Nat. Hazards Earth Syst. Sci. Discuss., 1, 3305–3371, 2013
www.nat-hazards-earth-syst-sci-discuss.net/1/3305/2013/
doi:10.5194/nhessd-1-3305-2013

Natural Hazards and Earth System Sciences
Open Access
Discussions

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

J. T. Castillo-Rodríguez[1], **I. Escuder-Bueno**[1], **L. Altarejos-García**[1,2], **and A. Serrano-Lombillo**[2]

[1] Research Institute of Water and Environmental Engineering (IIAMA), Universitat Politècnica de València (UPV), Camino de Vera SN, 46022 Valencia, Spain
[2] iPresas Risk Analysis, UPV Spin-off company, Valencia, Spain

Received: 16 April 2013 – Accepted: 18 June 2013 – Published: 15 July 2013

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

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

Abstract

This article presents a methodology for estimating flood risk in urban areas integrating pluvial flooding, river flooding and failure of both small and large dams.

The first part includes a review of basic concepts and existing methods on flood risk analysis, evaluation and management. Traditionally, flood risk analyses have focused on specific site studies and qualitative or semi-quantitative approaches. However, in this context, a general methodology to perform a quantitative flood risk analysis including different flood hazards was still required.

The second part describes the proposed methodology, which presents an integrated approach – combining pluvial, river flooding and dam failure, as applied to a case study: a urban area located downstream a dam under construction. Such methodology represents an upgrade of the methodological piece developed within the SUFRI project.

This article shows how outcomes from flood risk analysis provide better and more complete information to inform authorities, local entities and the stakeholders involved on decision-making with regard to flood risk management.

1 Introduction

Floods may result from a combination of meteorological and hydrological extreme occurrences (WMO/GWP, 2008). In most cases, floods are additionally influenced by human factors. Urban areas may basically be affected by local floods, river floods, flash floods or coastal floods and they may present high flood risk levels due to population density rates, multiple economic activities, infrastructures and property values (Pelling, 2003). Furthermore, present requirements of residential and industrial areas have resulted in new urban developments in flood-prone areas, increasing risk for people and inducing significant economic costs.

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

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

In the European context, three Directives have been approved in recent years to establish the basis for present and future actions in the field of flood risk and critical infrastructure management: Directive 2000/60/EC, Directive 2007/60/EC and Directive 2008/114/EC (EC, 2008). According to EU (European Union) Floods Directive (EC, 2008), all EU Member States must undertake the necessary actions to provide an assessment of potential risks including preliminary flood risk assessments, flood hazard maps, flood risk maps and flood risk management plans for each river basin district.

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

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

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

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

2 From flood risk analysis to flood risk management

2.1 Risk definition and components

A wide range of definitions for the term *risk* can be found in the literature (Gouldby and Samuels, 2005). Attempts to develop common understanding on risk management concepts and terms among organizations are relatively new (IEC, 2009) or in process. The term risk may present multiple dimensions relating to safety and security, as well as economic, environmental and social issues. These different meanings are the result of its extensive use in multiple disciplines thus there is no unique definition for risk. In the context of flood risk analysis, the project FLOODsite (Gouldby and Samuels, 2005) put widespread effort in defining basic concepts related to flood risk analysis.

First of all, a distinction between the words *hazard* and *risk* should be established. Hazard can be defined as “a physical event, phenomenon or human activity with the potential to result in harm”, or “source of potential harm” (IEC, 2009). Consequently, the definition of risk may be established by the identification of several components (Gouldby and Samuels, 2005): nature and probability of the hazard, degree of exposure to the hazard, susceptibility to the hazard, and value of the potential consequences. In this context, the definition of vulnerability includes the characteristics of a system and it can be considered as a combination of susceptibility to the hazard and value of the potential consequences.

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:

$$\text{Risk} = \text{Hazard} \times (\text{Exposure}) \times \text{Vulnerability} \tag{1}$$

or

$$\text{Risk} = \text{Probability} \times \text{Consequences} \tag{2}$$

where consequences are the impact in terms of economic, social, cultural or environmental damage, expressed quantitatively (e.g. monetary value) or descriptively (e.g. high, medium, low).

However, attention should be paid since there is no univocal relationship between hazard and probability (as probability includes also exposure) neither between vulnerability and consequences.

Based on the aforementioned definition of risk, *flood risk* may be defined as the product of the probability of potential flood events and their consequences. Flood events may include flooding from rivers, mountain torrents, Mediterranean ephemeral water courses, and floods from the sea in coastal areas.

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. According to this, flood risk may be assessed in terms of societal, economic or ecological risk (Kubal et al., 2009). Despite the fact that there are examples of multi-criteria flood risk assessment and mapping approaches that cover the three dimensions of potential consequences (Meyer et al., 2011), in practice, each type is generally obtained separately (e.g. different flood risk maps, risk calculations, etc.) due to differences on their definition, nature and characterization. Indeed, these three dimensions are generally evaluated at a different level of detail. In most cases, ecological risk is not evaluated due to a lack of applications for quantitative risk assessment.

With regard to *flood risk reduction*, it can be achieved through 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 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, increase of awareness, knowledge development, public commitment, methods and operating practices (Escuder-Bueno et al., 2011; Schanze et al., 2008). In general, risk cannot be entirely eliminated since structural measures handle the consequences of a specific severe event, typically called 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 efficacy and efficiency of risk reduction measures.

As already mentioned, risk is commonly expressed by the following notation: Risk = Hazards × Vulnerability (or Probability × Consequences). Accordingly, tools for flood risk analysis can be classified as partial or complete depending on whether they obtain one component of risk (hazard or vulnerability) or both (Escuder-Bueno et al., 2010). In addition, they can be classified as quantitative or qualitative depending on whether they provide or not a numerical value of risk. Among these four groups, complete and quantitative tools are the most convenient but a high-demanding option. Data and time requirements for these tools are usually more demanding than for other methods, though their results may pay back by providing significant information and recommendations for decision makers.

F–N curves provide a comprehensive and robust method to represent societal and economic risk quantitatively. When analyzing societal risk, *F–N* curves represent the annual cumulative probability of exceedance (F) of a certain level of potential fatalities (N). In case of economic risk, these curves are called *F–D* curves and represent the annual cumulative probability of exceedance of a certain level of potential economic damages (D).

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

Among the available complete and quantitative methods, risk models arise as robust tools that allow to integrate all information for estimating risk. Risk models incorporate data on loading scenarios, system response and potential consequences for flood risk identification, calculation and analysis. Outcomes from risk modelling can be later used to represent *F–N* and *F–D* curves.

Figure 1 shows the *F–D* curve for a hypothetic case study as the example given in Escuder-Bueno et al. (2012). Both axes show theoretical but typical values.

In addition, the use of risk models and F–N curves allows to identify main variables and to reduce uncertainty on the analysis.

In a first level, sensitivity analyses can be conducted to study the relationships between the information used for the risk model and improve their understanding. For example, the use of expected, median or worst-case values can affect the results when important parameters are highly variable. There exist several reviews on sensitivity analysis methods (e.g. Frey and Patil, 2002). Among them, some examples can be found in the field of flood risk (e.g., Pappenberger et al., 2008). Different methods can lead to a difference in ranking of importance of model factors. Procedures for sensitive analyses may include, for example, one-at-a-time methods (varying one part of the input while other parts keep the same value) or variance-based techniques (e.g. Gouldby, 2007).

In a second level, more complex analyses can be used to analyze epistemic and random uncertainty. First, epistemic uncertainty refers to the incomplete knowledge about the system and it depends on our ability to understand, measure and describe the system (Merz and Thieken, 2009). Second, random uncertainty (or natural uncertainty) results from the variability of the process. 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. Among them, Monte-Carlo procedures are the most comprehensive and robust methods. These methods involve assigning probability distributions to input variables (Gouldby, 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).

2.2 From risk analysis to risk management

Before describing how outcomes of flood risk analysis are used to inform flood risk management, the following definitions are given:

- *Risk analysis and risk evaluation:* risk analysis can be defined as the methodology aiming at determining risk by characterizing, calculating, analyzing and combining both risk components. Risk evaluation includes the consideration of legal regulations, guidelines and tolerability criteria applicable to the subject under study.
- *Risk assessment:* comprises the understanding, evaluation and interpretation of the perceptions of risk and its societal tolerances to inform decision making and to determine the need for corrective actions.
- *Risk management*: requires the combination of results from risk analysis, evaluation and assessment. In this level, risk control measures are also included as part of the process. These measures include risk re-evaluation and reduction by monitoring defence structures and through the application of mitigation measures, respectively.

Risk management does not necessarily imply a reduction of the risk level, as the reduction or acceptance of a certain level of risk depends on the agreed 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 the FLOODsite project (Gouldby and Samuels, 2005), established as "the continuous and holistic societal analysis, assessment and mitigation of flood risk". Nevertheless, flood risk management involves a wide range of considerations that cannot be easily reproduced in a concise statement. Among other aspects, flood risk management should consider structural and non-structural measures similarly, turning into a continuing cycle of assessing, implementing and maintaining measures to achieve acceptable residual risk and aiming at a sustainable development (Klijn et al., 2008). Hence, risk management combines results, information and recommendations from risk analysis and assessment practices, which are used as key information for the definition and prioritization of risk reduction measures.

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

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, 2009). Event trees are particularly applicable for risk identification and analysis but not for risk evaluation. F–N and F–D curves outstand as effective tools to support risk evaluation.

3 Proposed methodology

The proposed methodology is divided into 11 phases. These phases are based on the methodology proposed in Escuder-Bueno et al. (2012) that has been adapted to incorporate the analysis of small and large dams as common flood defence infrastructures, including potential flooding from failure and non-failure cases (i.e. flooding due to discharges from flood routing). In addition, it includes aspects of risk uncertainty, risk reduction, risk management and governance as illustrated in Fig. 2.

The proposed methodology describes how to estimate flood risk from the three considered flood hazards, compiling information that is used as input data for a risk model, whose architecture definition is also part of the methodology. The model is used to perform risk calculations providing risk outcomes that can be plotted on F–N and F–D

curves. Representations are then used to visualize different situations (e.g. existent risk or situations with new risk reduction measures), and propose risk reduction measures based on an integrated and comprehensive risk analysis.

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

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

3.2 Phase II: review of available data

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

3.3 Phase III: definition of the current situation

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

3.4 Phase IV: risk model architecture

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

An event tree starts with an initiating event. Depending on the characteristics of the case study, two situations may be distinguished:

First, situation A represents urban areas where initiating events, i.e. rainfall events within the urban and the river catchment areas, can be considered as independent phenomena thus potential flooding from these sources of hazard are assumed independent. In this case, different risk models may be used to analyze each flood hazard separately. Then, results are later combined to obtain total flood risk. In this methodology, two overall schemes are provided for this situation (risk models A1 and A2). Figures 3 and 4 show the scheme for defining the risk model architecture for risk models A1 and A2, which correspond to the analysis of pluvial and river flooding (including the existence of dams), respectively.

Second, situation B represents urban areas where rainfall events within the urban and the river catchment areas (including, e.g., the river catchment area upstream the dam) are related, i.e. potential flood events are the result of the same initiating event. Therefore, one risk model can be used for the analysis. Figure 5 shows the overall scheme for defining the risk model architecture for this situation (risk model B).

The overall schemes given in Figs. 3–5 are proposed as reference risk model architectures but they should be adapted for each case study.

3.5 Phase V: input data

Phase V includes all necessary estimations to provide the risk model with input data on three main categories: loads (nodes with solid line in Figs. 3–5), system response (dotted nodes) and consequences (dashed nodes).

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

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

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

Finally, 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 that include the use of hydraulic models to calculate flood characteristics at the river course and at the site under study. Flood depths, velocities, arrival wave times, flood severity levels, flood exposure, etc. are obtained to estimate potential consequences.

Risk models A1 and A2, shown in Figs. 3 and 4, are two independent schemes that start with different (and independent) initiating events:

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

Regarding pluvial flooding, the first scheme (risk model A1) shows a generic diagram that can be used to analyze flooding from rainfall events at any urban catchment area. Table 1 lists overall information that is necessary to develop the corresponding influence diagram.

Regarding river flooding and dam failure, the second scheme (risk model A2) shows a generic diagram that can be used to analyze flooding from rainfall events at the river catchment area. The scheme diverges in different branches depending on the existence of dams upstream the urban area. Information for this second diagram will include the aspects listed in Table 2.

The second scheme may vary depending on the existence of dams. In this scheme, the risk model includes dam failure and non-failure cases (e.g. flood routing discharges). Potential consequences have to be estimated for all cases, including rebuilding costs.

In some cases, it can be assumed that rainfall events in both catchment areas (urban and river catchment area) do not occur independently, then a unique risk model can be established based on the same initiating event. Therefore, information on loads, system response and consequences are necessary to incorporate input data into the risk model architecture proposed in risk model B (Fig. 5) which results from the combination of risk models A1 and A2, by adding a common initiating event.

This model can be used in systems where rainfall events at the urban and river catchment area are correlated, i.e. local or regional rainfall distributions do not differ substantially and spatial and temporal variability on rainfall patterns is not significant.

3.6 Phase VI: risk calculation

In Phases IV and V, the definition of the risk model architecture provides the framework for compiling information to estimate flood risk for the current situation as well as other alternatives with risk reduction measures. With that purpose, the defined influence diagrams are the compact representation of the event tree that includes all possibilities that can lead to flooding. This event tree allows to estimate conditional probabilities and consequences in a mathematically rigorous way.

For situation A, independent risk models for analyzing each flood hazard are considered. In this case, outcomes can be later incorporated to an overall model which obtains total flood risk due to three sources of flood hazard, adapting input data to avoid double counting in areas potentially affected by several flood hazards. Figure 6 shows a general scheme of the process for combining results from independent risk models.

The exceedance probability functions that result from each independent risk model (Models 1, 2, and 3 in Fig. 6) are discretized into a number of intervals. Each interval has two endpoints defined by the values of the damage variable (N_i, N_{i+1}) and their corresponding exceedance probabilities (PE_i, PE_{i+1}). Intervals are generally evenly spaced in the exceedance probability axis. For each interval, the N value for the range i will be computed as the average of the pair N_i, N_{i+1} and the probability as $\mathrm{prob} = \mathrm{PE}_{i+1} - \mathrm{PE}_i$. Finally, the overall model obtains the F–N (or F–D) curve that represents flood risk by integrating the three sources of flood hazard.

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

3.7 Phase VII: risk representation

The use of F–N and F–D curves is proposed in this methodology to represent outcomes of the risk model based on the schemes provided in Phase IV and outcomes from Phase VI.

3.8 Phase VIII: sensitivity and uncertainty

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

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

3.9 Phase IX: risk evaluation

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

3.10 Phase X: risk reduction measures

The analysis of the impact of risk reduction measures (e.g., structural or non-structural measures) is developed in Phase X by analysing different situations and by comparing new outcomes with the results of the *Base Case*.

Based on the *Base Case* risk model, risk reduction measures can be analyzed by estimating new input data. Variations will depend on the type of measure. On the one hand, structural measures may need new nodes and information to characterize system response and failure modes within the risk model architecture. In general, structural measures act by reducing flood probability and modifying system response in case of flooding. On the other hand, non-structural measures affect generally flood potential consequences, reducing vulnerability of people exposed to the flood and potential economic consequences. Non-structural measures include a wide range of options such as urban planning, flood forecasting, advanced warning systems, flood emergency plans, aids and insurance, etc.

3.11 Phase XI: risk management and governance

The aim of analyzing and evaluating current flood risk is to support decision making on flood risk management and governance. Outcomes from risk analysis and the comparison of existent flood risk with other situations that capture the impact of risk reduction measures may help local authorities, emergency services and action forces to develop improved flood emergency action plans. Prioritization of risk reduction measures based on equity and efficiency principles is required to allocate investments and establish risk reduction programmes. Therefore, outcomes of risk analysis provide the necessary information to evaluate existent risk and different alternatives for flood risk reduction. Different indicators can be found (Bowles, 2004) to analyze and justify prioritization of risk reduction measures. Software tools are also available to analyze and compare risk calculations for several alternatives (SPANCOLD, 2012). These tools define the optimal sequence of risk reduction measures according to different efficiency and equity principles.

4 Case study

This section presents and summarizes the application of the proposed methodology to a case study. The urban area is suitable for the analysis since a river crosses this town, dividing the urban area in two parts and it is located 8 km downstream a dam under construction. A simplified scheme of the location of the urban area is shown in Fig. 7.

The purpose of this analysis is to provide information on flood risk after dam construction and the future situation if public education programmes are implemented to improve risk awareness and emergency action planning.

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

4.1 Flood risk analysis

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

4.1.1 Phase I: definition of the scope of the study

Three situations are analyzed for the case study:

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

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

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

Location

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

General description of the system

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

Demography

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

Economy and land use

The land in the municipality is mainly devoted to residential, industrial and rural uses, as listed in Table 3.

4.1.3 Phase III: study of the current situation – definition of the Base Case

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

Therefore, flood events are related to two main sources:

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

Due to climate and topographic conditions of the study area, it can be assumed that both rainfall events are related. Consequently, the overall scheme shown in Fig. 5 (model B) has been used to develop the risk model for this case study.

4.1.4 Phase IV: definition of the risk model architecture

Two risk models have been developed ad hoc for the case study. The first risk model (Fig. 8) is used to analyze the current situation (i.e. the natural flow regime of the river and considering the existence of the drainage system). The second risk model scheme (Fig. 11) makes possible the incorporation of all information regarding pluvial flooding and river flooding including the existence of the dam (Phase X).

Figure 8 shows the influence diagram for the first risk model whereas nodes are defined in Table 4.

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

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

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

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

Loads

Input data regarding pluvial flooding includes information of flood events resulting from rainfall episodes for return periods up to 100 yr. This upper value is based on the characteristics of the urban catchment area where it is assumed that rainfall rates for higher return periods do not exceed significantly the obtained estimates for the rainfall event of 100 yr of return period. Maximum annual daily rainfall rates are listed in Table 5.

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

Concerning the natural flow regime of the river (with a mean annual peak discharge of 29.3 $m^3 s^{-1}$), hydrographs from return periods that range from 2 to 10 000 yr are used.

System response

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

Concerning the natural flow regime of the river, flooded areas, flood depths, peak discharges, and arrival wave times provided by the analysis carried out in 2010 (Sanz-Jiménez et al., 2012) are used from load scenarios resulting from the aforementioned hydrographs.

Potential consequences

The estimated population in this case study is 2004 inhabitants. However, daily and seasonal variations exist according to the available demographic data. Therefore, four time categories are set as shown in Table 6 in order to reflect that variability (where summer season ranges from 1 July to 15 September and day-time category ranges from 08:00 UTC+1 to 22:30 UTC+1). Probabilities for each category are listed in Table 6.

Potential fatalities for each time category and flood event are obtained by multiplying population at risk by fatality rates. For the analysis, fatality rates proposed in

Escuder-Bueno et al. (2012) are used for estimating potential loss of life in case of pluvial and river flooding (natural flow regime of the river).

Potential economic damages are obtained by estimating direct costs from flooded areas, land-use, reference costs and percentage of damages depending on flood depths. Two land-use categories are considered: residential and industrial. According to existing studies (COPUT, 2002), the reference rates shown in Table 7 are considered, based on a scale ranging from 0 to 100, where 100 is equivalent to an economic value of 82 € m^{-2} (2002). The given values of these rates are calculated based on Consumer Price Index values for 2011.

Total costs are estimated by adding direct and indirect costs, estimated as a 27 % percentage of direct costs. Direct costs are obtained by multiplying the estimated percentage of damages and the reference cost of the affected area (residential or industrial land-use). Percentage of damages is obtained from the depth-damage curve proposed by USACE (2003) for buildings with two or more stories without basement. Total costs for the *Base Case* in case of pluvial flooding and the natural flow regime of the river are shown in Table 8.

4.1.6 Phase VI: risk calculation

All previous information on loads, system response and consequences in case of pluvial and river flooding is incorporated to the risk model defined in Fig. 8, then risk calculations are performed using the iPresas software (Serrano-Lombillo et al., 2009).

4.1.7 Phase VII: risk representation

Risk estimations are obtained to represent F–N and F–D curves for the situation before dam construction (*Base Case*). Results for the *Base Case* (Figs. 9 and 10) show that the total societal and economic risks (area under the F–N and F–D curve) have been estimated in 0.097 lives yr^{-1} and 3 864 323 € yr^{-1}, respectively. These values are obtained from risk calculation or by considering the area under F–N and F–D curves.

4.1.8 Phases VIII: flood risk evaluation

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

4.1.9 Phase IX: sensitivity and uncertainty analyses

A sensitivity analysis of the established conditional probabilities for all dam failure modes is further described in Phase X, after the study of the situation with the dam.

4.1.10 Phase X: risk reduction measures

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

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

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

Dam construction costs are established in 100 M€ and EAP annual maintenance costs in 30 000 €.

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

Risk model architecture

Figure 11 shows the influence diagram for the second risk model. All the information required to characterize loads, system response and consequences is listed in Table 9 (failure modes are later described). The risk model includes four dam failure modes (San-Jiménez et al., 2012): two failure modes related to structural-geotechnical aspects (slippage of dam blocks) and two failure modes related to failure of outlet works (e.g. stilling basin erosion or undermining of the toe of the dam).

Loads: river flooding including the dam

Annual exceedance probabilities of different inflow rates at the reservoir are considered. Figure 12 shows inflow discharge distributions at the reservoir for five different annual exceedance probabilities (PAE, with units of yr^{-1}). Dam failure is analyzed based on inflow rates at the reservoir for return periods up to 100 000 yr. Estimations of feasible previous water pool levels at the reservoir are also obtained (Fig. 13). Gate reliability of bottom outlet works is estimated in 85 % (the spillway is uncontrolled).

System response: river flooding including the dam

A multidisciplinary group of professionals (33 participants), covering different areas of knowledge such as geology, hydrology, seismicity, materials, dam design, construction, monitoring, hydrology, etc. was actively involved in 2010 in the development of the different risk assessment activities to characterize loads, system response and consequences in case of failure of this dam (Jiménez-Sanz et al., 2012). Four failure modes are considered in this analysis (denoted as FM2, FM3, FM5, and FM6). These failure modes are related to potential slippage due to the existence of the *San Fermín* fault or failure of outlet works in a hydrological event. Table 10 gives a short description of each failure mode. The conditional probabilities that characterize each failure mode were obtained by expert judgment.

Two series of flow discharges are considered: discharges due to failure cases and flood routing cases (Table 11). For each case, flooded areas are obtained based on inundation maps from hydraulic simulations using the software tool MIKE11. Flood depths and arrival wave times are also obtained from hydraulic modelling.

A sensitivity analysis of established conditional probabilities for all failure modes is also conducted. With that purpose, lower and upper estimates obtained from expert judgment are also incorporated into the risk model and results are denoted as Case L and Case U, respectively (best estimates were used in the *DEAP-Case*). Table 13 shows the established values from expert judgment for all nodes of the risk model associated with failure modes (nodes N and D, where a, b, c denote different estimates for the same node based on discharges or overtopping heights).

Potential consequences: river flooding including the dam

Potential affected elements (e.g. households, industrial areas, etc.) are identified from hydraulic simulations. Based on flood characteristics (e.g. flooded surface, flood depth, peak discharge at the study site, arrival wave time, etc.), population at risk is obtained by quantifying the number of affected households and the number of inhabitants. Fatality rates are obtained from reference fatality rates proposed in Escuder-Bueno et al. (2012) based on available warning times and flood severity. The number of potential fatalities (N) for the *DEAP-Case* is given in Table 12 for the largest flood events in failure (Q_{br8}) and non-failure cases (Q_{nbr6}).

Results

Figures 14 and 15 illustrate the results for the three cases with lower (Case L), upper (Case U) and best estimates (DEAP-Case) of probabilities for failure mode characterization. As it can be observed in both graphs, the F–N and F–D curves for both cases move upwards or downwards as the dam failure probabilities shifts in comparison with the DEAP-Case. However, results on total societal or economic risk do not present significant differences since these values are more influenced by the impact of pluvial flooding in the urban area.

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

Based on the *DEAP-Case*, the situation with new non-structural measures, denoted as *NonSt-Case*, includes a Public Education and Warning Programme (PEWP). The implementation cost of this Programme is 50 000 € (annual maintenance costs of 15 000 €).

Its impact can be incorporated into the risk model by estimating new consequences. With regard to potential fatalities, lower fatality rates can be used for analyzing pluvial flooding for situations with advanced warning systems. In case of river flooding including the dam, fatality rates associated with this situation are established at level 10 from the classification proposed by Escuder-Bueno et al. (2012). In general, the impact of non-structural measures on potential economic damages is estimated by considering the state of knowledge on the relationship between warning times and flood hydraulic characteristics (Messner et al., 2007; Parker et al., 2005; Penning-Rowsell et al., 1978). However, it is considered that a measure involving warning systems should be implemented along with public education actions, as it is assumed that warnings are only effective if population at risk have a certain level of knowledge on how-to-act in case of flood. Therefore, reduction of potential economic damages (e.g., from installation of waterstops to prevent water from entering households) can only be considered if public educational activities are in place. In this case, a reduction of the estimated damages can be achieved.

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

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
|◀ | ▶|
◀ | ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

Eq. (3)

$$C_\mathrm{A} = C_\mathrm{man} + \frac{C_\mathrm{int}}{(1+r)} \cdot \frac{r \cdot (1+r)^n}{(1+r)^n - 1}, \tag{3}$$

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

Annualized costs are obtained to calculate an indicator of the economic risk reduction generated by the implementation of the measure. The ACSLS (Adjusted Cost per Statistical Life Saved) indicator is used in this article (ANCOLD, 2003) and it follows the expression given in Eq. (4). This indicator can be used to figure out whether measures reduce risk in an efficient and equitable way. Bowles (2004), in a preliminary way, proposed that a measure is very justified with an ACSLS lower than \$3 million and is not much justified with an ACSLS higher than \$140 million. This indicator is defined as:

$$\mathrm{ACSLS} = \frac{C_\mathrm{A} - (E[R_\mathrm{E}] - E[R_\mathrm{R}]) - (O[R_\mathrm{E}] - O[R_\mathrm{R}])}{(E[N_\mathrm{E}] - E[N_\mathrm{R}])}, \tag{4}$$

where C_A is the annualized cost of the risk reduction measure, $E[R_\mathrm{E}]$ and $E[R_\mathrm{R}]$ are the estimates of total economic risk before and after implementing the measure, $O[R_\mathrm{E}]$ and $O[R_\mathrm{R}]$ are the operational costs of the dam, and, $E[N_\mathrm{E}]$ and $E[N_\mathrm{R}]$ are the estimates of total societal risk. In this case study, dam operational costs are considered constant.

Figures 16 and 17 show the F–N and F–D curves, which represent societal and economic flood risk for the analyzed situations: the *Base Case* (solid line), the *DEAP-Case* (dashed line) and the *NonSt-Case* or situation with non-structural measures (dotted line).

Results for the *DEAP-Case* show that approx. 360 fatalities result for an annual cumulative exceedance probability (F) of 1×10^{-8} for the situation after dam construction.

Results show that the total probability of failure is 3.7×10^{-7}, which corresponds to the horizontal part of the *F–N* curve. The combination of pluvial flooding and flood routing cases reach a maximum number of approx. 3 fatalities. This value is only exceeded by dam failure cases.

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

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

Table 14 shows the results of total societal and economic flood risk for each situation (*Base Case*, *DEAP-Case* and *NonSt-Case*). These values are obtained from *F–N* and *F–D* curves where they represent the area under each curve. Therefore, values are given in terms of lives yr^{-1} or € yr^{-1}.

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

4.1.11 Phase XI: risk management and governance

From the risk outcomes shown in Figs. 16 and 17, it has been demonstrated that potential fatalities in case of dam failure are significant but related to low probabilities. Therefore, the implementation of non-structural measures of public education, warning and improved coordination schemes in case of flood emergency are necessary to reduce existent risk and to improve the implementation of the Dam Emergency Action Plan. The guiding principle should be ensuring effective communication mechanisms among dam operators, emergency services and local authorities exist to ensure a quick response in case of emergency. Annual education programs on flood risk, improved warning systems and training exercises require relatively low economic and technical resources when compared to their potential risk reduction as they may increase the risk awareness and flood severity understanding of the population at risk.

5 Conclusions and further research lines

In the first part of this article the main aspects on flood risk analysis, assessment and management are discussed, including references to existing methods for estimating flood risk and its components (probability and consequences).

This article presents a comprehensive methodology to integrate the analysis of pluvial flooding, river flooding and dam failure into urban flood risk analysis to provide better and more complete information to decision makers on flood risk management. The methodology starts from a methodological piece developed within the SUFRI project and includes the analysis of dam failure to quantify and evaluate flood risk in urban areas. The goal of this methodology is to provide a tool for flood risk analysis that integrates all information regarding several sources of flood hazard.

The use of risk models provides a logic and mathematically rigorous framework for compiling information. In addition, integrated societal and economic quantitative risk outcomes can be obtained. The relevance of quantitative flood risk analysis in urban areas is supported by the obtained results, indicating that F–N and F–D curves are helpful and comprehensive tools to represent flood risk. These curves are the basis to illustrate risk quantification and the effect of different measures on flood risk reduction. Thereby, they prove to be helpful in planning and managing mitigation measures. Furthermore, F–N and F–D curves may be used to compare predicted risks against tolerability criteria or historical data. Reinforcement of best policies (e.g., urban planning, emergency management, civil protection, etc.) and good governance may be achieved by using the outcomes of flood risk analysis.

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

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

Regarding tolerability risk guidelines, there is still a lack of general standards for flood risk analysis in urban areas. Several individual and societal criteria can be found for regional cases, e.g. in the Netherlands (Vrijling, 2001). Therefore, further investigation should focus on developing common standards to assess urban flood risk.

The proposed methodology goes one step forward in the process towards a comprehensive flood risk management that integrates all sources of flood hazard (natural and man-made threats), analyzing all related flood defence infrastructures (e.g. dams, dikes, levees, etc.) and involves all phases from risk analysis to risk governance (Fig. 18). Within this framework, further research would be conducted to integrate human-induced hazards and to incorporate potential failure of other flood defence infrastructures such as fluvial dike systems into quantitative flood risk analysis.

Acknowledgements. The work presented in this paper 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).

References

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

Bowles, D. S.: ALARP Evaluation: Using Cost Effectiveness and Disproportionality to Justify Risk Reduction, ANCOLD Bulletin, 127, 89–106, 2004.

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.: ICOLD Bulletin 130 on “Risk Assessment in Dam Safety Management”, IPENZ Proceedings of Technical Groups 33/2, Paris, France, 2005.

COPUT: “Conselleria d’Obres Públiques, Urbanisme i Territori” – Plan de Acción Territorial de Carácter Sectorial sobre Prevención de Riesgo de Inundación en la Comunidad Valenciana (PATRICOVA), 2002 (in Spanish).

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.

Engel, H.: The flood event 2002 in the Elbe river basin causes of the flood, its course, statistical assessment and flood damages, Houille Blanche, 6, 33–36, doi:10.1051/lhb:200406003, 2004.

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

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

Escuder-Bueno, I., Castillo-Rodríguez, J. T., Zechner, S., Jöbstl, C., Perales-Momparler, S., and Petaccia, G.: A quantitative flood risk analysis methodology for urban areas with integration of social research data, Nat. Hazards Earth Syst. Sci., 12, 2843–2863, doi:10.5194/nhess-12-2843-2012, 2012.

Frey, H. C. and Patil, S. R.: Identification and review of sensitivity analysis methods, Risk Anal., 22, 553–78, 2002.

Gouldby, B.: Uncertainty and sensitivity analysis: method description, FLOODsite project, Report: T24-10-07, HR Wallingford, UK, October 2007.

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

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

ISO: International Standard, Risk management – Vocabulary, International Organization for Standardization, ISO GUIDE 73, 2009.

Jonkman, S. N.: Global perspectives on loss of human life caused by floods, Nat. Hazards, 34, 151–175, 2005.

Jonkman, S. N., Maaskant, B., Boyd, E., and Levitan, M. L.: Loss of life caused by the flooding of New Orleans after hurricane Katrina: analysis of the relationship between flood characteristics and mortality, Risk Anal., 29, 676–98, doi:10.1111/j.1539-6924.2008.01190.x, 2009.

Jonkman, S. N., Jongejan, R., and Maaskant, B.: The use of individual and societal risk criteria within the Dutch flood safety policy – nationwide estimates of societal risk and policy applications, Risk Anal., 31, 282–300, doi:10.1111/j.1539-6924.2010.01502.x, 2011.

Klijn, F., Samuels, P., and van Os, D.: Towards flood risk management in the EU: state of affairs with examples from various European countries, International Journal River Basin Management (JRBM), 6, 307–321, 2008.

Kubal, C., Haase, D., Meyer, V., and Scheuer, S.: Integrated urban flood risk assessment – adapting a multicriteria approach to a city, Nat. Hazards Earth Syst. Sci., 9, 1881–1895, doi:10.5194/nhess-9-1881-2009, 2009.

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

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, HR Wallingford, UK, January 2007.

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.: RISK MAP, improving flood risk maps as a means to foster public participation and raising flood risk awareness: toward flood resilient communities, Final Report, ERA-NET CRUE, London, UK, September 2011.

Munger, D. F., Bowles, D. S., Boyer, D. D., Davis, D. W., Margo, D. A., Moser, D. A., and Regan, P. J.: Interim tolerable risk guidelines for US Army Corps of Engineers Dams, USSD Conference, 20–24 April 2009, Nashville, Tennessee, USA, 2009.

Pappenberger, F., Beven, K. J., Ratto, M., and Matgen, P.: Multi-method global sensitivity analysis of flood inundation models, Adv. Water Resour., 31, 1–14, 2008.

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.

Pelling, M.: The Vulnerability of Cities – Natural Disasters and Social Resilience, Earthscan Publications Ltd., London, UK, ISBN 1-85383-830-6, 2003.

Penning-Rowsell, E., Chatterton, J. B., and Parker, D.: The effect of flood warnings on flood damage reduction, Middlesex Polytechnic Flood Hazard Research Project, Flood Hazard Research Centre, Middlesex University, UK, 1978.

PGOU (Plan General de Ordenación Urbana): Urban general plan, City of Benaguasil, Valencia, Spain, September 2009 (in Spanish).

Sanz-Jiménez, D., Escuder-Bueno, I., and Silva-Tulla, F.: Quantitative risk analysis for a dam under construction in Spain, in: Proceedings of the 32nd Annual USSD Conference, 23–25 April, United States Society on Dams, New Orleans, Louisiana, 2012.

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, ERA-NET CRUE, London, UK, 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, 25–29 May 2009.

SPANCOLD: Risk Analysis as applied to dam safety, Technical Guide on Operation of Dams and Reservoirs, Spanish National Committee on Large Dams, Madrid, Technical Guides on Dam safety, 8, 91–93 2012.

Thieken, A. and Beurton, S.: Addressing the key findings of research related to Flood resilient communities – managing the consequences of flooding, ERA-NET CRUE, London, UK, Flood Risk Management Research Monograph Series, Synthesis Report No II-2012, 2012.

USACE: Economic Guidance Memorandum (EGM), 04-01, Generic Depth-Damage Relationships for Residential Structures with Basements, US Army Corps of Engineers, Washington, USA, October 2003

Vrijling, J. K.: Probabilistic design of water defence systems in the Netherlands, Reliab. Eng. Syst. Safe., 74, 337–344, 2001.

WMO/GWP: Urban flood risk management, A tool for integrated flood management, World Meteorological Organization (WNO) & Global Water Partnership (GWP), Associated Programme on Flood Management, Switzerland, March 2008.

Table 1. Information for the influence diagram for pluvial flooding.

Information for risk model A1
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
Potential consequences (fatalities and economic damages) estimated for the aforementioned flood characteristics at the site under study

Table 2. Information for the influence diagram for river flooding, incorporating existence of dams.

Information for risk model A2
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.)
Reliability of water control infrastructures (outlet works)
Previous water pool levels at the reservoir (if applicable)
Results of flood routing analysis
Potential failure modes and probabilities
Flow discharges in case of dam failure and in non-failure cases
Characteristics of the flood at the site under study
Potential consequences (fatalities and economic damages) estimated for the aforementioned flood characteristics at the study site

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀| |▶
◀ ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

Table 3. Land uses.

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

Table 4. Nodes for risk model 1.

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

Table 5. Maximum annual daily rainfall rates at the case study.

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

Table 6. Time categories and probabilities.

Time category	Population (inhabitants)	Season probability	Time category probability
TC1 Summer/day	3060	0.208	$0.208 \cdot 0.604 = 0.126$
TC2 Summer/night	2804	0.208	$0.208 \cdot 0.369 = 0.077$
TC3 Winter/day	2260	0.792	$0.792 \cdot 0.604 = 0.478$
TC4 Winter/night	2004	0.792	$0.792 \cdot 0.369 = 0.292$

Table 7. Reference costs for estimating potential economic damages.

	Rate	Value	
		2002	2011
Residential areas	56.3/100	46.2 €	58.5 €
Industrial areas	18.8/100	15.4 €	19.5 €

Table 8. Example of estimated potential fatalities and economic damages for the *DEAP-Case*.

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

Table 9. Nodes for risk model 2.

Node	Definition
season; day/night	Probabilities of different time categories (e.g. summer/day, winter/night) to incorporate seasonal and daily variations of population at risk
flood	Range of return periods related to inflow hydrographs into the reservoir and rainfall events at the urban area
runoff	Runoff characteristics at the study site
lives_plu; eur_plu	Consequence estimations in case of pluvial flooding (life-loss and potential economic damages, respectively)
WPL; BO Op; Spil.Op	Previous water pool levels (WPL) and reliability of dam outlet works
Routing	Maximum water levels and peak flow discharges obtained from flood routing analyses based on previous information on water pool levels, gate reliability, etc.
FM	Four failure modes are characterized and conditional failure probabilities are included in nodes denoted as *N* or *D*.
N08	FM2 and FM3 First node: Existing sliding plane
N09	FM2 and FM3 Second node: Degradation surface
N10	FM2 and FM3 Third node: Loss of efficiency of drain wells
N11	FM2 and FM3 Forth node: Hydraulic connection
N13	FM2 and FM3 Fifth node: Permeability injections

Table 9. Continued.

Node	Definition
D02	FM2 Sixth node: No detection
Nfailure	FM2 and FM3 Last node: Failure probabilities based on water pool levels
N16	FM3 Sixth node: Silting of drains
D03	FM3 Seventh node: No detection
N31	FM5 First node: Stilling basin erosion
N32	FM5 Second node: Stilling basin breach
D05	FM5 Third node: No detection
N33	FM5 Forth node: Scouring
N34	FM5 Last node: Failure probabilities based on discharges at the stilling basin
N35	FM6 First node: Foot erosion
N36	FM6 Second node: Upwards erosion
N37	FM6 Last node: Failure probabilities based on water pool levels (overtopping)
Qbr	Peak flow discharges in case of dam failure based on water pool levels
lives_br; eur_br	Estimations of potential loss of life and economic damages in case of dam failure
lives_nobr; eur_nobr	Estimations of potential loss of life and economic damages in case of flood routing
lives_total; eur_total	Overall results including the three sources of flood hazard

Table 10. Failure modes considered for the analysis.

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

Table 11. Selected flow discharges in dam failure and non failure cases for estimating consequences.

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

Table 12. Example of estimated potential fatalities and economic damages for the *DEAP-Case* (river flooding including dam failure and flood routing).

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

Table 13. Probability estimates for failure mode identification (lower, best and upper estimates).

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

Table 14. Total flood risk for the case study.

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

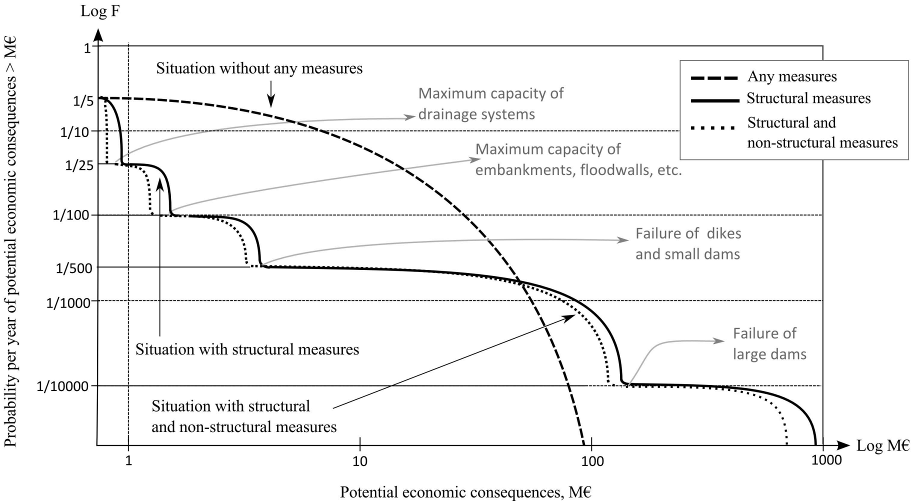


Fig. 1. Example of *F*–*D* curves of a hypothetic case study (Escuder-Bueno et al., 2012).

Title Page
Abstract
Introduction
Conclusions
References
Tables
Figures
◀◀
▶▶
◀
▶
Back
Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

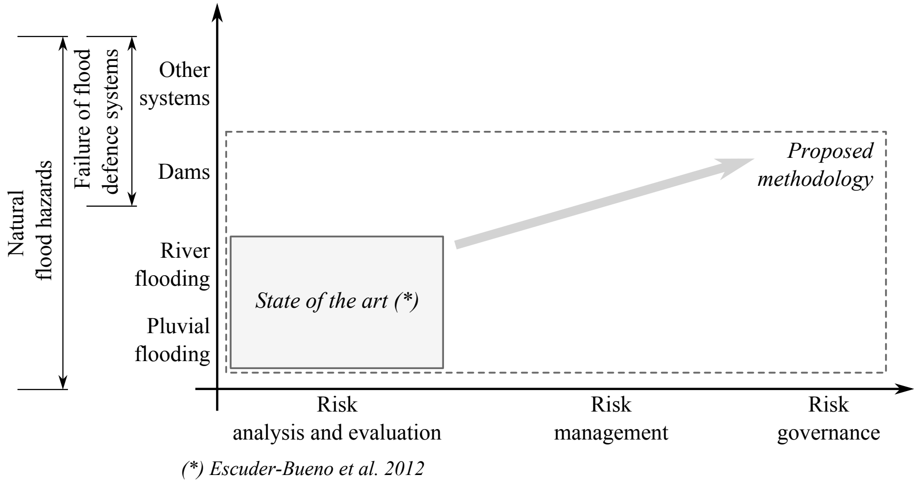


Fig. 2. Proposed methodology within the risk analysis – governance framework.

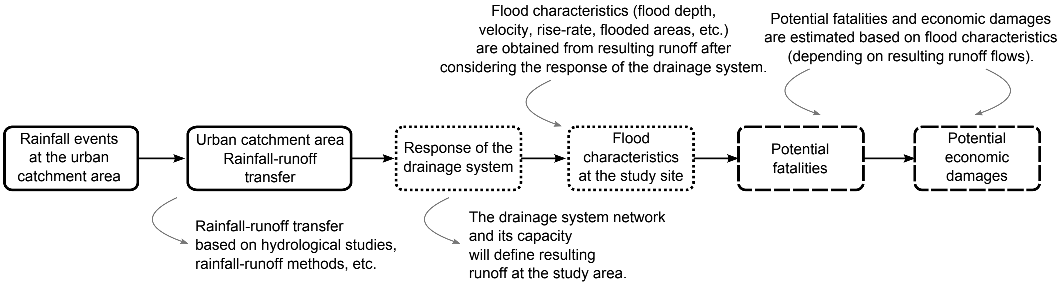
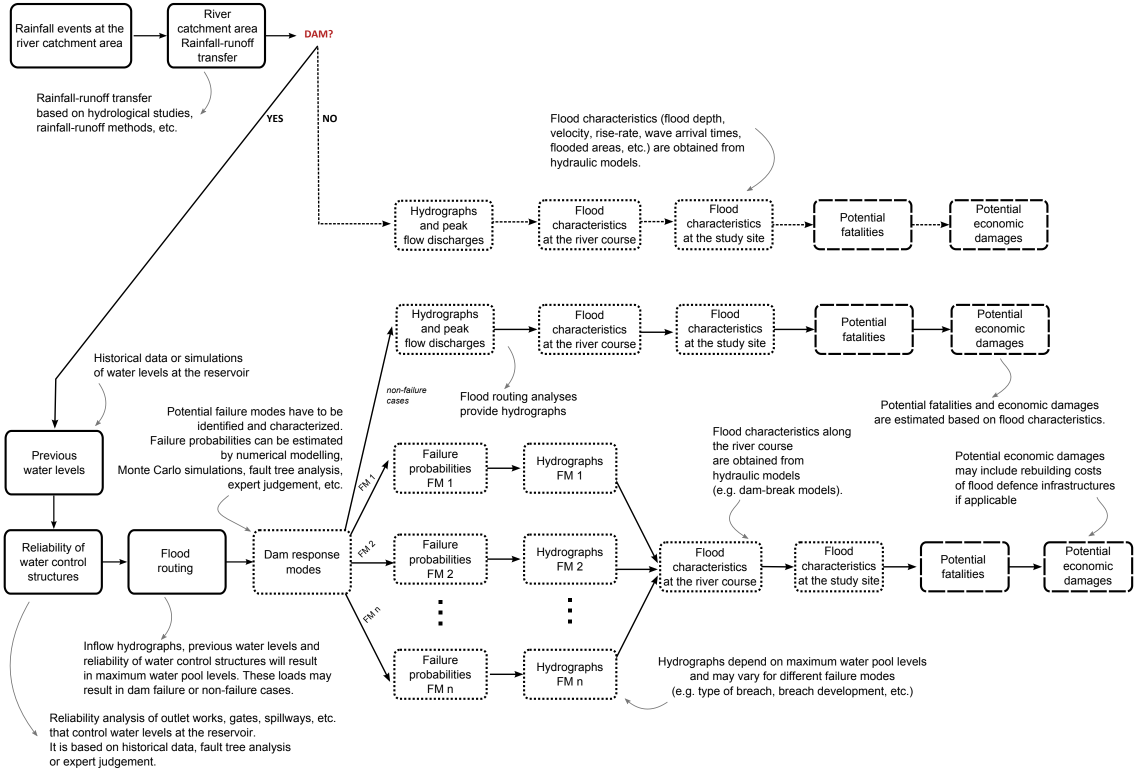


Fig. 3. Generic diagram for risk model architecture on flood risk analysis: independent initiating event (Model A1).

Title Page
Abstract
Introduction
Conclusions
References
Tables
Figures
◀◀
▶▶
◀
▶
Back
Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion



Rainfall-runoff transfer based on hydrological studies, rainfall-runoff methods, etc.

Flood characteristics (flood depth, velocity, rise-rate, wave arrival times, flooded areas, etc.) are obtained from hydraulic models.

Historical data or simulations of water levels at the reservoir

Flood routing analyses provide hydrographs

Potential fatalities and economic damages are estimated based on flood characteristics.

Potential failure modes have to be identified and characterized. Failure probabilities can be estimated by numerical modelling, Monte Carlo simulations, fault tree analysis, expert judgement, etc.

Flood characteristics along the river course are obtained from hydraulic models (e.g. dam-break models).

Potential economic damages may include rebuilding costs of flood defence infrastructures if applicable

Inflow hydrographs, previous water levels and reliability of water control structures will result in maximum water pool levels. These loads may result in dam failure or non-failure cases.

Hydrographs depend on maximum water pool levels and may vary for different failure modes (e.g. type of breach, breach development, etc.)

Reliability analysis of outlet works, gates, spillways, etc. that control water levels at the reservoir. It is based on historical data, fault tree analysis or expert judgement.

Fig. 4. Generic diagram for risk model architecture on flood risk analysis: independent initiating event (Model A2).

NHESSD

1, 3305–3371, 2013

Integrating information for flood risk management

J. T. Castillo-Rodríguez et al.

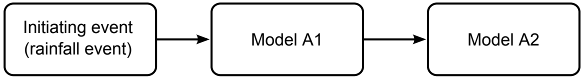


Fig. 5. Generic diagram for risk model architecture on flood risk analysis: common initiating event (Model B).

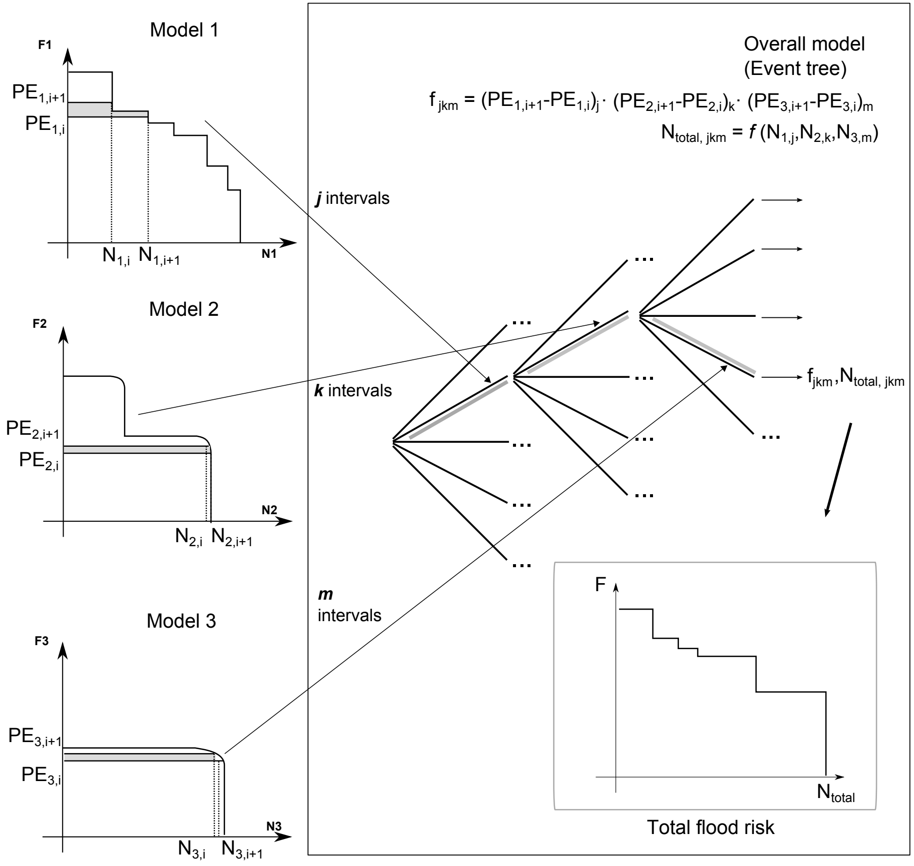


Fig. 6. Combination of outcomes of different risk models.

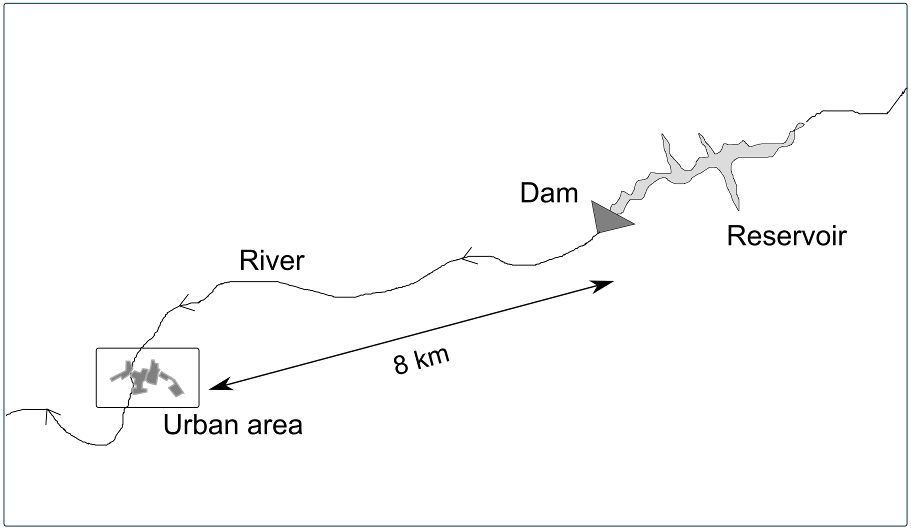


Fig. 7. Overall scheme of the urban area downstream the dam.

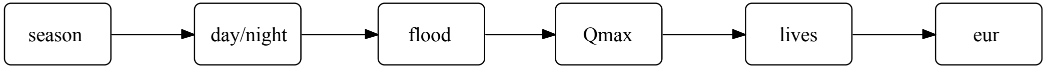


Fig. 8. Risk model 1. *Base Case* (natural flow regime of the river and drainage system).

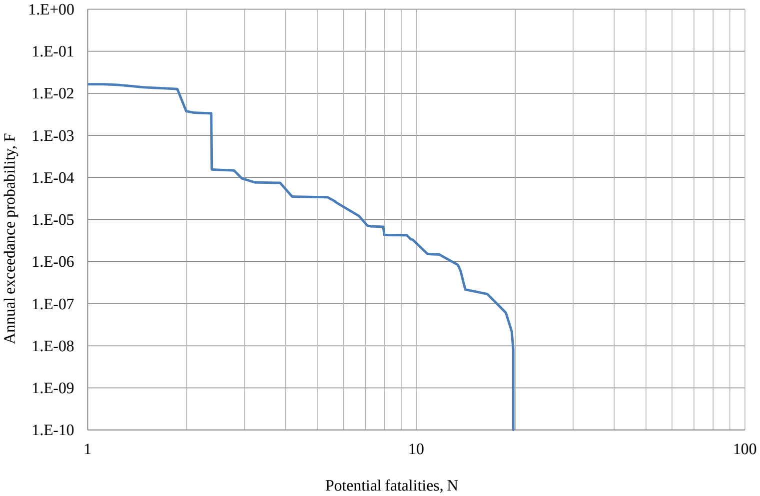


Fig. 9. *F–N* curve for the *Base Case*.

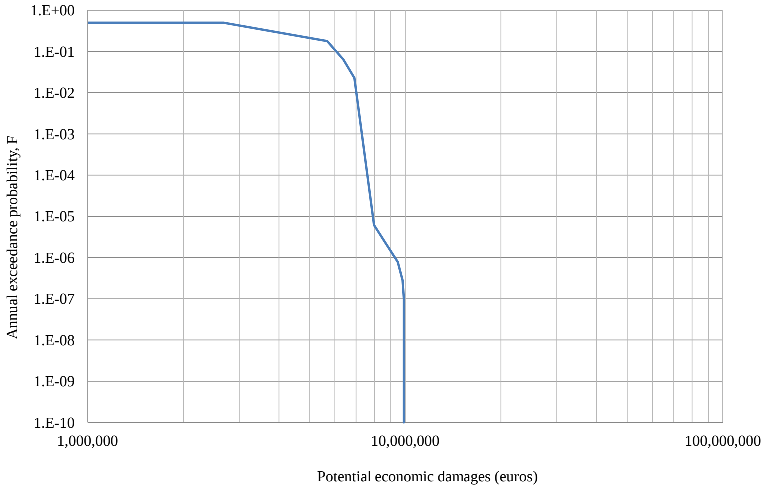


Fig. 10. *F–D* curve for the *Base Case*.

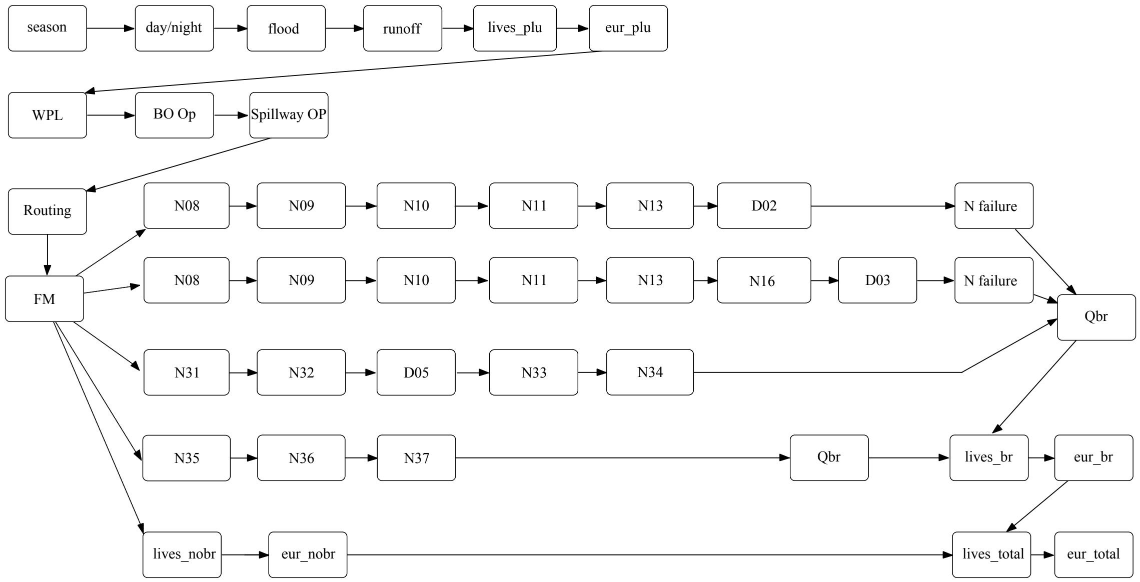


Fig. 11. Risk model 2. Pluvial flooding and river flooding including the existence of the dam.

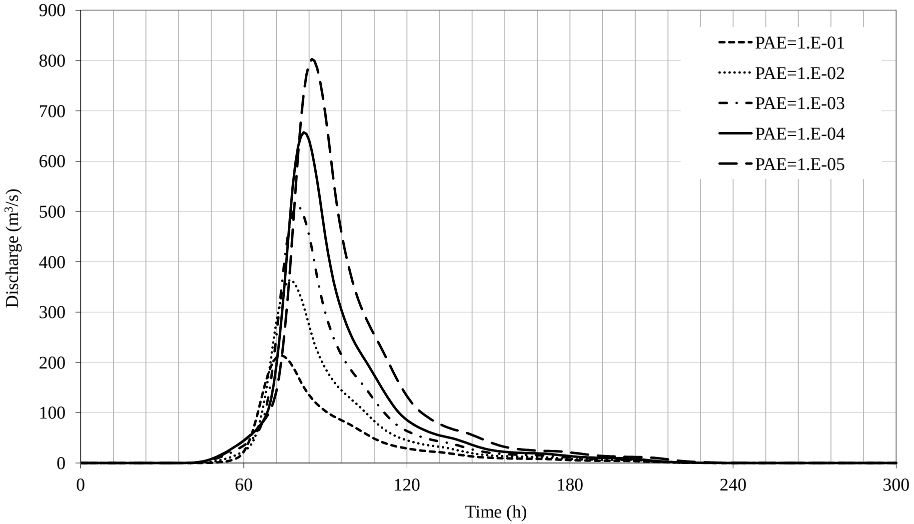


Fig. 12. Inflow rates at the reservoir for several annual exceedance probabilities (PAE).

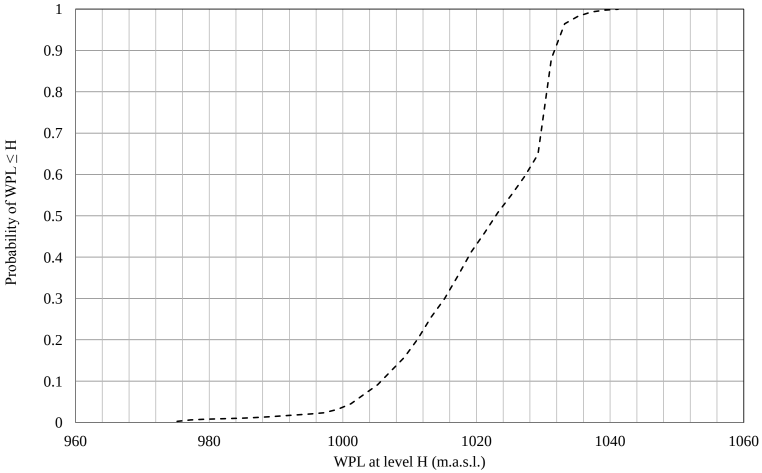


Fig. 13. Exceedance probabilities of water pool levels (WPL) at the reservoir.

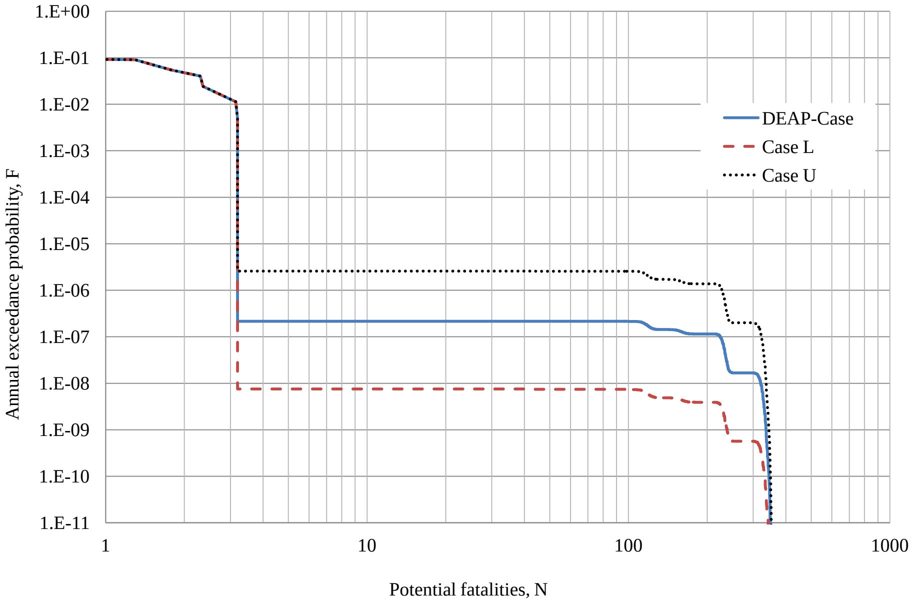


Fig. 14. *F*–*N* curves for the DEAP-Case and sensitivity analysis.

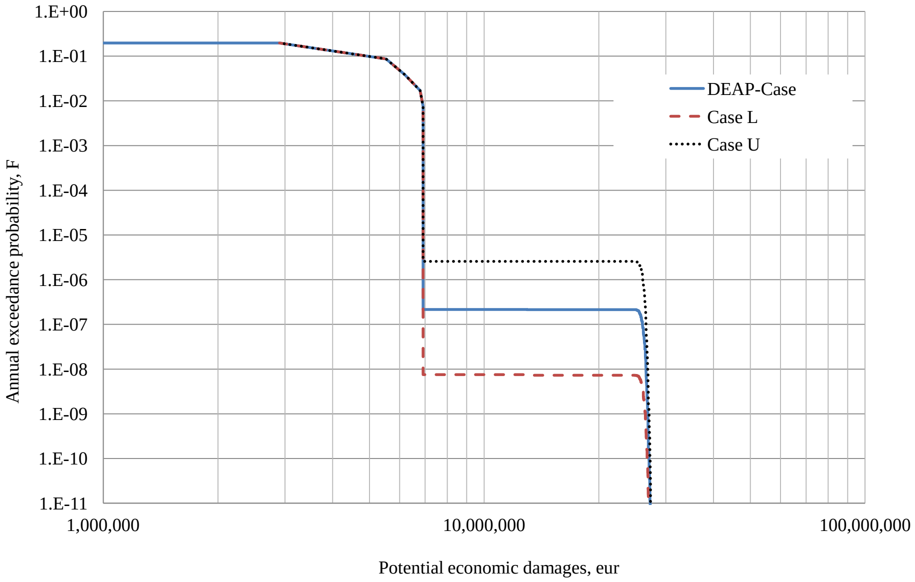


Fig. 15. *F–D* curve for the DEAP-Case and sensitivity analysis.

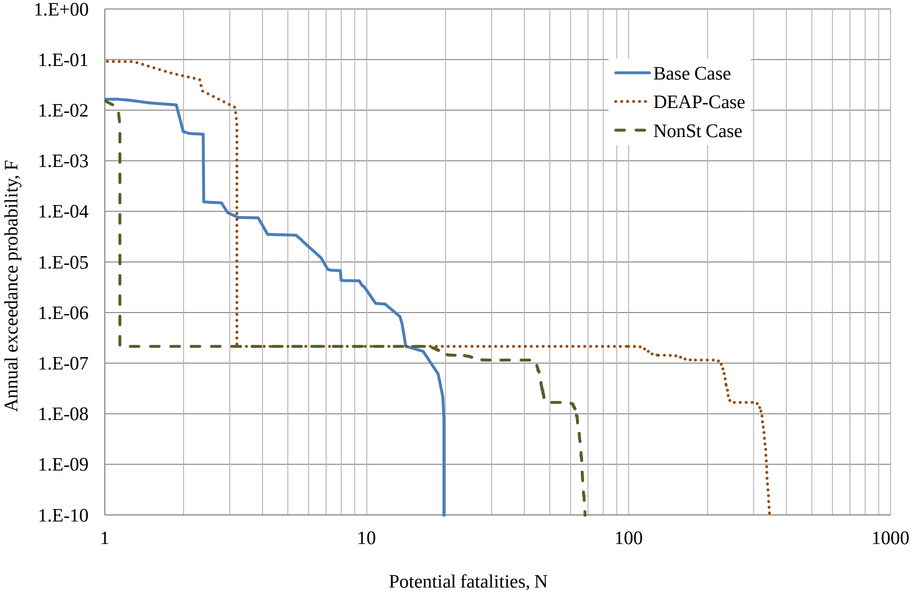


Fig. 16. *F–N* curves for all analyzed situations.

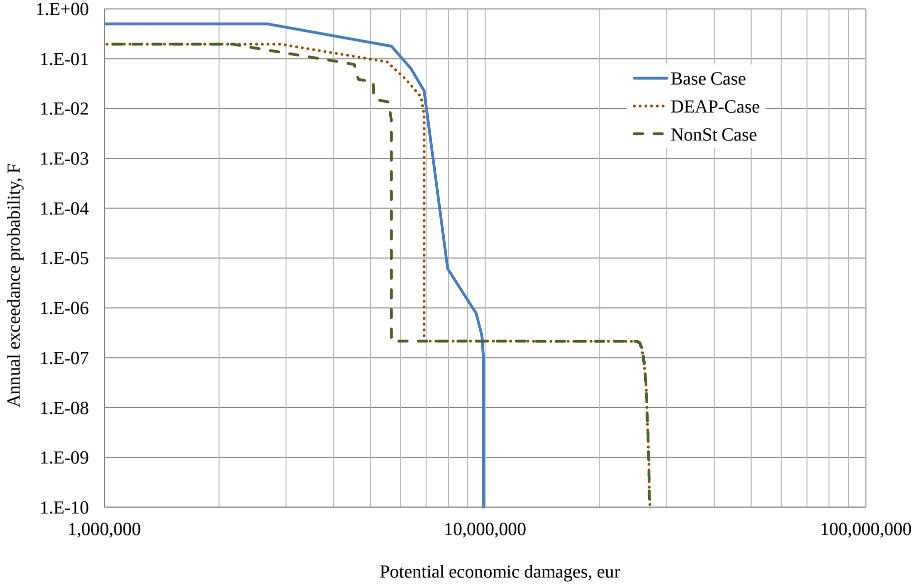


Fig. 17. *F–D* curves for all analyzed situations.

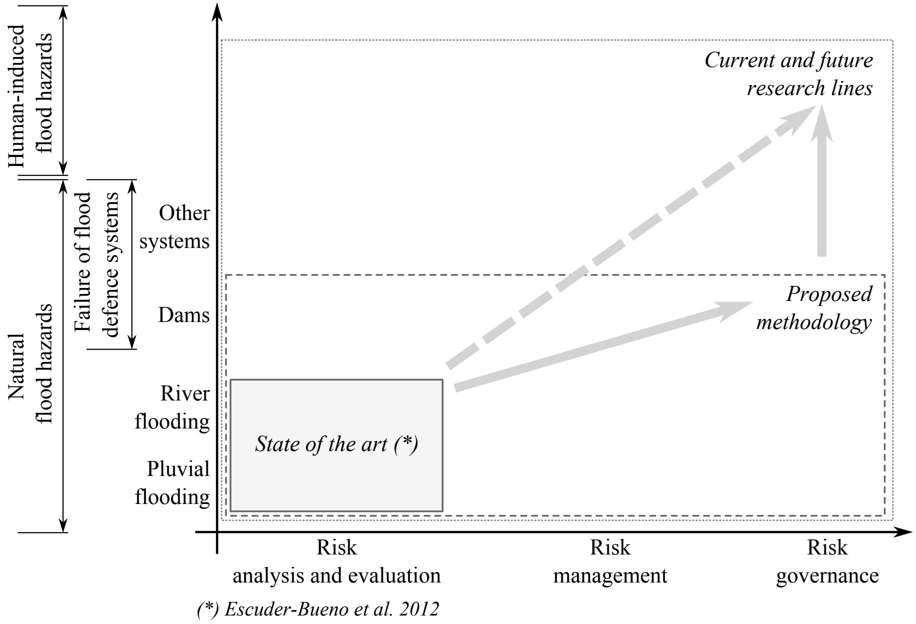


Fig. 18. Current and future research lines within the risk analysis-governance framework.