TITLE

A combined risk analysis approach for complex dam-levee systems

ABSTRACT

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

KEYWORDS

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

1. INTRODUCTION

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

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

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

1.1. Current challenges on flood risk reduction

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

1.4. Towards risk-informed dam and levee safety governance

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

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

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

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

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

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

2. PROPOSED METHODOLOGY

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

2.1. Concepts and overall analysis framework

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

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

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

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

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

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

2.2 Proposed risk model architecture for complex dam-levee systems

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

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

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

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

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

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

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

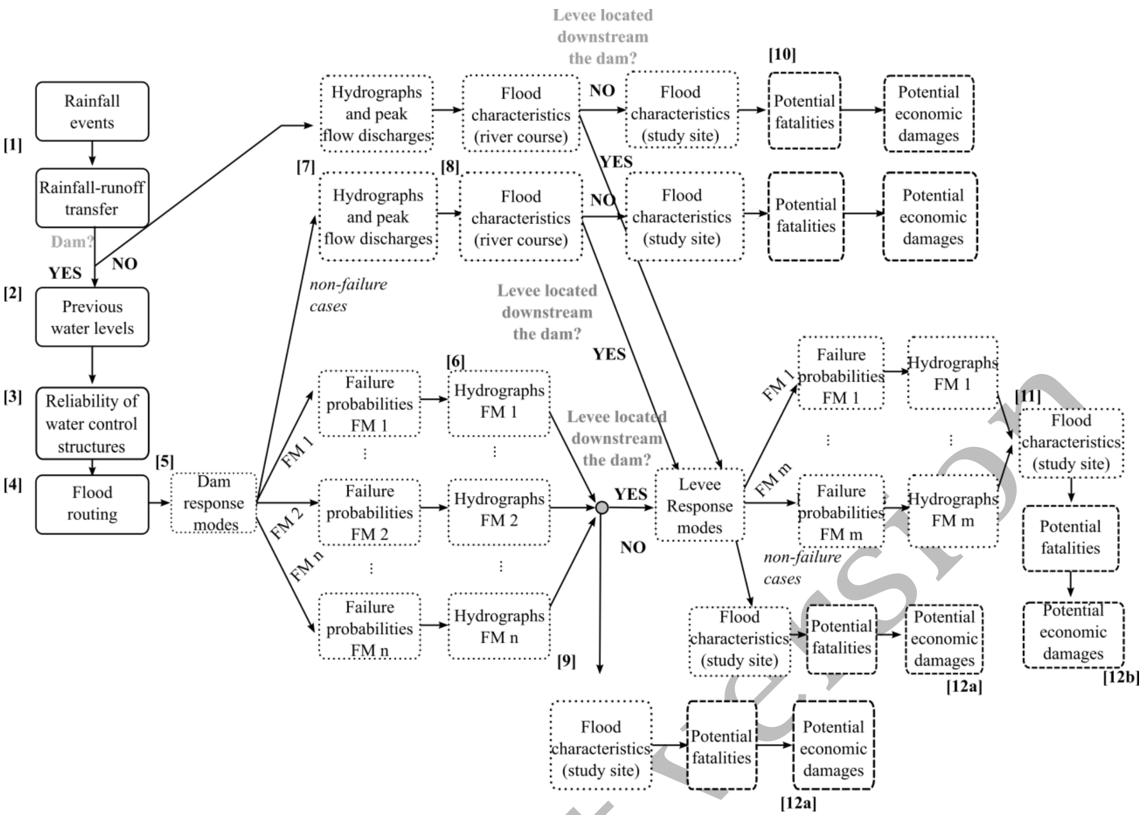


Figure 1. Generic combined risk model scheme. Nodes outlined with solid, dotted and dashed lines refer to loads, system response and consequences, respectively.

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

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

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

3. CASE STUDY ANALYSIS

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

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

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

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

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

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

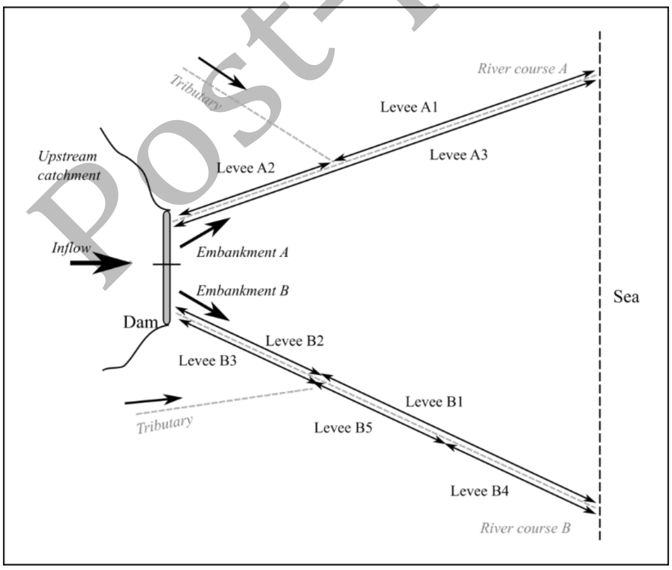


Figure 2. Simplified scheme representing analysed dam-levee system. (B1 and B2 are segmented because levee breach along one segment would not lead to flooding in the other).

3.2 Phase II: review of available data

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

3.3 Phase III: definition of the current situation

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

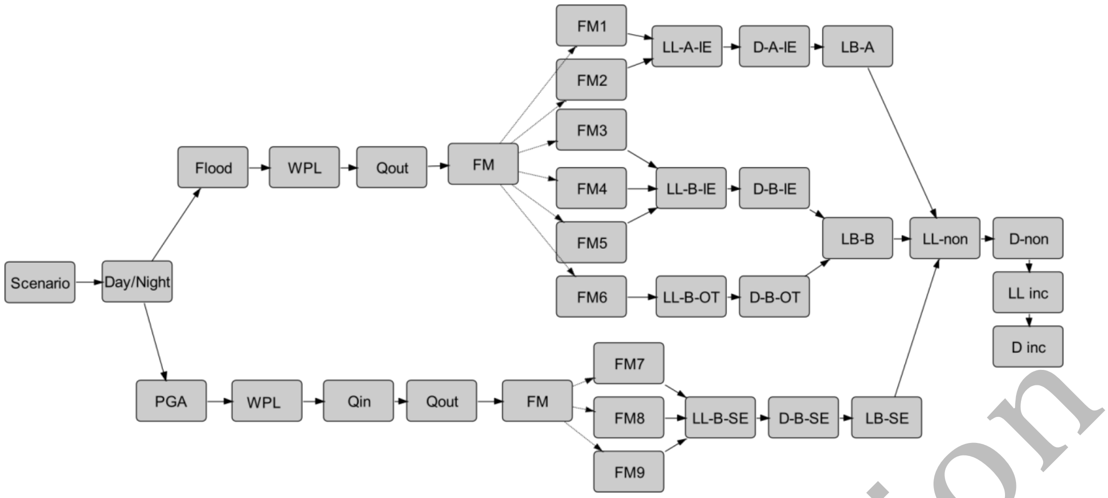
3.4 Phase IV: risk model architecture

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

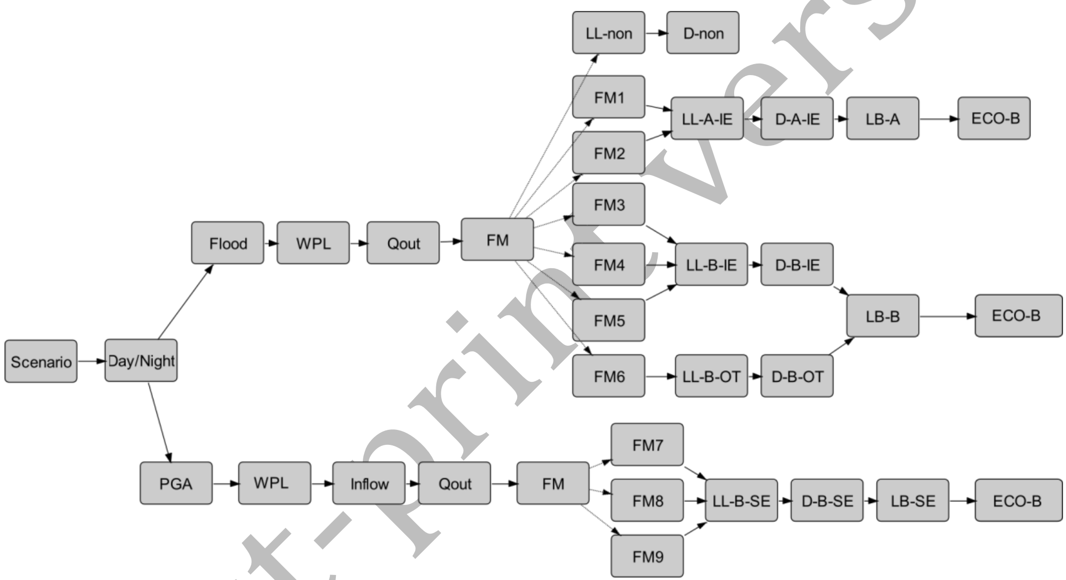
The risk model architecture depicted in Fig. 3(a) is used for computing incremental dam risk, including hydrologic and seismic scenarios (abbreviations in are provided in Table 1 and Table 3). Nodes in Fig. 3(a) include input data on loads, system response and consequences to estimate risk from hydrologic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

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

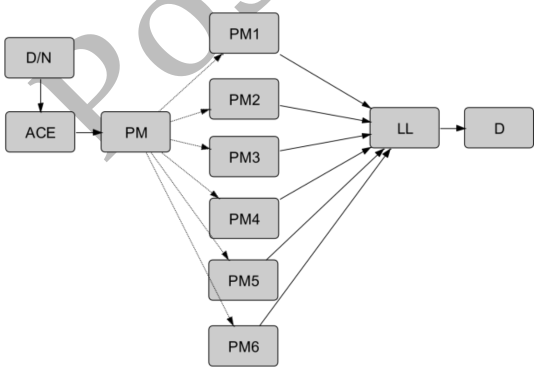
Similarly, the risk model architecture shown in Fig. 3(b) is used for computing total risk from both dam failure and non-failure cases, including hydrologic and seismic scenarios. Node names used in both dam risk models are defined in Table 3. In this influence diagram, a non-failure branch is included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



(a)



(b)



(c)

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

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

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

Table 2. System response combinations.

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

Table 3. Description of nodes used in dam risk models

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

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

Table 4. Description of nodes for levee risk models.

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

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

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

3.5 Phase V: input data

3.5.1. Loads

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

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

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

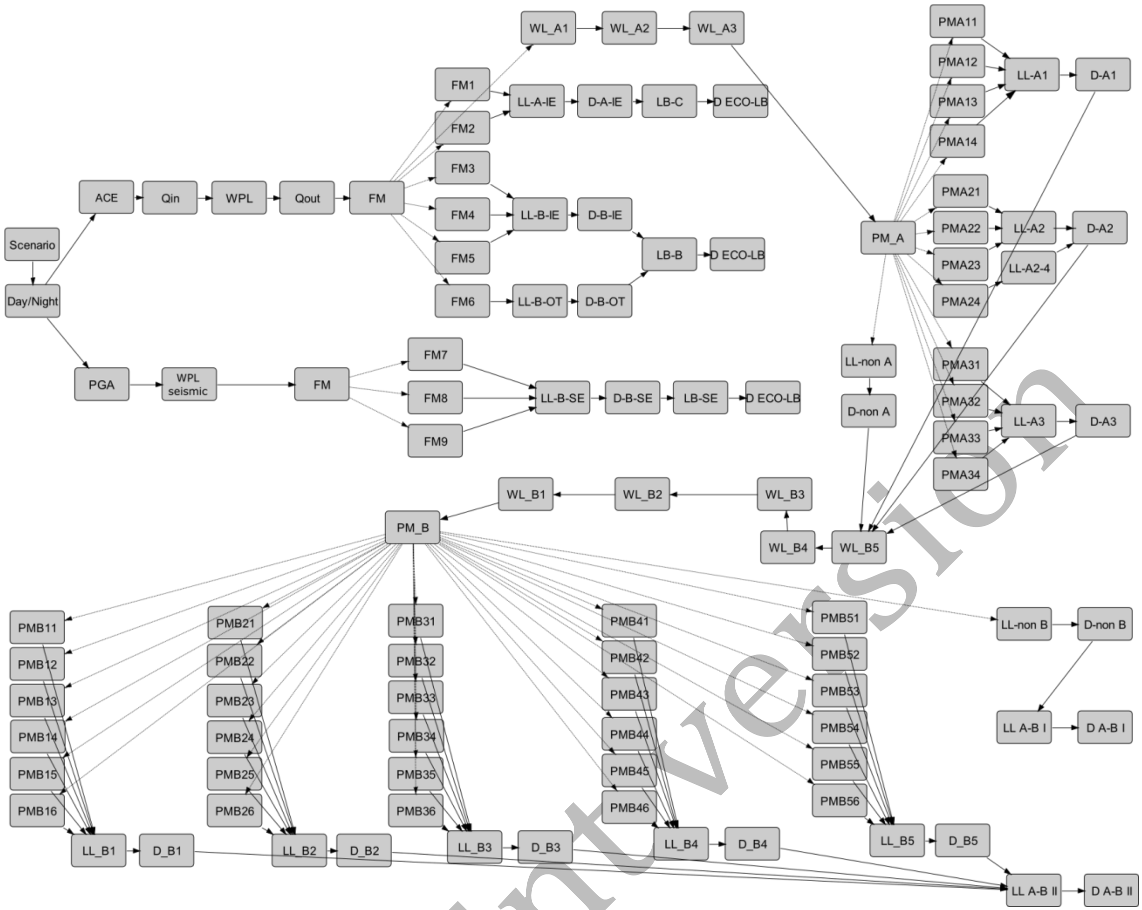


Figure 4. Combined dam-levee system risk model.

3.5.2. System response

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

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

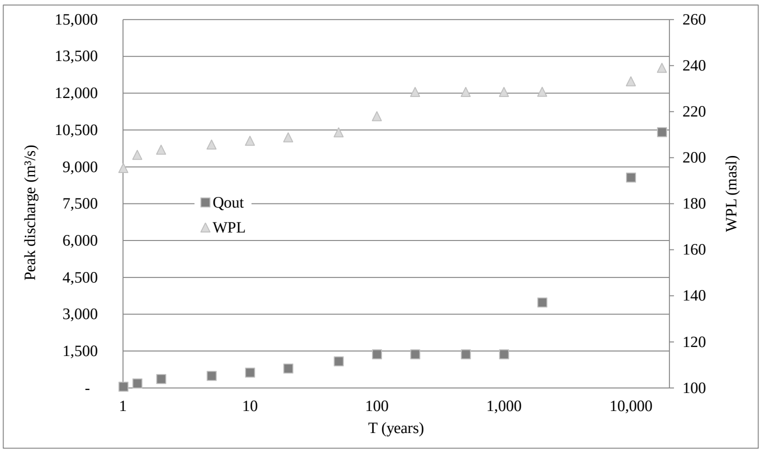


Figure 5. Outflow peak discharges (Q_{out}) in case of dam failure and water levels at reservoir (WPL) per return period of inflow flood event.

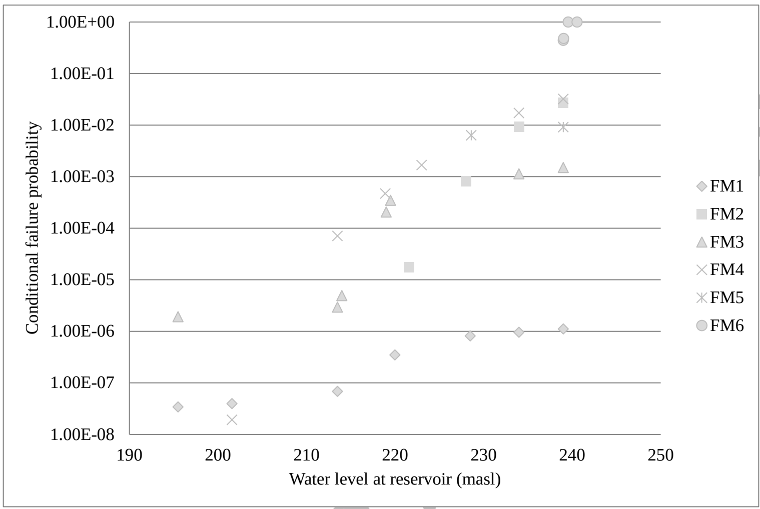


Figure 6. Conditional failure probabilities per dam failure mode: hydrologic scenario.

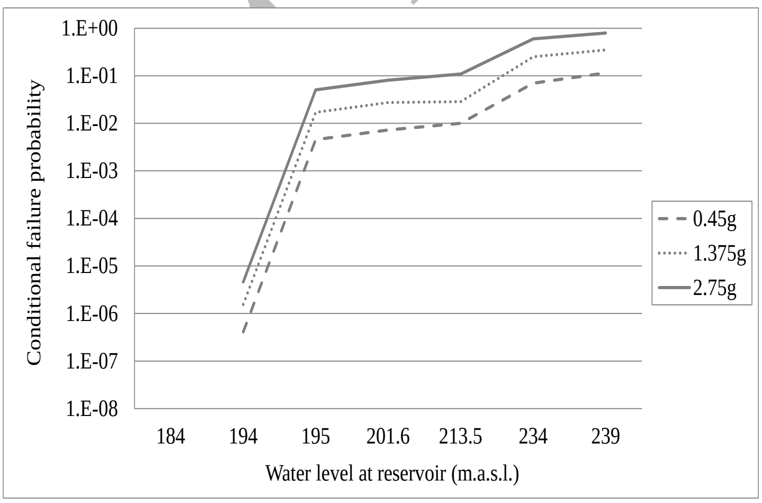


Figure 7. Extract of dam fragility curves for seismic scenario (peak ground acceleration 0.45g, 1.375g and 2.75g).

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

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

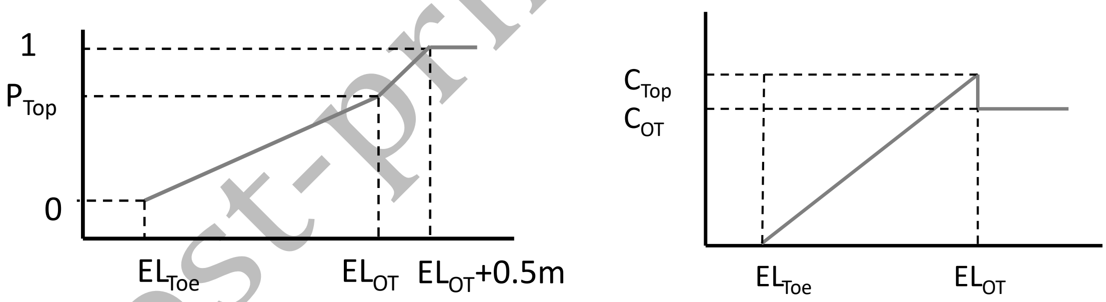


Figure 8. Failure probability (left) and consequence distribution (right) for levee segments based on water elevations (EL).

3.5.3. Consequences

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

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

d) dam non-failure with no levee breaches.

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

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

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

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

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

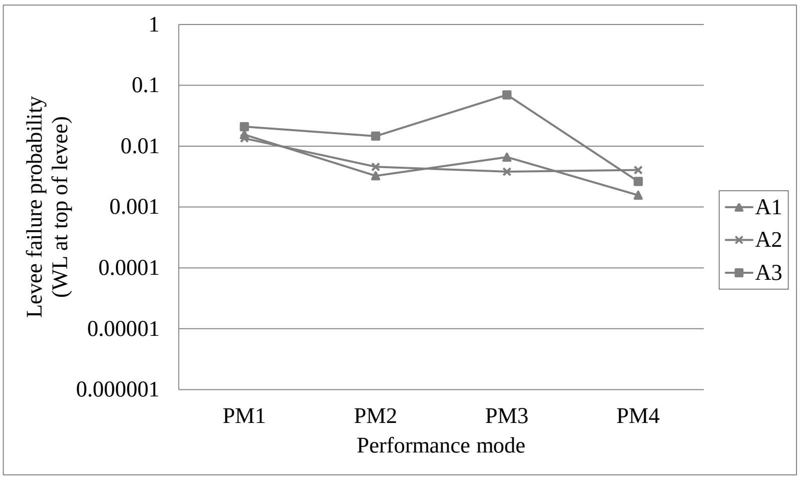


Figure 9. Levee failure probabilities per performance mode for water elevation at top of levee crest (levee segments A1, A2 and A3).

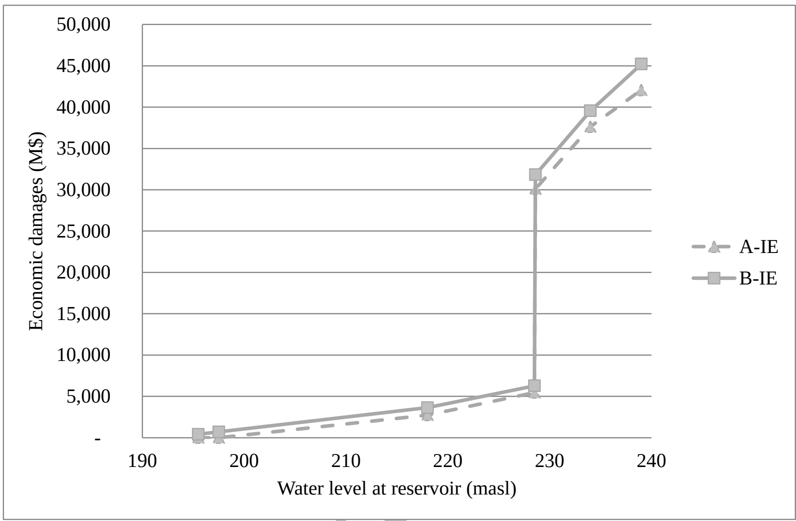


Figure 10. Economic consequences from dam failure (internal erosion failure modes: embankments A and B).

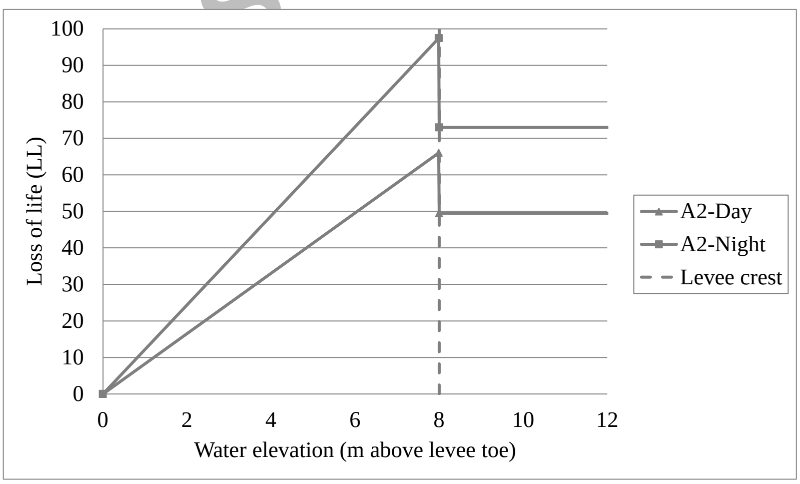


Figure 11. Life-loss consequences from levee failure for levee segment A2.

3.6 Phase VI: risk calculation

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

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

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

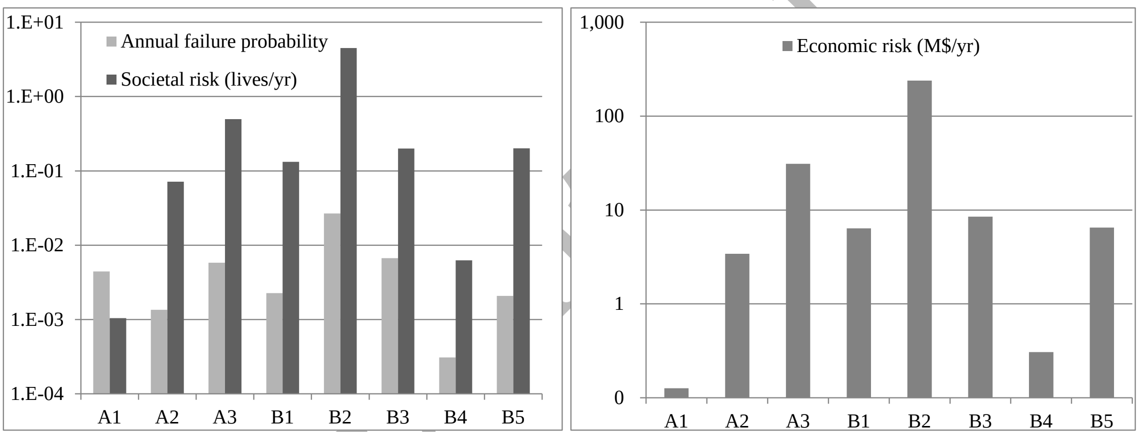


Figure 12. Failure probability, societal and economic risk per levee segment based on risk outcomes from separate risk models.

3.7 Phase VII: risk representation

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

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

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

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

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

Table 6. Results from separate levee risk models.

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

Table 7. Results from combined dam-levee model.

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

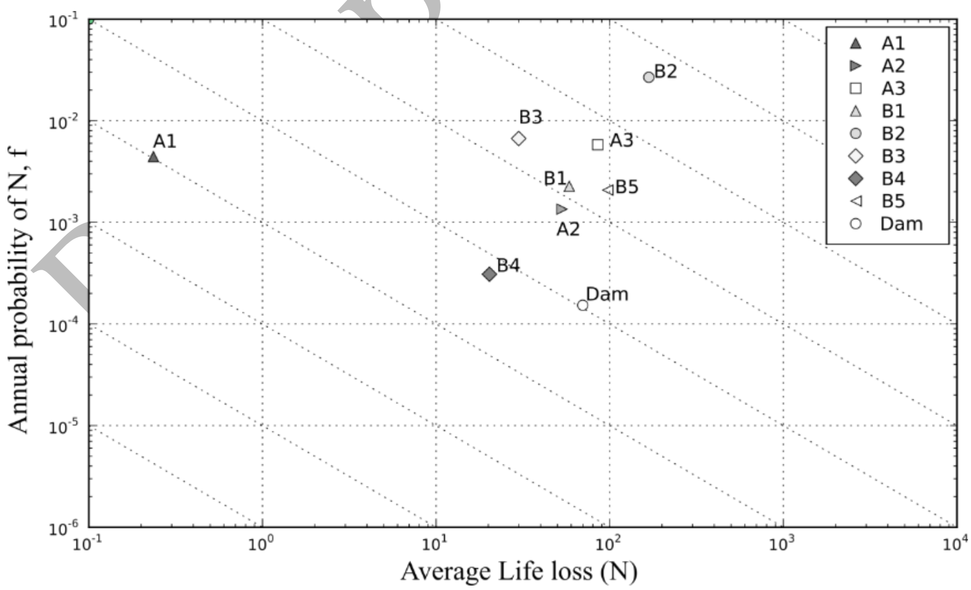


Figure 13. fN graphs from separate risk models.

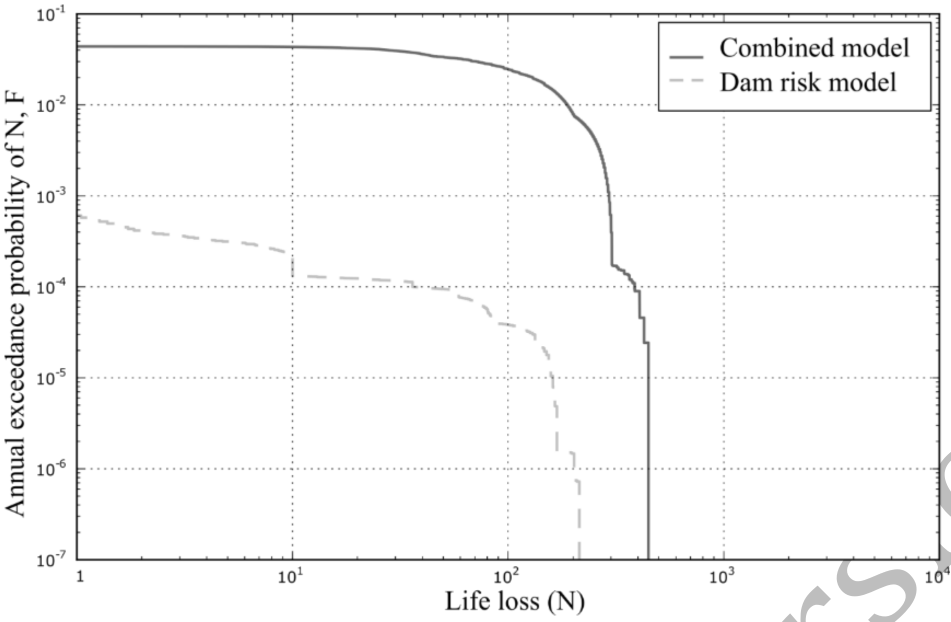


Figure 14. FN curves from dam risk model vs. combined dam-levee risk model.

3.8 Phase VIII: sensitivity analyses

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

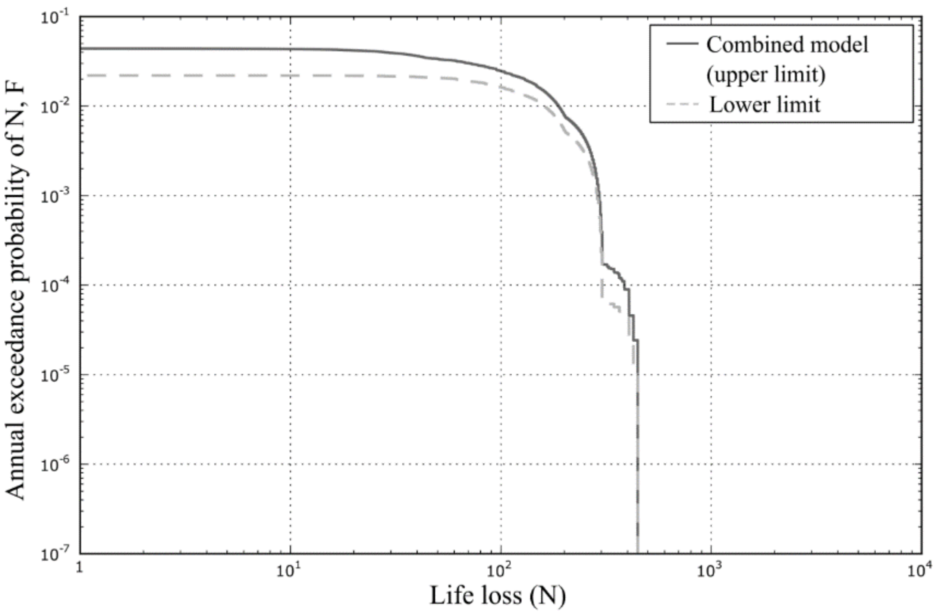


Figure 15. FN curves from combined model (upper and lower limit from CCA).

4. DISCUSSION

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

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

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

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

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

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

5. CONCLUSIONS

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

Several points are herein summarized.

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

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

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

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

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

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