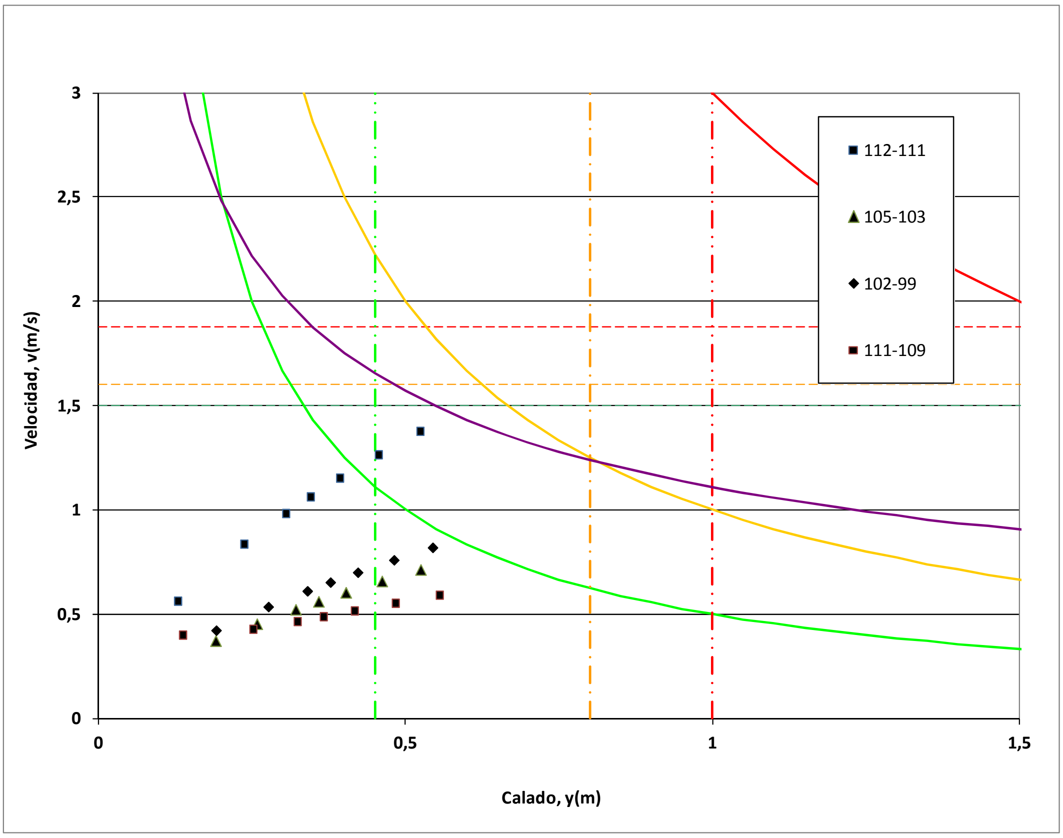


Figura 8.8. Calado y velocidad para cada escenario de precipitación para los tramos 14 a 16.

La Tabla 8.16 muestra los niveles de severidad de inundación obtenidos en cada caso (donde los números 0, 1, 2, etc. denotan los niveles de severidad S0, S1, S2…; las casillas en gris indican que no se produce escorrentía en el tramo para dicho escenario de precipitación).

Zona	Tramo		Periodo de retorno (años)						
			2	5	10	15	25	50	100
BNG1	1	849A-840			0	0	0	0	0
BNG1	2	840-77		0	0	0	0	1	1
BNG1	2b	73B-73E	0	0	0	1	1	1	1
BNG1	3	77-65		0	0	0	0	0	0
BNG1	3b	514-65	0	0	0	0	1	2	2
BNG1	4	33-25	0	0	0	0	0	0	0
BNG1	4b	33-73	0	0	0	0	0	0	0
BNG2	5	11-14						0	0
BNG2	6	14-19		0	0	0	0	1	2
BNG2	7	19-25		0	0	1	2	3	3
BNG6	8	34-35	0	0	0	0	1	1	3
BNG23	8b	438-442	0	0	0	0	1	1	1
BNG3	9	172-178	0	0	0	0	0	1	2
BNG3	10	178-147		0	0	1	2	3	3
BNG3	11	125-122		0	1	2	3	3	3
BNG3	12	116-113	0	3	3	3	3	3	3
BNG7	13	86-49	0	2	3	3	3	3	3
BNG4	14	112-111	0	0	0	0	0	1	1
BNG5	14b	111-109	0	0	0	0	0	1	1
BNG5	15	105-103	0	0	0	0	0	1	1
BNG5	16	102-99	0	0	0	0	0	1	1

Tabla 8.16. Niveles de severidad para cada tramo de estudio.

Tasas de mortalidad

Para el establecimiento de las tasas de mortalidad a aplicar, la metodología SUFRI presenta tres categorías (C_{p1}, C_{p2} y C_{p3}) asociadas a la existencia de sistemas de aviso a la población. El municipio de Benaguasil no dispone de sistemas de aviso, por lo que pertenece a la categoría C_{p1}. La Tabla 8.17 muestra las tasas de mortalidad asociadas a cada nivel de severidad de la inundación para la categoría C_{p1}.

Nivel de severidad	S0	S1	S2	S3	S4
Tasa de mortalidad (a aplicar a la población expuesta)	0,0003	0,0021	0,0038	0,0105	0,0448

Tabla 8.17. Tasas de mortalidad para la categoría Cp1.

Personas afectadas

La población potencialmente expuesta a la inundación se estima según el área del municipio asociada a cada uno de los 21 tramos, obteniendo la población residente, y un factor de exposición (porcentaje de población que puede encontrarse expuesta a la inundación durante el evento de precipitación) que depende del entendimiento de la población, del momento del día (según sea de día o de noche) y la estación del año.

Los valores de densidad de población y factores de exposición empleados se muestran en la Tabla 8.18 (donde TC1 indica la categoría verano-día, TC2 indica verano-noche, TC3 equivale a invierno-día y TC4 a invierno-noche).

Categoría	TC1	TC2	TC3	TC4
Densidad de población (habitantes/km^2)	9.227	9.390	9.065	9.227
Factor de exposición (f)	0,2	0,02	0,1	0,01
Factor de exposición (población expuesta respecto de población total)	20%	2%	10%	1%

Tabla 8.18. Factores de exposición según categoría de tiempo.

La población residente se obtiene como el producto de la superficie definida por la densidad de población. El número de personas potencialmente expuestas a la inundación para cada tramo se estima como el producto del factor de exposición y la población residente.

La Tabla 8.19 resume las áreas consideradas para el cálculo así como el número de personas potencialmente afectadas por la inundación en cada tramo, para la categoría más desfavorable (verano-día) en cada tramo de estudio para los escenarios de precipitación de 2, 15 y 100 años. Estos valores se muestran en los planos 2.1.1 a 2.3.3 del **Anexo IV**.

Zona	Tramo	Área para el cálculo de población residente (m^2)	Periodo de retorno (años)		
			2	15	100
BNG1	849A-840	33160	0	61	61
BNG1	840-77	10990	0	20	20
BNG1	73B-73E	14555	27	27	27
BNG1	77-65	16700	0	31	31
BNG1	514-65	16760	31	31	31
BNG1	33-25	14850	27	27	27
BNG1	33-73	13380	25	25	25
BNG2	11-14	15570	0	0	29
BNG2	14-19	27770	0	51	51
BNG2	19-25	42270	0	78	78
BNG6	34-35	7980	15	15	15
BNG23	438-442	8590	16	16	16
BNG3	172-178	8510	16	16	16
BNG3	178-147	27650	0	51	51
BNG3	125-122	16375	0	30	30
BNG3	116-113	23430	43	43	43
BNG7	86-49	26410	49	49	49
BNG4	112-111	27360	50	50	50
BNG5	111-109	0 (se considera integrada en el tramo anterior)	0	0	0
BNG5	105-103	34970	65	65	65
BNG5	102-99	0 (se considera integrada en el tramo anterior)	0	0	0

Tabla 8.19. Personas potencialmente expuestas a la inundación para cada tramo.

Como ejemplo, el tramo 1 (849A-840) presenta un área asociada igual a 33.160 m², lo que corresponde a un total de 306 habitantes en la categoría verano-día. Para un factor de exposición del 20%, el número estimado de personas potencialmente afectadas por la inundación en el tramo 1 sería de 61.

Número de víctimas

Conocido el número de personas potencialmente expuestas a la inundación (Tabla 8.19), aplicando las tasas de mortalidad asociadas al nivel de severidad de inundación de cada escenario de precipitación, puede obtenerse la estimación del pérdida potencial de vidas por inundación.

La Tabla 8.20 muestra los resultados obtenidos para las cuatro categorías de tiempo contempladas (TC1 a TC4).

	Periodo de retorno (años)						
Categoría	**2**	**5**	**10**	**15**	**25**	**50**	**100**
TC1	0	1	1	2	2	3	4
TC2	0	0	0	0	0	0	0
TC3	0	0	1	1	1	2	2
TC4	0	0	0	0	0	0	0

Tabla 8.20. Pérdida potencial estimada de vidas.

Pérdidas económicas estimadas

La estimación de los costes económicos de la inundación se obtiene como la suma de costes directos e indirectos. Los costes directos se obtienen como el producto de un valor de referencia (en euros por metro cuadrado) según el uso del suelo, el porcentaje de daños producido (que depende del calado de la inundación) y el área afectada. La relación entre los costes directos esperados y los costes indirectos se establece en función de la actividad económica del municipio y su relevancia a nivel regional o nacional. Para el caso de Benaguasil, los costes indirectos se estiman en un 27% de los costes directos.

Valor del uso del suelo

El valor de referencia (CR) en euros por metro cuadrado depende del uso del suelo. Para el caso de Benaguasil, en base a datos recogidos en el PATRICOVA, se establece un valor de 55,5 €/m² para uso residencial (valor medio para uso residencial de media densidad) y 16,7 €/m² para uso industrial.

Áreas de afección

Para cada uno de los tramos analizados se establece una superficie de afección (A_{af}) para la estimación de las potenciales consecuencias económicas de la inundación, distinguiendo tres rangos de calado:

- Calado inferior a 0,15 m: El área considerada es igual al producto de la longitud del tramo (L) y ancho de la calle (w), pues no se consideran afecciones a viviendas o locales.
- Calado entre 0,15 y 0,45 m: Se considera afección a los bloques de viviendas del propio tramo, definiendo el área como L·(w+2d) donde d es la mitad del ancho

promedio de un bloque de viviendas. Para el municipio de Benaguasil, se establece un valor igual a 18 metros.

- Calado superior a 0,45 m: Se considera afección a bloques de viviendas de calles adyacentes, definiendo el área como L·(w+5d).

Porcentaje de daños

El porcentaje de daños (PD) se obtiene de la curva calado-daños propuesta en el PATRICOVA (Figura 8.9). Esta curva relaciona el nivel del agua alcanzado por la inundación con un porcentaje o grado de destrucción de los bienes afectados (con respecto al valor de referencia asociado al uso del suelo).

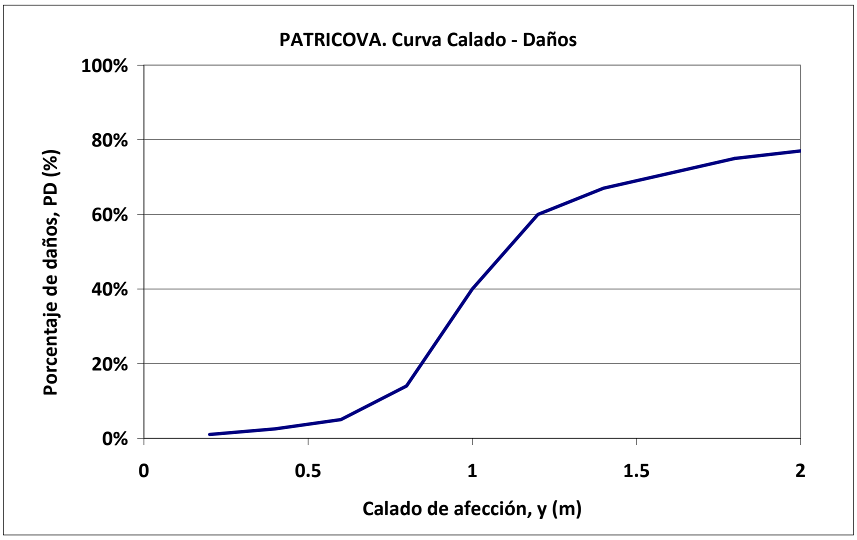


Figura 8.9. Porcentaje de daños (PD) en función del calado de afección (y). Fuente: PATRICOVA (2003).

Costes totales

Los costes directos se obtienen como el producto del área de afección, el porcentaje de daños y el valor de referencia. Los costes indirectos se estiman como una fracción de los costes directos (f_C igual a 1.27). Por tanto, los costes totales de la inundación (CT) se obtienen aplicando la siguiente ecuación para cada tramo de estudio:

$$CT = f_C \cdot CR \cdot A_{af} \cdot PD \qquad (1)$$

Agrupando los costes de todos los tramos, la Tabla 8.21 muestra los costes totales para cada escenario de inundación.

Periodo de retorno (años)	2	5	10	15	25	50	100
Costes totales (CT) en euros	35.047	111.210	218.279	284.981	380.877	649.916	1.027.565

Tabla 8.21. Pérdidas económicas estimadas.

Inundación por escorrentía, avenida o desbordamiento de cauces

Resumen de la metodología de estimación de consecuencias

La metodología planteada para el análisis de consecuencias de inundación por escorrentía, avenida o desbordamiento de cauces se basa en una combinación de los criterios propuestos por el Plan Especial ante el Riesgo de Inundaciones en la Comunitat Valenciana y la metodología de análisis del riesgo del proyecto SUFRI. A partir de la clasificación establecida por el Plan Especial y las zonas identificadas en los Planos 8.3 y **8.4**, se analizan las consecuencias de la inundación siguiendo las recomendaciones del proyecto SUFRI para el cálculo de consecuencias potenciales en las zonas afectadas, que dependen de la población en riesgo, la severidad de la inundación y valor de uso del suelo, entre otros factores.

Cabe destacar que el estudio en el que se basa el PATRICOVA fue realizado con anterioridad a la construcción del nuevo tramo de autovía de la CV-50 que circula por el norte del municipio, por lo que la afección al casco urbano en esa zona se prevé diferente en la actualidad. Para la redacción del presente PAM no se ha reevaluado dicha afección, según se justifica en el apartado 2.2.1.*Estudios previos* de la memoria del PAM.

Pérdida potencial estimada de vidas

Zonas de afección

En los **Planos 8.3** y 8.4 se muestran las áreas de afección identificadas por el PATRICOVA.

La Tabla 8.22 incluye la superficie afectada por uso del suelo para cada una de las zonas identificadas en el PATRICOVA.

				Área afectada por uso del suelo (m²)			
Zona	**PERIODO DE RETORNO (años)**	**CALADO (m)**	**AFECCIONES**	**RESIDENCIAL**	**INDUSTRIAL**	**EQUIP.**	**AGRÍCOLA**
A	<5	>0.8	SI	3,130	135,000	-	514,403
B	<25	<0.8	SI	28,633	19,424	30,074	-
C	>100	<0.8	NO	-	-	-	-

Tabla 8.22. Afecciones por inundación por escorrentía, avenida o desbordamiento de cauces.

La zona A corresponde al área de influencia del cauce del río Turia y sus afluentes (Ramblas Castellarda y Escarihuela). Entre las afecciones identificadas se encuentra un número reducido de viviendas aisladas (un total de 20 viviendas), identificadas por comparación del área inundada definida por el PATRICOVA y la información disponible en el Visor Web de Cartografía de la Conselleria d'Infrastructures, Territori i Medi Ambient (CITMA). El área de afección de la zona A incluye también una cantera situada junto a la confluencia del río Turia con la Rambla Castellarda. El área de afección restante es de uso predominantemente agrícola. Estas áreas están identificadas con una frecuencia de inundación inferior a 25 años y un calado superior a 0,80 m.

Figura 8.10. Imagen del entorno de la Rambla Castellarda. Fuente: Visor Web del CITMA.

La zona B corresponde con el área de influencia del Barranco de Benaguasil y produce afecciones al casco urbano en la zona situada junto al polideportivo municipal, identificada con una frecuencia de inundación inferior a 25 años y un calado inferior a 0,80 m.

La zona C se sitúa fuera del término municipal de Benaguasil.

Tasas de mortalidad

Según la metodología SUFRI, el municipio debe clasificarse entre una de las diez categorías establecidas en función del nivel de comunicación y aviso a la población existente, coordinación entre servicios de emergencia y autoridades, existencia de Planes de Emergencia, etc. La Tabla 8.23 muestra dicha clasificación, donde el municipio de Benaguasil se clasifica dentro de la categoría C5.

Categoría		t aviso TA (h)	Severidad (Sv) Alta	Media	Baja
1	- No existe formación a la población. - No se dispone de sistemas de aviso ni PEP. - No hay coordinación entre servicios de emergencia y autoridades. - No existen medios de comunicación a la población.	*0*	0.9	0.3	0.02
		0.25	0.9	0.3	0.02
		0.625	0.7	0.08	0.015
		1	-	0.06	0.0006
		1.5	-	0.0002	0.0002
		24	-	0.0002	0.0001
2	- No existe formación a la población. - **No se dispone de PEP,** aunque existen otros sistemas de aviso. - No hay coordinación entre servicios de emergencia y autoridades. - No existen medios de comunicación a la población.	*0*	0.9	0.3	0.02
		0.25	0.9	0.3	0.02
		0.625	0.675	0.075	0.014
		1	-	0.055	0.00055
		1.5	-	0.0002	0.0002
		24	-	0.0002	0.0001
3	- No existe formación a la población. - Existe PEP, pero **no se ha implantado.** - Existe **coordinación** entre servicios de emergencia y autoridades (no existen protocolos). - No existen medios de comunicación a la población.	*0*	0.9	0.3	0.02
		0.25	0.85	0.2	0.015
		0.625	0.6	0.07	0.012
		1	-	0.05	0.0005
		1.5	-	0.0002	0.0002
		24	-	0.0002	0.0001
4	- No existe formación a la población. **- PEP implantado con sistemas de aviso correspondientes.** - Existe coordinación entre servicios de emergencia y autoridades, **protocolos** de comunicación. - No existen medios de comunicación a la población.	*0*	0.9	0.3	0.02
		0.25	0.75	0.15	0.01
		0.625	0.5	0.04	0.007
		1	-	0.03	0.0003
		1.5	-	0.0002	0.0002
		24	-	0.0002	0.0001
5	- No existe formación a la población. - PEP implantado con sistemas de aviso correspondientes. - Coordinación entre servicios de emergencia y autoridades. - Medios de **comunicación** a la población (sin comprobar).	*0*	0.9	0.3	0.02
		0.25	0.75	0.15	0.01
		0.625	0.5	0.0375	0.0065
		1	-	0.0275	0.000275
		1.5	-	0.0002	0.0002
		24	-	0.0002	0.0001
6	- No existe formación a la población. - PEP implantado con sistemas de aviso correspondientes. - Coordinación entre servicios de emergencia y autoridades. - Medios de **comunicación** a la población **implantados.**	*0*	0.9	0.3	0.02
		0.25	0.75	0.15	0.01
		0.625	0.475	0.035	0.006
		1	-	0.025	0.00025
		1.5	-	0.0002	0.0002
		24	-	0.0002	0.0001
7	- **Formación** a la población. - PEP implantado con sistemas de aviso. - Coordinación entre servicios de emergencia y autoridades. - Medios de comunicación a la población implantados. *****Si se produce rotura instántanea en categorías 8, 9 y 10.**	*0*	0.9	0.3	0.02
		0.25	0.65	0.1	0.0075
		0.625	0.4	0.02	0.002
		1	-	0.01	0.0002
		1.5	-	0.0002	0.0002
		24	-	0.0002	0.0001
8	- Formación a la población. - PEP implantado. **Simulacros o PEP empleado prev.** - Coordinación entre servicios de emergencia y autoridades. - Medios de comunicación a la población implantados.	*0*	0.9	0.3	0.02
		0.25	0.55	0.06	0.006
		0.625	0.35	0.01	0.0015
		1	-	0.005	0.00015
		1.5	-	0.0002	0.00015
		24	-	0.0002	0.0001
9	- Formación a la población. - PEP implantado. Simulacros o PEP empleado prev. - **Alta** coordinación entre servicios de emergencia y autoridades. - Medios de comunicación a la población implantados.	*0*	0.9	0.3	0.02
		0.25	0.55	0.06	0.006
		0.625	0.35	0.008	0.0015
		1	-	0.004	0.000125
		1.5	-	0.0002	0.0001
		24	-	0.0002	0.0001
10	- Planes de **formación continua** a la población. - PEP implantado. Simulacros o PEP empleado prev. - Alta coordinación entre servicios de emergencia y autoridades. - Medios de comunicación a la población implantados.	*0*	0.9	0.3	0.02
		0.25	0.5	0.03	0.005
		0.625	0.3	0.005	0.001
		1	-	0.002	0.0001
		1.5	-	0.0002	0.0001
		24	-	0.0002	0.0001

Tabla 8.23. Categorías de la metodología SUFRI para el análisis de consecuencias de inundación por escorrentía, avenida o desbordamiento de cauces.

Niveles de severidad de la inundación

La severidad de la inundación por escorrentía, avenida o desbordamiento de cauces distingue tres categorías (alta, media y baja) en función del caudal pico de la avenida y el ancho máximo del área inundada.

En este caso, dadas las características de calado de las áreas afectadas se establece nivel de severidad medio (calado superior a 0,8 m) para la zona A y nivel de severidad bajo (calado inferior a 0,8 m) para la zona B. Además, se estima un tiempo de aviso de una hora en ambas zonas.

Número de víctimas

Conocida la categoría a la que pertenece el municipio (C5), la severidad de la inundación (baja o media según la zona) y el tiempo de aviso estimado (una hora), se obtiene la tasa de mortalidad a emplear para la estimación de la pérdida potencial de vidas según los valores propuestos en la Tabla 8.23. En el caso de Benaguasil, para la zona A se establece una tasa a emplear del 0.000275 y para la zona B del 0.00275.

La pérdida potencial estimada de vidas se obtiene como el producto de la población en riesgo (población residente en el área afectada) y la tasa de mortalidad correspondiente. Para el caso de Benaguasil, la densidad de población para la zona A se considera igual a 0,5 habitantes/vivienda afectada (dada la tipología de vivienda ubicada en zona rural o agrícola) y la densidad de población empleada para la zona B se obtiene como el cociente entre el número de habitantes (en función de la categoría de tiempo) y la superficie del casco urbano. Los resultados obtenidos son los siguientes*:*

Categoría de tiempo	TC1	TC2	TC3	TC4
	Zona A (viviendas afectadas)			
Población en riesgo	10	10	10	10
Pérdida potencial de vidas (N)	0	0	0	0
	Zona B (zona residencial afectada)			
Población en riesgo	554	360	448	354
Pérdida potencial de vidas (N)	0	0	0	0

Tabla 8.24. Pérdida potencial de vidas para el análisis de consecuencias de inundación por escorrentía, avenida o desbordamiento de cauces.

La Tabla 8.24 muestra la población en riesgo y pérdida potencial de vidas obtenida para cada categoría de tiempo (TC1 a TC4). En la zona A no se considera variaciones diaria o estacional de la población.

Dada la baja población en riesgo y las tasas de mortalidad correspondientes a inundación por escorrentía, avenida o desbordamiento de cauces en Benaguasil, la pérdida potencial estimada de vidas es inferior a 1 en ambas zonas.

Pérdidas económicas estimadas

La estimación de los costes económicos de la inundación se realiza siguiendo la misma metodología que en el análisis de inundación por precipitación «in situ».

Para ello, se emplean los siguientes valores de referencia en función del uso del suelo (Tabla 8.25).

Uso del suelo	Ratio PATRICOVA (índice sobre 100 donde 100 = 82€/m²)	Coste de referencia (€/m²)
Residencial Baja Densidad	45,5	44,9
Residencial Media Densidad	56,3	55,5
Industrial	16,9	16,7
Equipamientos	35	34,5
Agrícola	0,34	0,3

Tabla 8.25. Costes de referencia según uso del suelo.

Conocida la superficie afectada para cada uso del suelo (Tabla 8.22), se obtienen los costes totales asociados a la inundación como el producto del valor de referencia (según uso del suelo en función de los ratios definidos por el PATRICOVA y actualizados según IPC 2011), el porcentaje de daños (estimado en un 14% para calado igual a 0,8 metros y del 40% para un calado superior a 0,8 m), el área afectada y la relación entre costes directos e indirectos (del 27%).

En el caso de la cantera (zona A) se considera solamente un 10% del total de la superficie afectada para el cálculo del coste económico asociado a la inundación, dado que el coste de referencia asignado corresponde a un valor de uso de suelo industrial definido en el PATRICOVA (16,7 €/m^2), que incluye afección a instalaciones, maquinaría, etc. que no se asocian a esta actividad.

o puede aplicarse Finalmente, se obtienen unos costes totales de ***250.213 euros*** para la zona A y de ***524.699 euros*** para la zona B asociados a una frecuencia de inundación de periodo de retorno inferior a 25 años.

En las tablas siguientes, Tabla 8.26 y Tabla 8.27, se muestra un resumen de la estimación de consecuencias efectuada para el análisis de inundación por escorrentía, avenida o desbordamiento de cauces, a partir de las zonas de afección identificadas en el PATRICOVA.

Afección Subzona	Descripción	Tipo	Población estimada	Uso del suelo	Coste Ref. (€/m²)	Superficie (m²)	PD (%)	Costes (€)
A1	Bco. del Tollo	Vivienda aisladas (13)	8	Residencial baja densidad	44,9	2.730	40%	48.980
A1	Resto inundación Bco.Tollo	Agrícola	-	Agrícola	0,3	181.548	40%	24.340
A2	Cantera	Industrial	-	Industrial	16,7	100.758	40%	67.306
A2	Resto inundación Subzona A2	Agrícola	-	Agrícola	0,3	232.961	40%	31.232
A2	Vivienda aislada junto cantera en margen izquierda de Rambla Castellana	Vivienda aisladas (1)	1	Residencial baja densidad	44,9	200	40%	3.588
A3	La Fenosa	Vivienda aisladas (1)	1	Residencial baja densidad	44,9	200	40%	3.588
A3	Resto inundación Subzona A3	Agrícola	-	Agrícola	0,3	99,894	40%	13.393
							Costes directos	197.018
							Costes totales	250.213

Tabla 8.26. Resumen de consecuencias para la zona A.

Afección Subzona	Descripción	Tipo	Población estimada	Uso del suelo	Coste Ref. (€/m²)	Superficie (m²)	PD (%)	Costes (€)
B1	Barranco Benaguasil Viviendas	Residencial		Residencial Media densidad	55,5	28.633	14%	222.478
B2	Barranco Benaguasil Políg. Ind.	Industrial		Industrial	16,7	19.424	14%	45.413
B3	Barranco Benaguasil Polideportivo	Equipamientos		Equipamientos	34,5	30.074	14%	145.257
							Costes directos	**413.149**
							Costes totales	**524.699**

Tabla 8.27. Resumen de consecuencias para la zona B.

8.4. Estimación cualitativa del riesgo

En este apartado se describen los principales aspectos de los mapas de riesgo elaborados para la representación de la estimación cualitativa del riesgo.

Inundación por precipitación «in situ»

A partir de la información obtenida del análisis del riesgo de inundación por precipitación «in situ» se han elaborado mapas de riesgo para cada uno de los tres niveles de aviso meteorológico seleccionados:

- Aviso AEMET: Nivel ***amarillo*** (20 mm en una hora, por precipitaciones)
- Aviso AEMET: Nivel ***naranja*** (40 mm en una hora, por precipitaciones)
- Aviso AEMET: Nivel ***rojo*** (60 mm en una hora, umbral para tormentas, por ser inferior al establecido para precipitaciones, igual a 90 mm en una hora)

Para cada nivel se elaboran tres mapas atendiendo a los siguientes grupos objetivo:

- Servicios de Emergencias
- Población
- Planeamiento urbanístico

Los mapas de riesgo se incluyen en el Anexo 4.3, en los **planos 2.1.1 a 2.3.3.**

Para cada uno de los 21 tramos de estudio se identifican en el mapa:

- Área afectada por la inundación: representada por una banda o región entorno al tramo de estudio.
- Nivel del agua alcanzado por la inundación (calado): distinguiendo tres rangos (bajo, medio, alto). El nivel de calado se identifica con tres sombreados diferentes dentro del área de afección.
- Velocidad del agua: distinguiendo tres rangos (media, alta, muy alta) en función del nivel de severidad obtenido en el cálculo de consecuencias (S1, S2 o S3, ya que no se obtienen escenarios de inundación asociados a la categoría S4). Se representan mediante flechas de distinto tamaño en función del nivel de severidad obtenido.

A continuación se muestra un resumen de los datos representados en cada mapa. Estos resultados se han obtenido a partir de los escenarios de inundación equivalentes a los tres umbrales seleccionados, siendo éstos los asociados a periodos de retorno de 2, 15 y 100 años.

Mapas para aviso AEMET de nivel amarillo (T=2 años)
Para este escenario de inundación no se produce escorrentía en los tramos 1, 2, 3, 5, 6, 7, 10 y 11. Dado que el resto de tramos presentan severidad S0 (baja), no se identifican en plano los símbolos correspondientes a la magnitud de la velocidad del agua.

Atendiendo al nivel del agua alcanzado por la inundación (calado) se obtiene la siguiente clasificación:

Tramos con y<0,15 m	3b,4,4b,9,14,14b	Bajo
Tramos con 0,15 m<y<0,45 m	2b,8,8b,12,13,15,16	Medio
Tramos con y>0,45 m	-	Alto

Tabla 8.28. Calado de inundación para nivel de aviso amarillo.

Los valores esperados del calado, la longitud del tramo de estudio en el que se esperan dichos valores y el ancho de inundación considerado para el cálculo de costes económicos se muestran en la tabla siguiente.

Zona	*Tramo*	*ID tramo*	*y (m)*	*L (m)*	*b (m)*
BNG1	849A-840	1	0,00	-	-
BNG1	840-77	2	0,00	-	-
BNG1	73B-73E	2b	0,21	130	48
BNG1	77-65	3	0,00	-	-
BNG1	514-65	3b	0,06	365	14
BNG1	33-25	4	0,11	214	10
BNG1	33-73	4b	0,14	120	10
BNG2	11-14	5	0,00	-	-
BNG2	14-19	6	0,00	-	-
BNG2	19-25	7	0,00	-	-
BNG6	34-35	8	0,26	78	45
BNG23	438-442	8b	0,22	125	40
BNG3	172-178	9	0,06	87	11
BNG3	178-147	10	0,00	-	-
BNG3	125-122	11	0,00	-	-
BNG3	116-113	12	0,37	96	44
BNG7	86-49	13	0,18	167	48
BNG4	112-111	14	0,13	40	11
BNG5	111-109	14b	0,14	84	13
BNG5	105-103	15	0,19	124	51
BNG5	102-99	16	0,19	102	48

donde *b* es el ancho del área afectada considerado para calcular costes económicos.

Tabla 8.29. Descripción de los tramos de estudio para nivel de aviso amarillo.

Mapas para aviso AEMET Nivel naranja (T=15 años)

Para este escenario de inundación no se produce escorrentía en el tramo 5. Atendiendo al nivel del agua alcanzado por la inundación (calado) se obtiene la siguiente clasificación:

Tramos con y<0,15 m	1,3	Bajo
Tramos con 0,15 m<y<0,45 m	2b,8,8b,12,13	Medio
Tramos con y>0,45 m	2,3b,4,4b,6,7,9,11,14-16	Alto

Tabla 8.30. Calado de inundación para nivel de aviso amarillo.

A diferencia del caso anterior, los niveles de severidad aumentan, obteniendo valores desde S0 a S3, tal y como se muestra en la tabla siguiente.

Zona	Tramo	*ID tramo*	y (m)	S	L (m)	b (m)
BNG1	849A-840	1	0,04	0	213	12
BNG1	840-77	2	0,37	0	347	48
BNG1	73B-73E	2b	0,47	1	130	48
BNG1	77-65	3	0,11	0	321	12
BNG1	514-65	3b	0,16	0	365	50
BNG1	33-25	4	0,23	0	214	46
BNG1	33-73	4b	0,32	0	120	46
BNG2	11-14	5	0,00	-	-	-
BNG2	14-19	6	0,20	0	176	47
BNG2	19-25	7	0,23	1	366	46
BNG6	34-35	8	0,52	0	78	99
BNG23	438-442	8b	0,45	0	125	40
BNG3	172-178	9	0,21	0	87	47
BNG3	178-147	10	0,17	1	168	47
BNG3	125-122	11	0,26	2	62	46
BNG3	116-113	12	0,72	3	96	98
BNG7	86-49	13	0,57	3	167	102
BNG4	112-111	14	0,34	0	40	47
BNG5	111-109	14b	0,37	0	84	49
BNG5	105-103	15	0,36	0	124	51
BNG5	102-99	16	0,38	0	102	48

Tabla 8.31. Descripción de los tramos de estudio para nivel de aviso amarillo.

Mapas para aviso AEMET Nivel rojo (T=100 años)

Todos los tramos de estudio presentan escorrentía para el escenario de inundación asociado al nivel rojo de riesgo meteorológico por tormentas. Atendiendo al nivel del agua alcanzado por la inundación se obtiene la siguiente clasificación:

Tramos con y<0,15 m	1,5	Bajo
Tramos con 0,15 m<y<0,45 m	3,3b,4,6,7,9-11	Medio
Tramos con y>0,45 m	2,2b,4b,8,8b,12-16	Alto

Tabla 8.32. Calado de inundación para nivel de aviso amarillo.

Los valores obtenidos de calado y severidad se muestran en la tabla siguiente.

Zona	*Tramo*	*ID tramo*	*y (m)*	*S*	*L (m)*	*b (m)*
BNG1	849A-840	1	0,10	0	213	12
BNG1	840-77	2	0,60	1	347	48
BNG1	73B-73E	2b	0,69	1	130	48
BNG1	77-65	3	0,19	0	321	48
BNG1	514-65	3b	0,23	2	365	50
BNG1	33-25	4	0,32	0	214	46
BNG1	33-73	4b	0,46	0	120	100
BNG2	11-14	5	0,14	0	98	12
BNG2	14-19	6	0,39	2	176	47
BNG2	19-25	7	0,41	3	366	46
BNG6	34-35	8	0,74	3	78	99
BNG23	438-442	8b	0,65	1	125	94
BNG3	172-178	9	0,33	2	87	47
BNG3	178-147	10	0,33	3	168	47
BNG3	125-122	11	0,44	3	62	46
BNG3	116-113	12	1,02	3	96	98
BNG7	86-49	13	0,90	3	167	102
BNG4	112-111	14	0,52	1	40	101
BNG5	111-109	14b	0,55	1	84	103
BNG5	105-103	15	0,52	1	124	105
BNG5	102-99	16	0,54	1	102	102

Tabla 8.33. Descripción de los tramos de estudio para nivel de aviso amarillo.

Inundación por escorrentía, avenida o desbordamiento de cauces

El Plan Especial ante el Riesgo de Inundaciones en la Comunitat Valenciana establece 6 niveles de peligrosidad por combinación de intervalos de frecuencia y calados de inundación.

	Frecuencia		
Calado	**Baja (100-500 años)**	**Media (25-100 años)**	**Alta (< 25 años)**
Bajo (≤ 0,8 m.)	6	4	3
Alto (> 0,8 m.)	5	2	1

Tabla 8.34. Niveles de peligrosidad.

Los estudios del PATRICOVA identifican, según se recoge en el **Plano 8.4**, dos zonas de inundación por desbordamiento de cauces en el término municipal de Benaguasil (con niveles de peligrosidad 1 y 3, respectivamente) que son:

- PELIGROSIDAD 1 (zona A, apartado 8.3.3): corresponde a la zona de influencia del cauce del Río Turia y de sus ramblas. Se corresponde a una frecuencia alta (periodo de retorno inferior a 25 años) y calado alto (niveles superiores a 80 cm). No obstante, esta zona se encuentra alejada del casco urbano.

- PELIGROSIDAD 3 (zona B, apartado 8.3.3): abarca el área del Barranco de Benaguasil, por desaparición de su cauce al norte del núcleo urbano (conocido en el municipio como

Barranquet). Corresponde a una frecuencia alta (período de retorno inferior a 25 años) y calado bajo (niveles inferiores a 80 cm).

El PATRICOVA propone una actuación de restauración hidrológica-forestal (código VI02) para disminuir el impacto futuro de las inundaciones. Se propone la reforestación de 58 Ha, lo que supone el 13,7% respecto a la superficie total de la cuenca, correspondiendo a terrenos desarbolados con erosión grave o muy grave. Considerando un periodo de retorno de 100 años, se estima una reducción del 8,1% del caudal punta. No obstante, esta actuación no ha sido llevada a cabo hasta el momento.

Asimismo, el Plan diferencia las superficies inundables entre zonas de riesgo alto, medio y bajo teniendo en cuenta el tipo de uso del suelo o los elementos en peligro afectados, resultando la combinación mostrada en la tabla siguiente.

ELEMENTOS EN PELIGRO	USO DEL SUELO	RIESGO	ZONAS DE PELIGROSIDAD
Núcleos de población	Residencial, terciario y mixto; zonas de acampada; uso comercial	A.1. Alto frecuente	1
		A.2. Alto ocasional	2
		A.3. Alto excepcional	5
		B. Medio	3
			4
		C. Bajo	6
Instalaciones industriales	Uso industrial	A. Alto	1
			2
		B. Medio	3
			4
			5
		C. Bajo	6
Servicios básicos	Equipamientos, infraestructuras y elementos singulares	A. Alto	1
			2
		B. Medio	3
			4
			5
		C. Bajo	6

Tabla 8.35. Clasificación cualitativa para inundación por escorrentía, avenida o desbordamiento de cauces.

Basándose en la clasificación anterior, y teniendo en cuenta las superficies y la población residencial afectadas, el Plan Especial ante el riesgo de inundaciones en la Comunitat Valenciana identifica Benaguasil como municipio de riesgo **bajo**.

No obstante, analizando en detalle al área de afección del barranco de Benaguasil al casco urbano (zona B), se concluye que el riesgo asociado a esta zona del casco urbano es de tipo **medio**, dado que se trata de una zona de inundación de nivel de peligrosidad 3 que afecta a tres tipos de uso del suelo: residencial, industrial y equipamientos.

Sin embargo, los estudios del PATRICOVA fueron realizados con anterioridad a la construcción del nuevo tramo de autovía de la CV-50 que circula por el norte del municipio, por lo que la afección al casco urbano en dicha zona se prevé diferente en la actualidad.

Con todo lo anterior, y dado que para la elaboración del presente Plan de Actuación Municipal (PAM) no se ha realizado un estudio específico de inundabilidad por escorrentía o desbordamiento de cauces (como se justifica en el apartado 2.2.1), atendiendo a la finalidad del PAM y con el objetivo de poder combinar en un mismo plano la estimación cualitativa del riesgo para los diferentes tipos de inundación (por precipitación «in situ» y por desbordamiento de cauces), se considera oportuno incluir el área identificada con nivel de peligrosidad 3, riesgo medio, por el Plan Especial (periodo de retorno inferior a 25 años), en los nueve mapas descritos en el apartado anterior, referentes a inundación en el casco urbano, que en el caso de Benaguasil atienden a periodos de retorno de 2, 15 y 100 años (Anexo IV, **Planos 2.2.1 a 2.3.3**).

Este área se incluye con una codificación de colores diferente a la empleada para el riesgo por precipitación «in situ», para destacar la diferencia del nivel de detalle del estudio en el que se basan y la no concordancia directa de periodos de retorno y niveles de agua representados.

Además, se elaboran un mapa a escala de término municipal las áreas identificadas por el PATRICOVA (Anexo IV, **Plano 2.4**).

Inundación por precipitación «in situ» y por escorrentía, avenida o desbordamiento de cauces

Por tanto, como se ha descrito en el punto anterior, los nueve mapas elaborados para la representación de la estimación cualitativa del riesgo en el casco urbano consideran tanto inundación por escorrentía, avenida o desbordamiento de cauces como por precipitación «in situ» y están recogidos en el **Anexo IV**, **Planos 2.1.1 a 2.3.3.**

8.5. Estimación cuantitativa del riesgo

En este apartado se describe la estimación cuantitativa del riesgo por inundación efectuada para el municipio de Benaguasil.

Inundación por precipitación «in situ»

Con el fin de efectuar una estimación cuantitativa del riesgo de inundación en el municipio (como complemento a la estimación cualitativa descrita en el apartado anterior y representada en los mapas del **Anexo IV**) se ha elaborado un modelo de riesgo a tal efecto. El modelo de riesgo es una herramienta que permite incorporar toda la información referente a caracterización de avenidas, respuesta del sistema y consecuencias de inundación para el cálculo del riesgo social (pérdida potencial estimada de vidas) y económico (pérdidas económicas potenciales). Para este cálculo, se han considerado únicamente las afecciones al casco urbano.

El modelo de riesgo puede representarse de una forma conceptual y compacta mediante diagramas de influencia. La Figura 8.11 muestra el diagrama de influencia empleado para el análisis del municipio de Benaguasil, cuyo análisis se ha efectuado utilizando el software *iPresas* desarrollado por la empresa *iPresas Risk Analysis* (spin-off de la Universitat Politècnica de València)[3].

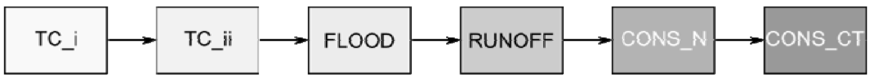


Figura 8.11. Diagrama de influencia asociado al modelo de riesgo del municipio de Benaguasil.

El modelo de riesgo incorpora la información descrita en el apartado 8.3 en una serie de nodos (Figura 8.11) y las variables empleadas se interrelacionan mediante conectores. La Tabla 8.36 muestra el contenido de cada nodo.

Nodo	Fase	Variable / Contenido
TC_i	General	Variabilidad estacional de la población según categoría de tiempo (verano/invierno).
TC_ii	General	Variabilidad diaria de la población según categoría de tiempo (verano/invierno/día/noche).
Flood	Caracterización de avenidas	Escenarios de precipitación y probabilidad asociada a cada escenario.
Runoff	Respuesta del sistema	Caudales de escorrentía para cada escenario de precipitación.
Cons_N	Consecuencias	Consecuencias por inundación en pérdida potencial estimada de vidas para cada escenario de precipitación y categoría de tiempo (verano/invierno/día/noche).
Cons_CT	Consecuencias	Consecuencias por inundación en pérdidas económicas estimadas para cada escenario de precipitación y categoría de tiempo (verano/invierno/día/noche).

Tabla 8.36. Variables empleadas para el cálculo del riesgo y nodos correspondientes en el modelo.

[3] iPresas Risk Analysis: www.ipresas.com

A continuación se muestran los datos de entrada introducidos en el modelo en los nodos Cons_N y Cons_CT, correspondientes a las consecuencias de la inundación para cada escenario de inundación y categoría de tiempo.

Estación	*Momento del día*	*Periodo de retorno (años)*	*Número de víctimas*
Verano	Día	2	0
Verano	Día	5	1
Verano	Día	10	1
Verano	Día	15	2
Verano	Día	25	2
Verano	Día	50	3
Verano	Día	100	4
Verano	Noche	2	0
Verano	Noche	5	0
Verano	Noche	10	0
Verano	Noche	15	0
Verano	Noche	25	0
Verano	Noche	50	0
Verano	Noche	100	0
Invierno	Día	2	0
Invierno	Día	5	0
Invierno	Día	10	1
Invierno	Día	15	1
Invierno	Día	25	1
Invierno	Día	50	2
Invierno	Día	100	2
Invierno	Noche	2	0
Invierno	Noche	5	0
Invierno	Noche	10	0
Invierno	Noche	15	0
Invierno	Noche	25	0
Invierno	Noche	50	0
Invierno	Noche	100	0

Tabla 8.37. Datos de entrada de pérdida estimada potencial de vidas.

Periodo de retorno (años)	*Costes totales (en euros)*
2	35.047
5	111.210
10	218.279
15	284.981
25	380.877
50	649.916
100	1.027.565

Tabla 8.38. Datos de entrada de pérdidas económicas potenciales.

El modelo de riesgo permite la estimación cuantitativa del riesgo. Los resultados del cálculo pueden representarse en curvas tipo F-N y F-D, donde F es la probabilidad anual acumulada de excedencia de un determinado nivel de consecuencias de inundación, bien en número de víctimas (N) o costes económicos (D).

A continuación se muestran las curvas obtenidas para el municipio de Benaguasil (Figura 8.12 y Figura 8.13), considerando el riesgo por inundación por precipitación «in situ».

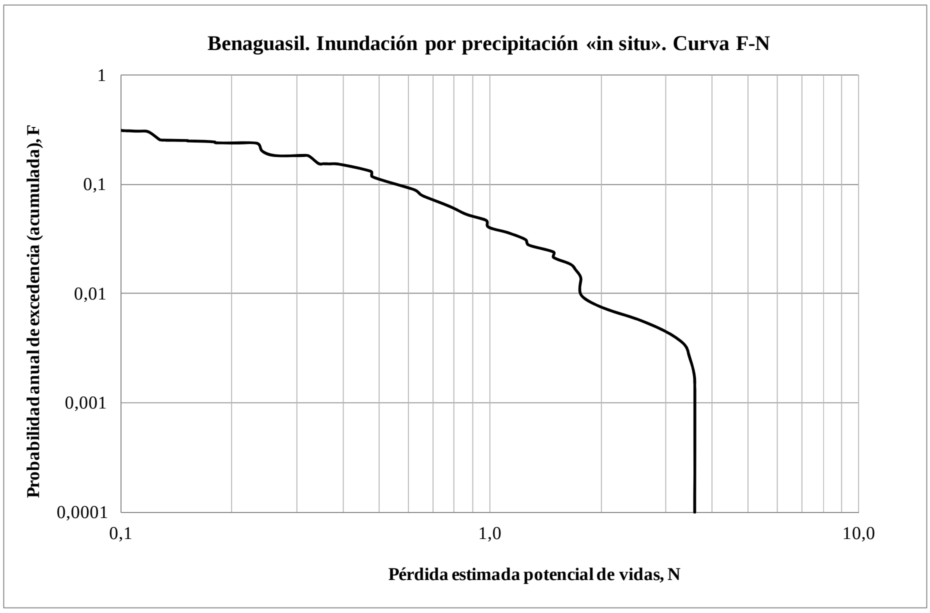


Figura 8.12. Curva F-N. Riesgo social de inundación por precipitación «in situ».

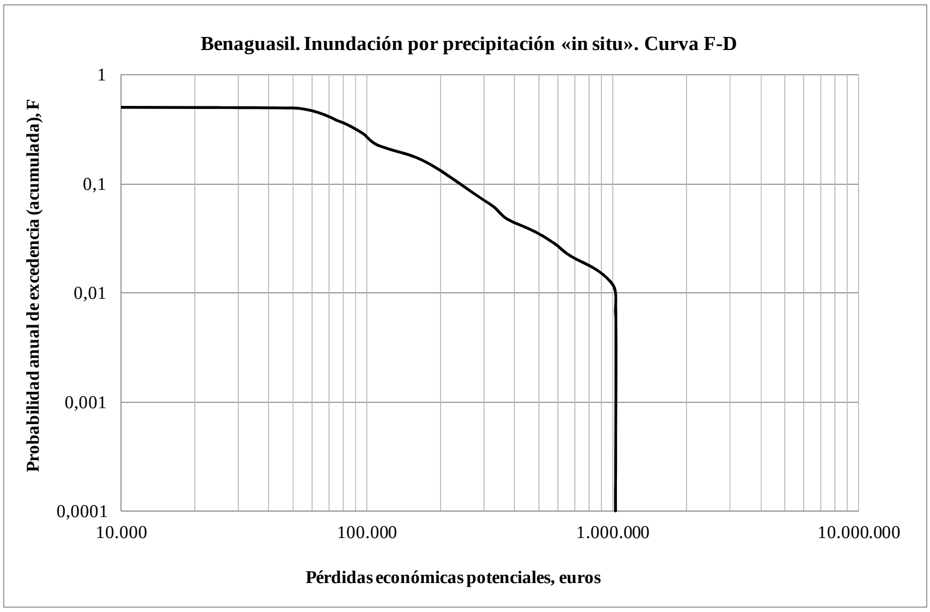


Figura 8.13. Curva F-D. Riesgo económico de inundación por precipitación «in situ».

La Figura 8.12 muestra que el riesgo social por inundación asociado a la situación actual corresponde con una pérdida potencial estimada de vidas igual a 1,8 asociada a un valor de probabilidad anual de excedencia de 0,01.

En el caso de las potenciales consecuencias económicas de la inundación, la Figura 8.13 muestra un riesgo económico igual a 241.480 euros para un valor de probabilidad anual de excedencia del 0,1.

Los resultados obtenidos demuestran la relevancia del análisis efectuado en Benaguasil, dado el significativo coste económico potencial asociado a inundación por precipitación «in situ».

Inundación por escorrentía, avenida o desbordamiento de cauces

Con los datos que se disponen del riesgo por inundación asociado a escorrentía, avenida o desbordamiento de cauces (evaluado por el Plan Especial basándose en los estudios del PATRICOVA), no es posible realizar una estimación cuantitativa equivalente a la efectuada para el análisis de inundación por precipitación «in situ», para diferentes escenarios de inundación, y por lo tanto no es posible obtener las curvas F-N y F-D.

No obstante, sí se han estimado las consecuencias potenciales de la inundación en las áreas de afección identificadas en el PATRICOVA. Esta estimación cuantitativa del impacto de la inundación se ha descrito en el apartado **8.3.3**.

En cualquier caso, se prevé que la existencia del nuevo tramo de la CV-50, que cruza el Barranco de Benaguasil, modifique la afección al casco urbano, y por tanto cualquier estimación cuantitativa del riesgo.

Inundación por precipitación «in situ» y por escorrentía, avenida o desbordamiento de cauces

En el caso de Benaguasil, con los datos que se disponen del riesgo por inundación asociado a escorrentía, avenida o desbordamiento de cauces no es posible obtener las curvas de riesgo F-N y F-D para este tipo de inundación, y por tanto no es posible la obtención de unas curvas conjuntas que contemplen el riesgo de inundación tanto por precipitación «in situ» como por escorrentía, avenida o desbordamiento de cauces.

8.6. Estudio del efecto de medidas no estructurales de reducción del riesgo

Introducción

En este apartado se incluye la evaluación del impacto que la implantación de una serie de medidas no estructurales de protección frente al riesgo de inundación podría tener sobre la situación actual del municipio de Benaguasil.

Las medidas no estructurales consideradas incluyen formación a la población y mejora de los sistemas de aviso en caso de emergencia.

A partir de las actividades planteadas en el Plan de Implantación y Mantenimiento del PAM, este caso puede considerarse como el escenario futuro del municipio de Benaguasil ante el riesgo de inundación una vez se haya implantado el Plan, y las medidas de formación, información y aviso a la población hayan sido llevadas a cabo.

Cambios introducidos respecto al caso base para la estimación de consecuencias

Dado que las medidas no estructurales de reducción del riesgo de inundación no afectan a las características de los eventos de precipitación considerados ni a la respuesta del sistema, el efecto de dichas medidas se ejerce sobre las potenciales consecuencias de la inundación.

A continuación se describen los cambios introducidos para la estimación de consecuencias para el caso con medidas no estructurales, partiendo de la información obtenida y el análisis realizado para la situación actual (también denominada Caso Base).

Pérdida potencial estimada de vidas

En relación a la estimación de la pérdida potencial de vidas humanas asociada a la inundación, la existencia de medidas de formación y aviso a la población puede evaluarse contemplando dos variaciones respecto a la situación actual: reduciendo el factor de exposición y modificando la categoría para el cálculo de tasas de mortalidad.

Factor de exposición

Un elevado nivel de formación de la población ante el riesgo de inundación resulta en un porcentaje menor de población expuesta a la inundación (las recomendaciones y consejos a la población recogidos en el Plan remarcan la importancia de permanecer en el interior de las viviendas y alejados de las zonas de riesgo).

Por tanto, los factores a considerar en este caso son los valores mostrados en la tabla siguiente.

Categoría	TC1	TC2	TC3	TC4
Densidad de población (habitantes/km^2)	9227	9390	9065	9227
Factor de exposición (f)	0,1	0,01	0,05	0,01
Factor de exposición (población expuesta respecto de población total)	**10%**	**1%**	**5%**	**1%**

Tabla 8.39. Factores de exposición para el caso con medidas no estructurales.

Categoría para el cálculo de tasas de mortalidad

La existencia de sistemas de aviso a la población y la comprobación periódica de su funcionamiento, alcance y eficacia resulta en menores tiempos de aviso, reduciendo la vulnerabilidad de la población ante la inundación.

Por tanto, las tasas de mortalidad a aplicar en este segundo caso corresponden a la categoría C_{p3}, cuyos valores se muestran en la tabla siguiente (para cada nivel de severidad de la inundación).

Nivel de severidad	S0	S1	S2	S3	S4
Tasa de mortalidad (a aplicar a la población expuesta)	**0,0002**	**0,0015**	**0,0027**	**0,0075**	**0,0320**

Tabla 8.40. Tasas de mortalidad a emplear en el caso con medidas no estructurales.

Costes económicos

Las campañas de formación e información a la población recogidas en el PAM tienen la finalidad de mejorar el conocimiento de los ciudadanos ante el riesgo de inundación y las medidas de autoprotección a llevar a cabo en caso de emergencia. Por ello, la existencia de medidas no estructurales de formación, información y aviso puede asociarse a una reducción de los costes económicos de la inundación por implantación de medidas de autoprotección en viviendas y locales.

Esta reducción puede analizarse como una variación de dos de las variables empleadas en el proceso de estimación de consecuencias económicas: el porcentaje de daños y el área afectada por la inundación.

Reducción en daños económicos en función del calado

Dado que el grado de destrucción o porcentaje de daños está relacionado con el nivel alcanzado por el agua, la implantación de medidas de autoprotección (por ejemplo, barreras instaladas en puertas y accesos a garajes y locales) puede evaluarse como una reducción del porcentaje de daños. Existen estudios[4] que estiman esta reducción en función del nivel alcanzado por el agua y el tiempo de aviso disponible. La tabla siguiente recoge los valores empleados para el cálculo del porcentaje de daños incluyendo el efecto de medidas de autoprotección.

[4] Parker et al (2005)

Calado y (m)	0	0,1	0,3	0,6	0,9	1,2
Reducción de daños	29%	29%	36%	33%	33%	31%

Tabla 8.41. Reducción de daños por existencia de formación y aviso a la población.

Área afectada para la estimación de costes para calados inferiores a 0,45 m

Las áreas identificadas para el cálculo de costes económicos por inundación se han determinado atendiendo a tres rangos de calado (inferior a 0,15 m, entre 0,15 m y 0,45 m, y superior a 0,45 m).

En este caso se establece que la implantación de medidas de autoprotección puede evaluarse como una reducción del área afectada, ya que para calados inferiores a 0,45 m (altura estimada de las barreras de autoprotección) se considera que la inundación no irrumpe en viviendas o locales. Por tanto, para el cálculo de costes económicos por inundación se considera la misma superficie de afección para los dos primeros rangos de calados (inferior a 0,45 m).

Datos de entrada al modelo de riesgo

Establecidos los nuevos valores de las variables afectadas por la existencia de medidas de formación, información y aviso a la población (factor de exposición, tasas de mortalidad a aplicar, porcentaje de daños y área de afección para el cálculo de costes), se obtienen nuevos datos de entrada para el análisis del caso con medidas no estructurales mediante el modelo de riesgo descrito en el apartado **8.5**.

Los datos de entrada a incorporar al modelo de riesgo se incluyen en las tablas siguientes.

Periodo de retorno (años)	*Costes totales (en euros)*
2	7.011
5	34.315
10	98.219
15	138.732
25	190.774
50	390.145
100	642.135

Tabla 8.42. Datos de entrada de pérdidas económicas potenciales.

Estación	*Momento del día*	*Periodo de retorno (años)*	*Número de víctimas*
Verano	Día	2	0
Verano	Día	5	0
Verano	Día	10	0
Verano	Día	15	1
Verano	Día	25	1
Verano	Día	50	1
Verano	Día	100	1
Verano	Noche	2	0
Verano	Noche	5	0
Verano	Noche	10	0
Verano	Noche	15	0
Verano	Noche	25	0
Verano	Noche	50	0
Verano	Noche	100	0
Invierno	Día	2	0
Invierno	Día	5	0
Invierno	Día	10	0
Invierno	Día	15	0
Invierno	Día	25	0
Invierno	Día	50	1
Invierno	Día	100	1
Invierno	Noche	2	0
Invierno	Noche	5	0
Invierno	Noche	10	0
Invierno	Noche	15	0
Invierno	Noche	25	0
Invierno	Noche	50	0
Invierno	Noche	100	0

Tabla 8.43. Datos de entrada de pérdida estimada potencial de vidas.

Comparación

A continuación se muestran las curvas F-N y F-D (Figura 8.14 y Figura 8.15) obtenidas para el caso con medidas no estructurales. Las gráficas muestran tanto las curvas resultantes de este segundo caso de análisis como las correspondientes a la situación actual del municipio de Benaguasil ante el riesgo de inundación por precipitación «in situ».

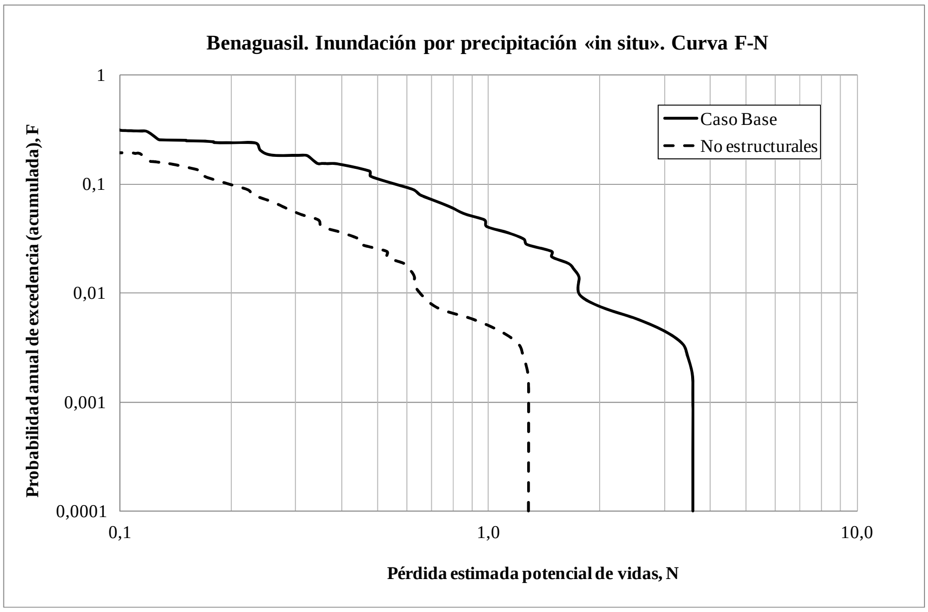


Figura 8.14. Curva F-N. Riesgo social de inundación por precipitación «in situ». Situación actual (Caso Base) y caso con medidas no estructurales.

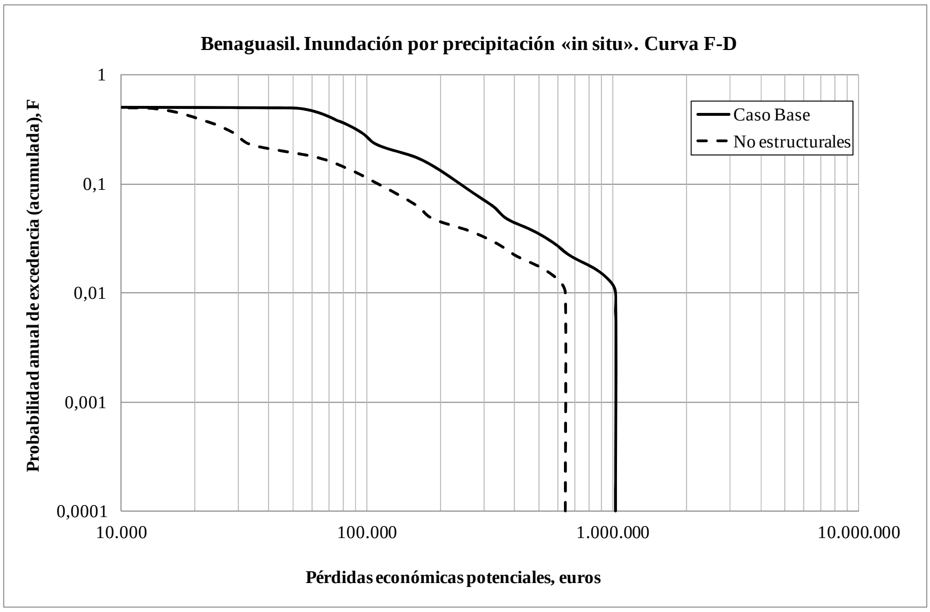


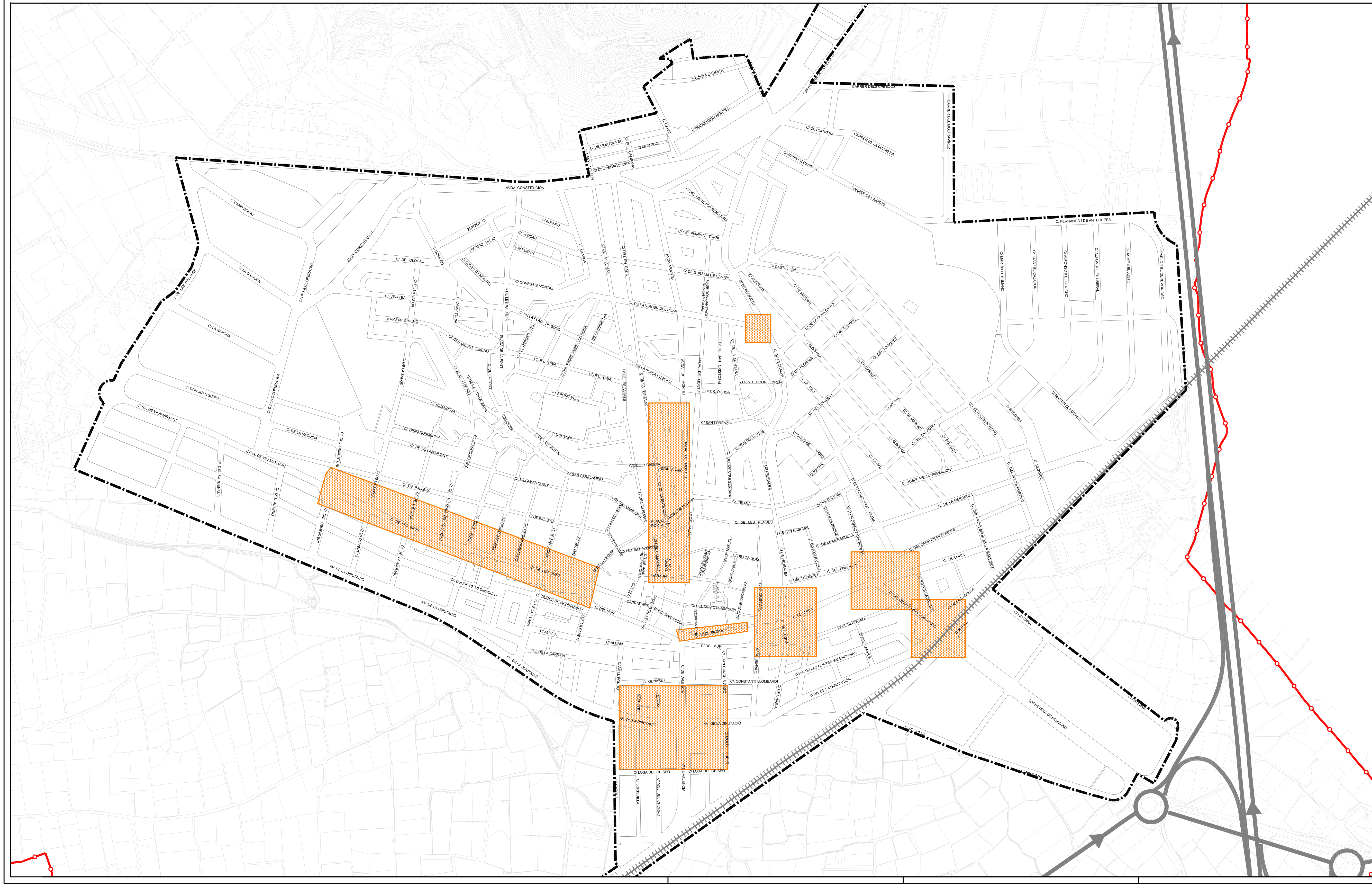
Figura 8.15. Curva F-D. Riesgo económico de inundación por precipitación «in situ». Situación actual (Caso Base) y caso con medidas no estructurales.

La Figura 8.14 muestra una notable reducción del riesgo social, con un descenso del 65% en la pérdida potencial estimada de vidas, asociada a un valor de probabilidad anual de excedencia de 0,0001 (pasando, aproximadamente, de 4 víctimas a 1) y del 63% para un valor de probabilidad anual de excedencia de 0,1 (pasando, aproximadamente, de 2 víctimas a 1).

La Figura 8.15 muestra también la reducción en el riesgo económico asociada a la existencia de medidas no estructurales. En este caso, las potenciales consecuencias económicas de la inundación se reducen en un 53% (pasando de 241.480 a 112.310 euros) para un valor de probabilidad anual de excedencia del 0,1.

Por tanto, los resultados obtenidos del análisis respaldan la reducción en riesgo que puede alcanzarse mediante la puesta en marcha y desarrollo de las actividades incluidas en el Plan de Implantación y Mantenimiento del PAM, cuyo fin, entre otros, es mejorar el entendimiento de la población y fomentar el uso de medidas de autoprotección para disminuir los daños asociados a la inundación.

Página en blanco.



INUNDACIONES HISTÓRICAS

(trama naranja)	ZONAS AFECTADAS EN EVENTOS HISTÓRICOS DE INUNDACIÓN EN EL CASCO URBANO

DELIMITACIÓN

(línea roja con puntos)	LÍMITE TÉRMINO MUNICIPAL
(línea de trazo y punto)	LÍMITE CASCO URBANO

PLAN DE ACTUACIÓN MUNICIPAL (PAM) ANTE EL RIESGO DE INUNDACIONES DE BENAGUASIL

TÍTULO: IDENTIFICACIÓN DE ZONAS AFECTADAS EN EVENTOS HISTÓRICOS - CASCO URBANO

PL. MAJOR DE LA VILA, 17
46180 BENAGUASIL (VALENCIA)
Telf. 96 273 11 00 - Fax: 96 273 72 56
www.benaguasil.com

PROMOTOR: AYUNTAMIENTO DE BENAGUASIL

ESCALA GRÁFICA: 0 25 50 75 m

ORIENTACIÓN: N

AUTOR: Benaguasil
MANUEL JUESAS SIERRA
ARQUITECTO TÉCNICO

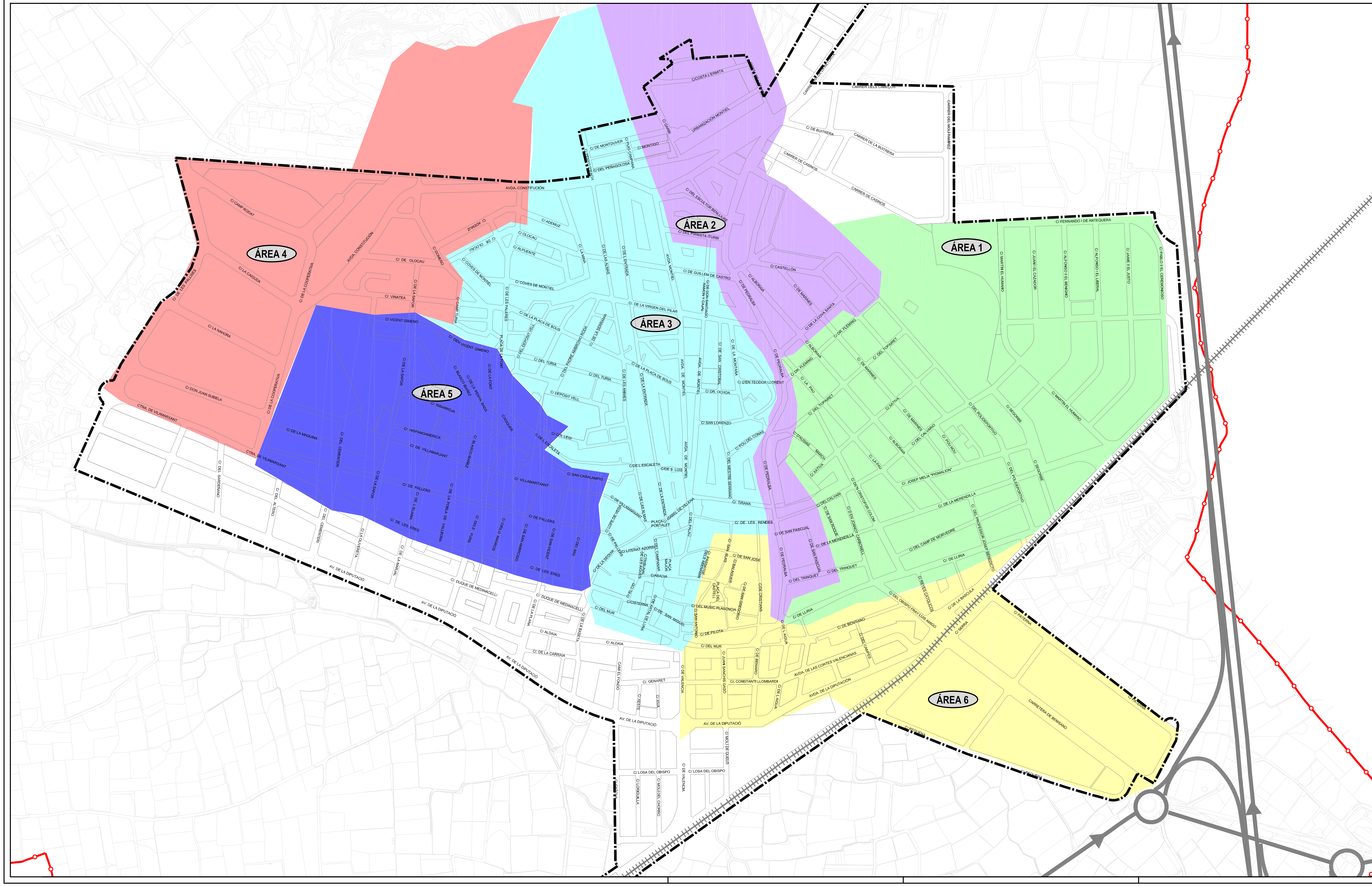
ESCALA: 1/2.500

FECHA: MAY 2012

REF: PAM BEN

Nº PLANO: 8.1

HOJA 1 DE 1



DELIMITACIÓN

(red line with dots)	LÍMITE TÉRMINO MUNICIPAL
(dash-dot line)	LÍMITE CASCO URBANO

PLAN DE ACTUACIÓN MUNICIPAL (PAM) ANTE EL RIESGO DE INUNDACIONES DE BENAGUASIL

TÍTULO: SUBCUENCAS DE CÁLCULO - CASCO URBANO RIESGO POR INUNDACIÓN «IN SITU»

PL. MAJOR DE LA VILA, 17
46180 BENAGUASIL (VALENCIA)
Telf. 96 273 11 00 - Fax: 96 273 72 56
www.benaguasil.com

PROMOTOR: AYUNTAMIENTO DE BENAGUASIL

ESCALA GRÁFICA: 0 25 50 75 m

ORIENTACIÓN: N

AUTOR: Benaguasil
MANUEL JUESAS SIERRA
ARQUITECTO TÉCNICO

ESCALA: 1/2.500

FECHA: MAY 2012

REF: PAM BEN

Nº PLANO: 8.2

HOJA 1 DE 1

ZONAS POTENCIALMENTE EN RIESGO DE INUNDACIÓN

- ZONAS POTENCIALMENTE EN RIESGO POR PRECIPITACIÓN «IN SITU»
- ZONAS POTENCIALMENTE EN RIESGO POR AVENIDA O DESBORDAMIENTO DE CAUCES (SEGÚN PATRICOVA)

DELIMITACIÓN

- LÍMITE TÉRMINO MUNICIPAL
- LÍMITE CASCO URBANO

PLAN DE ACTUACIÓN MUNICIPAL (PAM) ANTE EL RIESGO DE INUNDACIONES DE BENAGUASIL

TÍTULO: IDENTIFICACIÓN DE ZONAS POTENCIALMENTE EN RIESGO DE INUNDACIÓN - CASCO URBANO

PL. MAJOR DE LA VILA, 17
46180 BENAGUASIL (VALENCIA)
Telf. 96 273 11 00 - Fax: 96 273 72 56
www.benaguasil.com

PROMOTOR: AYUNTAMIENTO DE BENAGUASIL

ESCALA GRÁFICA: 0 25 50 75 m

ORIENTACIÓN: N

AUTOR: Benaguasil
MANUEL JUESAS SIERRA
ARQUITECTO TÉCNICO

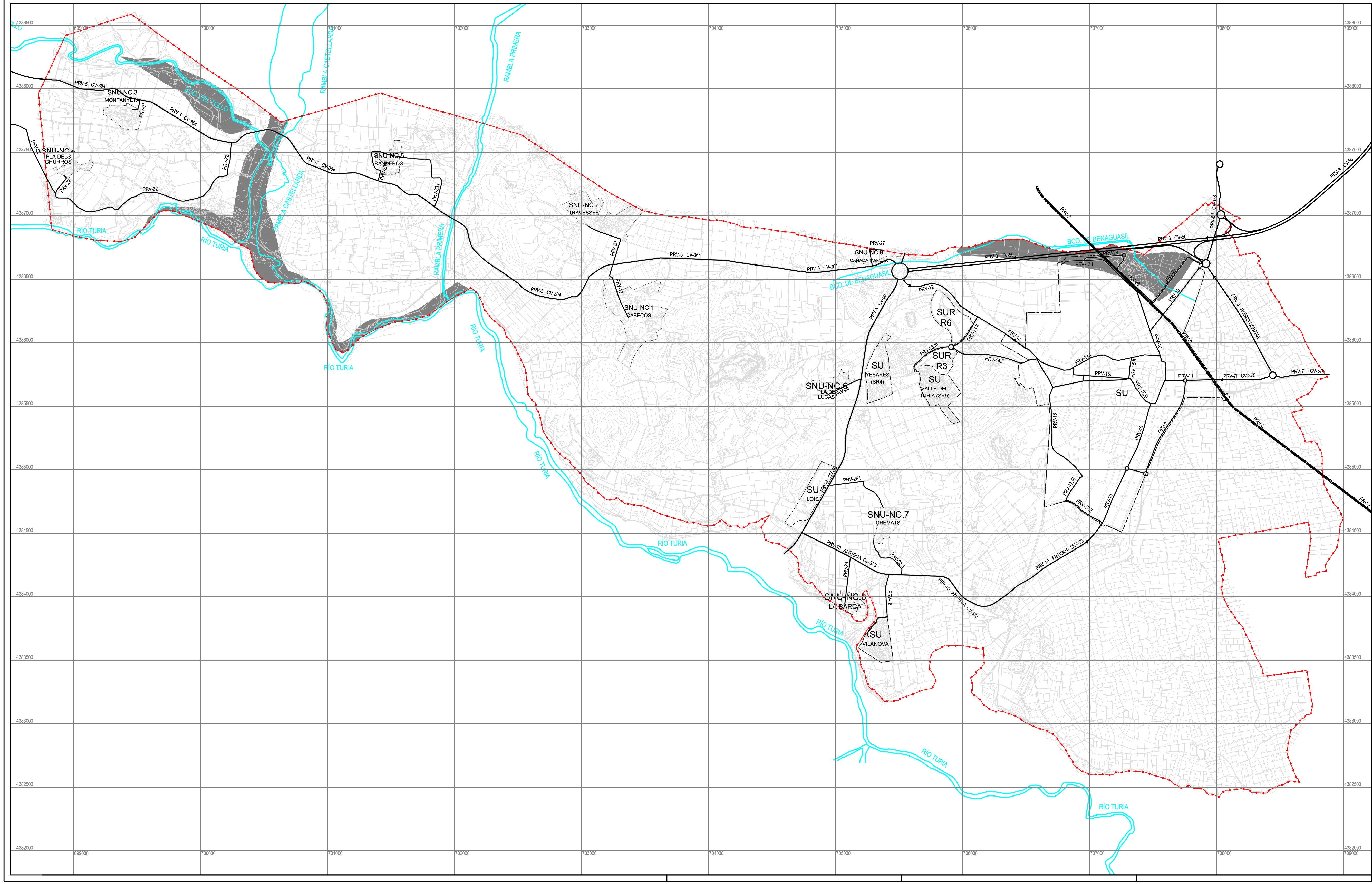
ESCALA: 1/2.500

FECHA: MAY 2012

REF: PAM BEN

Nº PLANO: 8.3

HOJA 1 DE 1



ZONAS POTENCIALMENTE EN RIESGO DE INUNDACIÓN

ZONAS POTENCIALMENTE EN RIESGO POR AVENIDA O DESBORDAMIENTO DE CAUCES (SEGÚN PATRICOVA)

DELIMITACIÓN

LÍMITE TÉRMINO MUNICIPAL

LÍMITE NÚCLEOS DE POBLACIÓN

PLAN DE ACTUACIÓN MUNICIPAL (PAM) ANTE EL RIESGO DE INUNDACIONES DE BENAGUASIL

TÍTULO: ZONAS POTENCIALMENTE INUNDABLES SEGÚN PATRICOVA - TÉRMINO MUNICIPAL

PL. MAJOR DE LA VILA, 17
46180 BENAGUASIL (VALENCIA)
Telf. 96 273 11 00 - Fax: 96 273 72 56
www.benaguasil.com

PROMOTOR: AYUNTAMIENTO DE BENAGUASIL

ESCALA GRÁFICA: 0 100 200 300 m

ORIENTACIÓN: N

AUTOR: MANUEL JUESAS SIERRA
ARQUITECTO TÉCNICO

ESCALA: 1/10.000

FECHA: MAY 2012

REF: PAM BEN

Nº PLANO: 8.4

HOJA 1 DE 1