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Adaptation strategies of dam safety management to new climate change scenarios informed by risk indicators

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Abstract

Large dams as well as protective dikes and levees are critical infrastructures whose failure has major economic and social consequences. Risk assessment approaches and decision-making strategies have traditionally assumed the stationarity of climatic conditions, including the persistence of historical patterns of natural variability and the likelihood of extreme events. However, climate change has a major impact on the world's water systems and is endangering dam safety, leading to potentially damaging impacts in terms of economic, social and environmental costs. Owners and operators of dams must adapt their mid- and long-term management and adaptation strategies to new climate scenarios.

This thesis proposes a comprehensive approach to incorporate climate change impacts on dam safety management and decision-making support. The goal is to design adaptation strategies that incorporate the non-stationarity of future risks as well as the uncertainties associated with new climate scenarios.

Based on an interdisciplinary review of the state-of-the-art research on its potential effects, the global impact of climate change on dam safety is structured using risk models. This allows a time-dependent approach to be established to consider the potential evolution of risk with time. Consequently, a new indicator is defined to support the quantitative assessment of the long-term efficiency of risk reduction measures. Additionally, in order to integrate the uncertainty of future scenarios, the approach is enhanced with a robust decision-making strategy that helps to establish the consensus sequence of measures to be implemented for climate change adaptation. Despite the difficulties to allocate probabilities to specific events, such framework allows a systematic and objective analysis, reducing considerably the subjectivity.

Such a methodology is applied to a real case study of a Spanish dam subjected to the effects of climate change. The analysis focus on hydrological scenarios, where floods are the main load to which the dam is subjected. The results provide valuable new information with respect to the previously existing analysis of the dam regarding the evolution of future risks and how to cope with it. In general, risks are expected to increase with time and, as a result, new adaptation measures that are not justifiable for the present situation are recommended. This is the first documented application of a comprehensive analysis of climate change impacts on dam failure risk and serves as a reference benchmark for the definition of long-term adaptation strategies and the evaluation of their efficiency.

Resumen

Las grandes presas, así como los diques de protección, son infraestructuras críticas cuyo fallo puede conllevar importantes consecuencias económicas y sociales. Tradicionalmente, la gestión del riesgo y la definición de estrategias de adaptación en la toma de decisiones han asumido la invariabilidad de las condiciones climáticas, incluida la persistencia de patrones históricos de variabilidad natural y la frecuencia de eventos extremos. Sin embargo, se espera que el cambio climático afecte de forma importante a los sistemas hídricos y comprometa la seguridad de las presas, lo que puede acarrear posibles impactos negativos en términos de costes económicos, sociales y ambientales. Los propietarios y operadores de presas deben por tanto adaptar sus estrategias de gestión y adaptación a medio y largo plazo a los nuevos escenarios climáticos.

En la presente tesis se ha desarrollado una metodología integral para incorporar los impactos del cambio climático en la gestión de la seguridad de presas y en el apoyo a la toma de decisiones. El objetivo es plantear estrategias de adaptación que incorporen la variabilidad de los futuros riesgos, así como la incertidumbre asociada a los nuevos escenarios climáticos.

El impacto del cambio climático en la seguridad de presas se ha estructurado utilizando modelos de riesgo y mediante una revisión bibliográfica interdisciplinaria sobre sus potenciales efectos. Esto ha permitido establecer un enfoque dependiente del tiempo que incorpore la evolución futura del riesgo, para lo cual se ha definido un nuevo indicador que evalúa cuantitativamente la eficiencia a largo plazo de las medidas de reducción de riesgo. Además, para integrar la incertidumbre de los escenarios futuros en la toma de decisiones, la metodología propone una estrategia robusta que permite establecer secuencias optimizadas de implementación de medidas correctoras para la adaptación al cambio climático. A pesar de las dificultades para asignar probabilidades a eventos específicos, esta metodología permite un análisis sistemático y objetivo, reduciendo considerablemente la subjetividad.

Esta metodología se ha aplicado al caso real de una presa española susceptible a los efectos del cambio climático. El análisis se centra en el escenario hidrológico, donde las avenidas son la principal carga a la que está sometida la presa. Respecto de análisis previos de la presa, los resultados obtenidos proporcionan nueva y valiosa información sobre la evolución de los riesgos futuros y sobre cómo abordarlos. En general, se espera un aumento del riesgo con el tiempo; esto ha llevado a plantear nuevas medidas de adaptación que no están justificadas en la situación actual. Esta es la primera aplicación documentada de un análisis exhaustivo de los impactos del cambio climático sobre el riesgo de rotura de una presa que sirve como marco de referencia para la definición de estrategias de adaptación a largo plazo y la evaluación de su eficiencia.

Resum

Les grans preses, així com els dics de protecció, són infraestructures crítiques que si fallen poden produir importants conseqüències econòmiques i socials. Tradicionalment, la gestió del risc i la definició d'estratègies d'adaptació en la presa de decisions han assumit la invariabilitat de les condicions climàtiques, inclosa la persistència de patrons històrics de variabilitat natural i la probabilitat d'esdeveniments extrems. Això no obstant, s'espera que el canvi climàtic afecte de manera important als sistemes hídrics, i comprometa la seguretat de les preses, la qual cosa pot implicar possibles impactes negatius en termes de costos econòmics, socials i ambientals. Els propietaris i operadors de preses, per tant, han d'adaptar les seues estratègies de gestió i adaptació a mitj i llarg termini als nous escenaris climàtics.

En aquesta tesi s'ha desenvolupat una metodologia integral per a incorporar els impactes del canvi climàtic en la gestió de la seguretat de les preses i en el suport a la presa de decisions. L'objectiu és plantejar estratègies d'adaptació que incorporen la variabilitat dels futurs riscos, així com la incertesa associada als nous escenaris climàtics.

L'impacte del canvi climàtic en la seguretat de les preses s'ha estructurat utilitzant models de risc i mitjançant una revisió bibliogràfica interdisciplinària sobre els seus potencials efectes. Això ha permès establir un enfocament dependent del temps, que incorpore l'evolució futura del risc; i per a això s'ha definit un nou indicador que avalua quantitativament l'eficiència a llarg termini de les mesures de reducció de risc. A més, per a integrar la incertesa dels escenaris futurs en la presa de decisions, la metodologia proposa una estratègia robusta que permet establir seqüències optimitzades d'implementació de mesures correctores per a l'adaptació al canvi climàtic. A pesar de les dificultats per a assignar probabilitats a esdeveniments específics, aquesta metodologia permet una anàlisi sistemàtica i objectiva, que redueix considerablement la subjectivitat.

Aquesta metodologia s'ha aplicat al cas real d'una presa espanyola susceptible al efectes del canvi climàtic. L'anàlisi se centra en l'escenari hidrològic, on les avingudes són la principal càrrega a la qual està sotmesa la presa. Respecte a les anàlisis prèvies de la presa, els resultats obtinguts proporcionen una nova i valuosa informació sobre l'evolució dels riscos futurs i sobre com abordar-los. En general, s'espera un augment del risc amb el temps; això ha portat a plantejar noves mesures d'adaptació que no estarien justificades en la situació actual. Aquesta és la primera aplicació documentada d'una anàlisi exhaustiva dels impactes del canvi climàtic sobre el risc de trencament d'una presa que serveix com a marc de referència per a la definició d'estratègies d'adaptació a llarg termini i l'avaluació de la seua eficiència.

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Chapter 1

Introduction

1.1 Context

Large dams as well as protective dikes and levees are critical infrastructures whose failure has major economic and social consequences. Although usually very low, these infrastructures have an associated risk that must be properly managed in a continuous and updated process. Dam safety is no longer seen as a static and deterministic process but rather from an active and ongoing management perspective.

Risk analysis techniques are useful tools for dam owners that encompass traditional and state-of-the-art approaches to make decisions in the field of safety management. They provide a framework for managing risk and effectively allocating and using resources for risk treatment (ISO 2018). These techniques help dam safety practitioners to understand uncertainties in critical infrastructures, and provide a logical process of identifying hazards, evaluating system response and vulnerabilities associated with each hazard, and assessing the effectiveness of risk reduction measures. The development and application worldwide of such techniques in the dam industry has helped to inform safety governance and support the decision-making process by optimizing the existing resources and pointing at the most efficient ways of using them (ANCOLD 2003; Central Water Commission 2019; ICOLD 2005; SPANCOLD 2012; USACE 2011a).

During the past years, the Research Institute of Water and Environmental Engineering (IIAMA) in the Universitat Politècnica de València (UPV) has led the application of risk analysis techniques to inform dam safety governance in Spain. The publication of the SPANCOLD Guidelines on Risk Analysis Applied to

Management of Dam Safety (SPANCOLD 2012) represented a key step for the definition of a methodology to develop quantitative risk models to analyze, assess and manage dam safety.

1.2 Motivation of research

Risk assessment approaches and decision-making strategies have traditionally assumed a stationary condition in climatic conditions, including the persistence of historical patterns of natural variability and the likelihood of extreme events (National Research Council 2009).

However, climate change has a major impact on the world's water systems and is endangering infrastructures safety, leading to potentially damaging impacts in terms of economic, social and environmental costs. In particular, changes in climate factors such as variations in extreme temperatures or frequency of heavy precipitation events (IPCC 2012; Walsh et al. 2014) are likely to affect the different factors driving dam failure risks (Bowles et al. 2013a; USBR 2014). The assumptions of past stationary climatic baselines are no longer appropriate for long-term dam safety management (USACE 2016). Dam designs are usually based on past conditions, but future patterns are likely to change. Owners and operators of dams (and in general all critical water infrastructure) must adapt their mid- and long-term management and adaptation strategies to new climate scenarios.

Although some reference institutions (ICOLD 2018; USACE 2014; USBR 2014, 2016) are developing and implementing guidance for including climate change in their decision support strategies (ISO 2019; U.S. Government Accountability Office 2013), its application to current dam safety practice is still uncertain (Bahls and Holman 2014). It is necessary to establish some technological bases that support the governance of those infrastructures, investments sustainability indicators, decision-making transparency, innovation and knowledge transfer.

The need to update adaptation strategies faces three main challenges (Figure 1-1):

- ***Challenge 1:*** *Multidisciplinarity of impacts*

  The effects of climate change are expected on a variety of factors affecting dam safety, from the incoming floods to the definition of downstream consequences. They are conditioned by climatic but also by non-climatic drivers (IPCC 2014) such as population increase, economic development, or water management adaptation.

  Usually, these effects are analyzed separately, aim at specific aspects that relegates other components (Bahls and Holman 2014; Chernet et al. 2014;

Novembre et al. 2015), or only reach qualitative assessments for screening analyses (Atkins 2013). Instead, quantitative assessments of climate change impacts must be performed through the integration of the various projected effects acting on each aspect of the risk, taking into account their interdependencies.

- ***Challenge 2:*** *Long-term effects*

Different factors make risks susceptible to evolve with time. For instance, due to changes in climate factors such as variations in extreme temperatures or the frequency of heavy precipitation events (IPCC 2012; Walsh et al. 2014). The increasing exposure of people and economic assets in at-risk areas as a result of population and economic growth (Bouwer 2011; Changnon et al. 2000) has also the potential for changing the potential socio-economic losses.

Decision-making processes based on current management priorities, safety standards and/or recent climate conditions are no longer enough and should be updated to consider risks and costs as time series rather than fixed values (Lind 2002a; National Research Council 2010). In this context, adaptation planning is of critical importance to ensure that relevant information is incorporated early on when developing long-term adaptation strategies, such as infrastructure investments or policy and operational changes (USBR 2014). Moreover, this will avoid adopting adaptation measures that would no longer be necessary in the future or missing some measures that could efficiently reduce future risk.

- ***Challenge 3:*** *Climate change uncertainty*

On top of this, inherent climate-related uncertainties affect the efficiency of risk analyses and hence the decisions based on their results (ISO 2019). Dam failure risks can be subjected to climate change uncertainties in different ways. The main component is the hydrology of river basins, and hence uncertainties related to these natural aspects will ineluctably affect the evaluation of floods but also of the distribution of water storage in the reservoir, which determine the loads to which the dam is subjected. Besides natural uncertainty, the socio-economic dimension of climate change impacts must also be considered. The evaluation of dam failure risks also includes the potential consequences downstream of the dam, which are directly related to the exposure and vulnerability of people, livelihoods, infrastructure or assets in at-risk areas. The evolution of exposure is subjected to global socio-economic trends that can be attributed to climatic drivers (Choi and Fischer 2003; Neumayer and Barthel 2011). The incorporation of these uncertainties into the process of dam safety governance is of paramount importance for a resilient and efficient adaptation strategy (Street and Nilsson 2014).

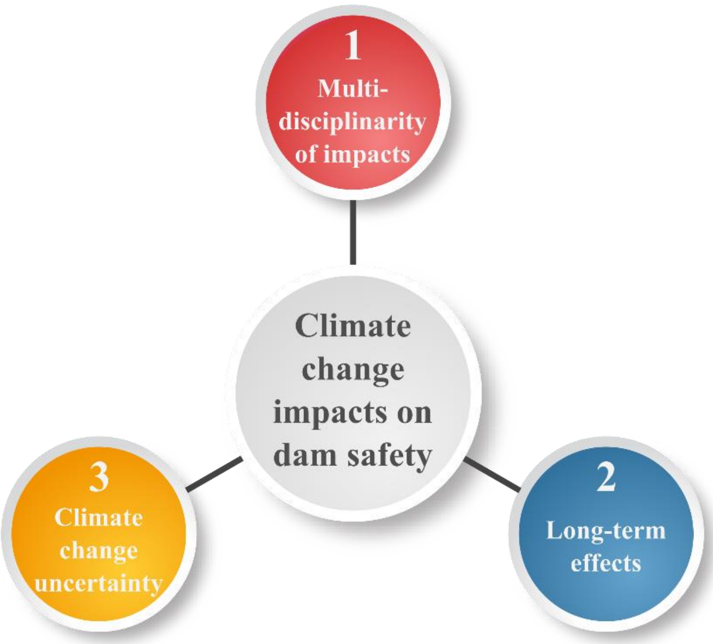

Figure 1-1. *Challenges identified to address climate change impacts on dam safety.*

1.3 Objectives

The overall goal of this thesis is the development of a practical methodology that helps to quantify and structure the impact of climate change on dam safety and to design adaptation strategies that incorporate the non-stationarity of future risks as well as the uncertainties associated with new climate scenarios. This would enable the reinforcement of the resilience of dams facing extreme events and the prioritization of investments for risk reduction measures.

The following research axes are defined for this thesis to tackle the challenges mentioned above:

- Multidisciplinary review of the state-of-the-art on projected climate change impacts on dam safety, attending to both climatic and non-climatic drivers, and screening of useful techniques for their direct application depending on the level of detail of the analysis.
- Structuring the global impact of climate change on dam safety through the use of risk models for the quantitative assessment of all the potential impacts by disaggregating them into the different components of risk and taking into account their interdependencies.

- Definition of an approach for risk management in the long term that considers the potential evolution of risk with time. Definition of a new indicator for quantitative assessment of the long-term efficiency of risk reduction measures.
- Proposal for a robust decision-making strategy to help establish the consensus sequence of risk reduction measures to be implemented for climate change adaptation, integrating the uncertainty of future scenarios.
- Consolidation of the research developed by applying it to a case study of a Spanish dam subjected to the effects of climate change. Such case study should serve as a reference benchmark in the analysis of other cases for the definition of long-term adaptation strategies and the evaluation of their efficiency.

1.4 General approach

In this thesis, the risk analysis framework is adopted to improve the adaptation strategies of dam safety management under the influence of climate change effects. The approach proposed in SPANCOLD (2012) has been updated and completed to overcome the challenges mentioned in Section 1.2. The outcome of such an approach consists in finding so-called robust adaptation strategies. In particular, the process encompasses all the phases from the calculation of the risk up to the definition and prioritization of risk reduction measures. Moreover, this is conceived as an evolutive process that must be updated as new information on future climate arises. This new process is presented in Figure 1-2, where the highlighted parts of the scheme (**Phase 2***, **Phase 6** and **Phase 7**) correspond to the contributions of this thesis to address challenges presented in Section 1.2.

The first step of the decision-making approach is the computation of dam failure risk in the present situation and its evolution with time. At this point, a methodology is needed to quantify the effect of new climate change scenarios on the dam risk. Once calculated for current and future scenarios, the calculated risk must be evaluated. That is, it is necessary to assess whether a risk is tolerable or not.

The previous step defines the convenience of adopting a certain risk reduction strategy. Based on the tolerability scenarios of the computed present and future risks, a set of potential risk reduction measures should be proposed. However, since it is assumed that risks are likely to evolve with time, measures that are justifiable at present may not be necessary in the future, and vice versa. This can greatly affect not only the decision time horizon but also the type of measures to be applied that should perform well under a wide range of scenarios considering risk variability and climate uncertainty.

The risk calculation process must be replicated, this time including the effect of the adaptation measures, not only in the short term but also in the future. This makes it possible to assess the efficiency of measures in optimally reducing dam risks, that is, options that reduce risk at a lower cost. This assessment must be applied for the long term, considering the aggregated risk assumed for the chosen decision time horizon, during which the investment is to be justifiably financed.

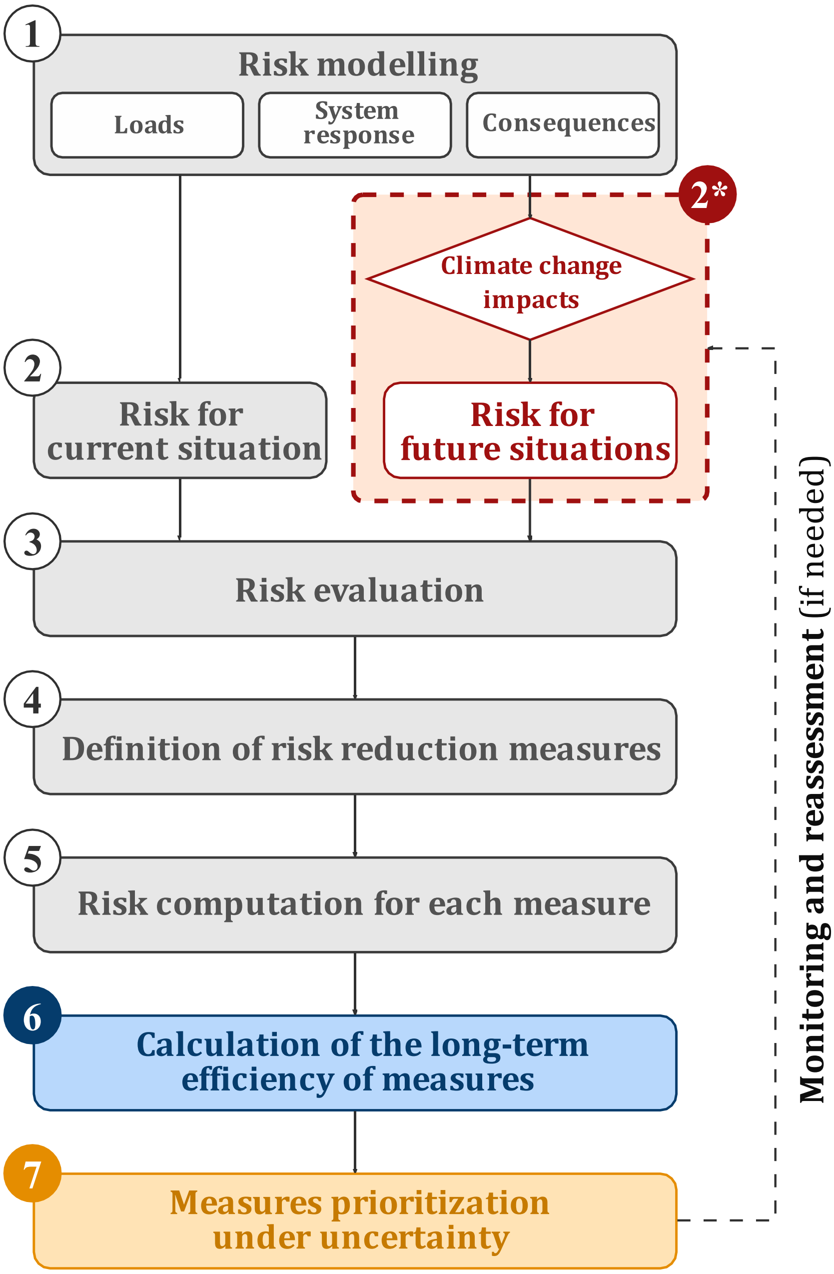

Figure 1-2. *Proposed process to incorporate climate change to dam failure risk management.*

The last phase consists in treating the information collected and generated during the entire process to define robust adaptation strategies that maximize the effectiveness of risk reduction measures for different timescales while considering the inherent uncertainties arising from climate change projections, resulting in the sequence of measures to be applied. The procedure is not intended to choose among different alternatives but to prioritize them, assuming that with enough time and resources, all of them could be implemented.

This is an evolutive process that must be updated with the forthcoming innovations and advances in climate science.

1.5 Structure of the thesis

This thesis is presented by compendium of four articles and includes the chapters corresponding to the following publications:

(1) *Fluixá-Sanmartín, J., Altarejos-García, L., Morales-Torres, A., and Escuder-Bueno, I. (2018). "Review article: Climate change impacts on dam safety." Natural Hazards and Earth System Sciences, 18(9), 2471–2488.*

(2) *Fluixá-Sanmartín, J., Morales-Torres, A., Escuder-Bueno, I., and Paredes-Arquiola, J. (2019). "Quantification of climate change impact on dam failure risk under hydrological scenarios: a case study from a Spanish dam." Natural Hazards and Earth System Sciences, 19(10), 2117–2139.*

(3) *Fluixá-Sanmartín, J., Escuder-Bueno, I., Morales-Torres, A., and Castillo-Rodríguez, J. T. (2020). "Comprehensive decision-making approach for managing time dependent dam risks." Reliability Engineering & System Safety, 203, 107100.*

(4) *Fluixá-Sanmartín, J., Escuder-Bueno, I., Morales-Torres, A., and Castillo-Rodríguez, J. T. (Forthcoming). "Accounting for climate change uncertainty in long-term dam risk management." Journal of Water Resources Planning and Management.*

Chapter 1 describes the context and the motivation of the research, the objectives and main contributions of the PhD thesis, as well as the general approach adopted.

Chapter 2 corresponds to *Publication (1)*. It focuses on Phase 2* of the proposed process (Figure 1-2) and contains a complete literature review of the impacts of climate change affecting dam safety. In order to organize the different climatic and non-climatic effects, the structure followed for such a review is based on the risk modelling approach in which all the variables concerning dam safety and their interdependencies are included in a comprehensive way. This chapter deals with Challenge 1.

Chapter 3 corresponds to *Publication (2)*. It presents a procedure for the calculation of climate change impacts on the safety of dams under hydrological scenarios, i.e. where the floods are the main loads to which the dam is subjected. It complements **Chapter 2** to cover Challenge 1.

Chapter 4 corresponds to *Publication (3)*. It deals with Phase 6 of the process: dam risk management in the long term considering the potential evolution of risk with time. For that, a new risk reduction indicator is defined for quantitative assessment of the long-term efficiency of risk reduction measures: the *Aggregated Adjusted Cost per Statistical Life Saved* (AACSLS). A methodology is proposed to define a prioritization of risk reduction measures based on this new indicator. This helps to plan measures more efficiently according to their long-term efficiency. This methodology tries to overcome the drawback of Challenge 2.

Chapter 5 corresponds to *Publication (4)*. The *Multi-Prior Weighted Scenarios Ranking* method is presented, an innovative approach for dam risks adaptation under the influence of climate uncertainty that covers Phase 7. This approach is based on robust decision-making strategies coupled with climate scenario probability assignation. The proposed methodology consists of a series of steps, from the risk estimation for current and future situations through the definition of the consensus sequence of risk reduction measures to be implemented. This represents a supporting tool for dam owners and safety practitioners to help in their decision-making processes. Challenge 3 will be addressed in this chapter.

Moreover, in **Chapter 3**, **Chapter 4** and **Chapter 5**, the approach developed in this thesis is applied to a case study of a Spanish dam, from the quantification of the effects of climate change to the definition of the most robust implementation of risk reduction measures.

Chapter 6 presents a discussion of the results obtained in the previous chapters and integrates the methodologies developed in an adaptive strategy for dam safety management to climate change.

Chapter 7 summarizes the main conclusions from this thesis, highlights the original contributions developed, and suggests future lines of research.

Chapter 2

Climate change impacts on dam safety

Authors: Javier Fluixá-Sanmartín, Luis Altarejos-García, Adrián Morales-Torres, Ignacio Escuder-Bueno

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Editor version can be found in PDF format in the following link:
www.nat-hazards-earth-syst-sci.net/18/2471/2018/nhess-18-2471-2018.html

Abstract

Dams as well as protective dikes and levees are critical infrastructures whose associated risk must be properly managed in a continuous and updated process. Usually, dam safety management has been carried out assuming stationary climatic and non-climatic conditions. However, the projected alterations due to climate change are likely to affect different factors driving dam risk. Although some reference institutions develop guidance for including climate change in their decision support strategies, related information is still vast and scattered and its application to specific analyses such as dam safety assessments remains a challenge.

This article presents a comprehensive and multidisciplinary review of the impacts of climate change susceptible to affect dam safety. The global effect can be assessed through the integration of the various projected effects acting on each aspect of the risk, from the input hydrology to the calculation of the consequences of the flood wave on population and assets at risk. This will provide useful information for dam owners and dam safety practitioners in their decision-making process.

2.1 Introduction

Large dams as well as protective dikes and levees are critical infrastructures whose failure has high economic and social consequences. Although usually very low, these infrastructures have an associated risk that must be properly managed in a continuous and updated process. In the dam safety context, risk can be estimated by the combined impact of all triplets of scenario, probability of occurrence and the associated consequence (ICOLD 2003). Risk analysis is a useful methodology that encompasses traditional and state-of-the-art approaches to manage dam safety in an accountable and comprehensive way (Bowles 2000; Serrano-Lombillo et al. 2013). The development and application of risk assessment techniques worldwide in the dam industry (ANCOLD 2003; ICOLD 2005; SPANCOLD 2012; USACE 2011a) has helped to inform safety governance and supporting decision-making in the adoption of structural and non-structural risk reduction measures.

Most risk assessments in the past assumed a stationary condition in the variability of climate phenomena, including the frequency and magnitude of extreme events (National Research Council 2009). However, changes in climate factors such as variations of extreme temperatures or frequency of heavy precipitation events (CH2014-Impacts 2014; IPCC 2012; Walsh et al. 2014) are likely to affect the different factors driving dam risks (Bowles et al. 2013a; USBR 2014). The assumptions of stationary climatic baselines are no longer appropriate for long-term dam safety management (USACE 2016). An update of risk components (loads, system response and consequences) to take into account the new climate change scenarios becomes imperative for adaptation and decision-making support under a more resilient approach.

In this context, some reference institutions (USACE 2014; USBR 2014, 2016) are actively developing and implementing guidance for including climate change in their decision support strategies (U.S. Government Accountability Office 2013). In other cases, efforts have been done in the evaluation of climate change impacts on dam safety surveillance but further research is subjected to new findings and advances in the knowledge level (OFEV 2014).

However, climate change related information is vast and scattered, and its application to specific analyses such as dam safety assessments remains a challenge for the dam engineering community. Although a considerable amount of research has been done so far, its application to current dam safety practice is still in prospect (Bahls and Holman 2014) and needs to be done based on national and supranational overall adaptation plans (Commonwealth of Australia 2015; European Commission 2013a; OECC 2008). Moreover, the impacts of climate change effects on dam safety are usually analyzed separately and aim at specific aspects. Most studies tend to focus only on the impact of climate change on the hydrological loads (Bahls and Holman 2014; Chernet et al. 2014; Novembre et al. 2015) relegating or ignoring other aspects. Other studies with a wider scope only reach qualitative assessments (Atkins 2013) limiting their applicability to screening analyses.

The global effect of climate change on dam risk must be assessed through the integration of the various projected effects acting on each aspect, taking into account their interdependencies, rather than by a simple accumulation of separate impacts. It is thus valuable to adopt a comprehensive approach to address climate change influence on dam safety management. In this context, dam risk models represent a useful basis on which such assessments can be structured.

In this work the authors seek a multidisciplinary and structured review of the most relevant impacts of climate change on the different dam safety components, from the input hydrology to the calculation of the downstream consequences of the inundation on population and assets at risk. In order to decompose such impacts on the different risk aspects, a risk analysis approach has been adopted. Moreover, practical techniques for their direct application are presented to provide useful information for dam owners and dam safety practitioners in their decision-making process.

2.2 Risk analysis approach for structuring climate change impacts

The effects of climate change are expected on a variety of factors affecting the dams, from the incoming floods to the definition of downstream consequences. Thus, in order to analyses the impacts of climate change on the global safety of a dam, it is necessary to decompose them in the different aspects that integrate the dam risk. Some techniques help to address such analyses in a comprehensive way and structuring the way in which the risk assessment is envisaged.

In particular, risk analysis is a useful methodology to manage dam safety in an accountable and comprehensive way (Bowles et al. 2013b). Risk can be defined as the combination of three concepts: what can happen (infrastructure failure), how likely is it to happen (failure probability), and what are its consequences (failure consequences) (Kaplan 1997). (Merz et al. 2010) propose a non-stationary definition of flood risk that includes damage and probability of occurrence. Based on these definitions, risk can be quantified with the equation set by Kaplan and Garrick (1981) and used extensively across different sectors in the industry (Altarejos-García et al. 2012; Aven 2012; Serrano-Lombillo et al. 2011):

$$risk = \sum_{e} p(e) \cdot p(f|e) \cdot C(f|e) \tag{2.1}$$

where the risk is expressed in consequences per year (social or economic), the summation is defined for all events *e* under study, *p(e)* is the probability of an event, *p(f|e)* is the probability of failure due to event *e* and *C(f|e)* represents the consequences produced as a result of each failure *f* and event *e*.

In this context, risk models are the basic tool used for the quantitative assessment of risk, integrating and connecting most variables concerning dam safety (Ardiles et al. 2011; Bowles et al. 2013a; Serrano-Lombillo et al. 2012a). These models can be structured using influence diagrams such as the one presented in Figure 2-1 (SPANCOLD 2012). Each node represents a variable related to each term of risk as defined in Equation (2.1):

- *Loads of the system*. This term corresponds to the loads to which the dam will be subjected and focuses on the upstream components of the dam. In particular, incoming floods are envisaged as the main hydrological load, and the rest of the component defines how the dam–reservoir system responds when confronted by such hydrological events.
- *System response (or failure probability)*. This contains the information of the failure modes and the definition of the conditional probability of failure.

- *Consequences (economic, loss of life or any other)*. This component includes an estimation of the consequences downstream of the dam for all the significant failure modes, including the dam break modelling.

In this work, the risk modelling approach shown in Figure 2-1 has been chosen to structure and organize the assessment of all the potential impacts by disaggregating them on the different components of risk. The advantage of using this approach is threefold:

- The analysis is performed in a comprehensive way where the total risk and the climate change impacts are evaluated jointly, taking into account their interdependencies.
- All the risk components are evaluated, which avoids neglecting certain factors affecting the global safety.
- It is also possible to determine the contribution of each dam safety component to the overall risk impact, thus highlighting which is more susceptible to climate change or has more influence in the final risk level.

2.3 Climate change impacts on dam risk components

What follows is a review of the main climate change impacts on the dam risk components as presented in Section 2.2. The overall effect of climate change on risk can be assessed based on how these components are susceptible to change.

The present review focuses on the impacts of climate change on dam's safety under a hydrological scenario, which means that floods are the main load component to which the dam-reservoir system is subjected.

It is worth mentioning that risk impacts of climate change are conditioned by climatic but also by non-climatic drivers (IPCC 2014) such as population increase, economic development, or water management adaptation. In certain cases, these non-climatic drivers may have a significant influence in the dam risk calculation and have been considered in the research.

Moreover, climate change is susceptible to impact both normal components (such as the population exposure downstream of the dam) and extreme components (such as the flood events) of risk, which can be captured by using the proposed risk analysis approach.

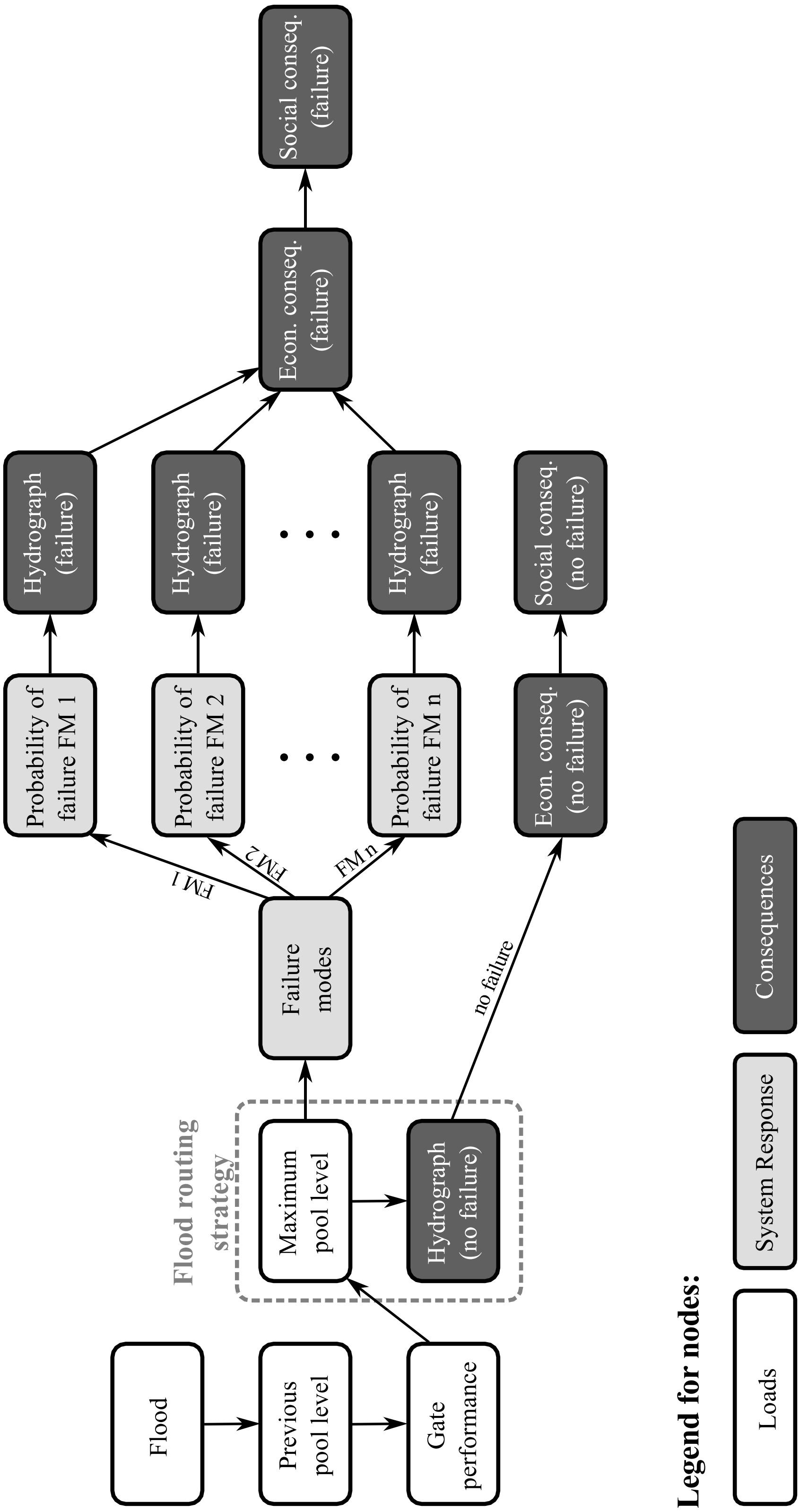

Figure 2-1. *Standard risk model diagram for the hydrologic scenario, divided into loads, system response, and consequence nodes (adapted from SPANCOLD (2012)).*

2.3.1 Loads of the system

2.3.1.1 Flood

In the hydrological scenario, floods are the initiating event (node) that creates the loads to which the dam is subjected and will be referred here as the upstream flow into the reservoir. The probabilities of the emerging branches are defined by the frequency occurrence linked to the inflow hydrographs (Figure 2-2 (a)), introducing the temporal component to the risk calculation [consequences/year]. These are associated with a given return period (T) or its equivalent annual exceedance probability (AEP). Different analyses can be performed to estimate the occurrence probability of these events using deterministic, parametric, probabilistic and stochastic methods (World Meteorological Organization 2008). Some of them seek relating the magnitude of one or more hydrological variables with T. A widely used approach to characterize this relation is to perform frequency analyses of the maximum values of peak discharge (Q_P) and/or volume (V) (Figure 2-2 (b)): while univariate analyses focus on the individual influence of each factor, multivariate analyses are used to obtain their joint distribution in order to know the probability of occurrence of a given inflow hydrograph (Requena et al. 2013; Serinaldi and Grimaldi 2007; Zhang and Singh 2006).

The main component of dam safety affected by climate change is the hydrology of river basins defined by the incoming floods. Heavy precipitation has an important influence, but floods are also affected by other factors including snow cover and snowmelt (Arheimer and Lindström 2015; Fassnacht and Records 2015), vegetation or soil moisture (Mostbauer et al. 2017). Changes already identified in these factors are likely to modify the characteristics of floods, namely their magnitude and/or frequency (IPCC 2014).

The assessment of the correspondence between changes in climate factors and flood occurrence remains however complex. Although there are abundant studies on the changes and trends for rivers over the past years (Hannaford and Marsh 2008; Petrow and Merz 2009; Villarini et al. 2009), there is still a lack of evidence regarding patterns in the magnitude and/or frequency of floods on a global scale (IPCC 2012). Nevertheless, physical reasoning suggests that projected variations in heavy rainfall and other factors in some catchments or regions would contribute to variations in local floods (Bates et al. 2008; Kundzewicz et al. 2007). Existing analyses of flood changes at the basin scale (Prudhomme and Davies 2009; Raff et al. 2009; Taye et al. 2011) justify the need for a re-evaluation of flood frequency and magnitude impacting dam safety. To take into consideration the non-stationarity hypothesis in flood frequency analysis, some works apply methods to account for the effects of climate change in flow regimes (Gilroy and McCuen 2012; López and Francés 2013).

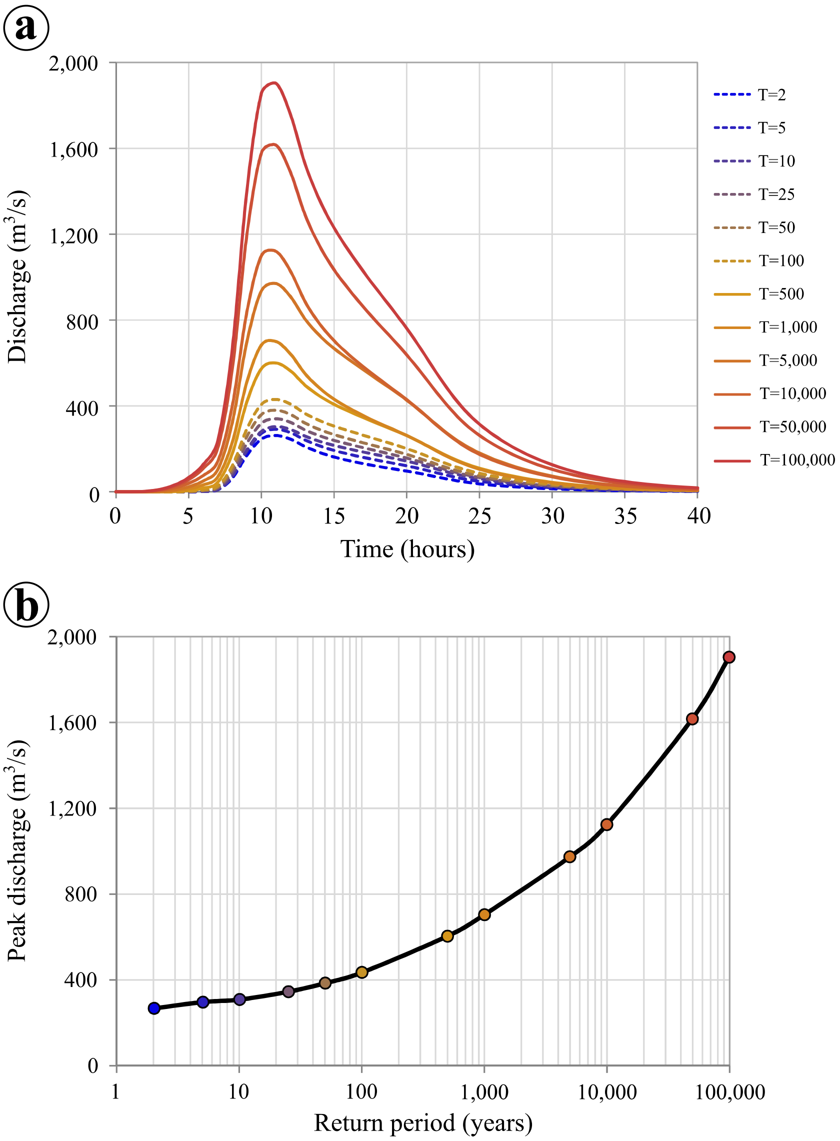

Figure 2-2. *(a) Example of upstream hydrographs as used in the flood routing computation. (b) Resulting flood frequency characterization of the maximum values of peak discharge (Q_P), used in the flood node.*

Direct analyses on the expected changes in flood's frequency and/or magnitude can be applied using existing studies of the matter on the study region. For instance, the works of Dankers and Feyen (2008), (Hirabayashi et al. 2013) or Wobus et al. (2017) present the expected variations of characteristic floods in magnitude or frequency at large scales (Figure 2-3). These variations can be then applied to the concerned floods of the basin by a simple extrapolation of the hydrographs based on the ratio between their peaks.

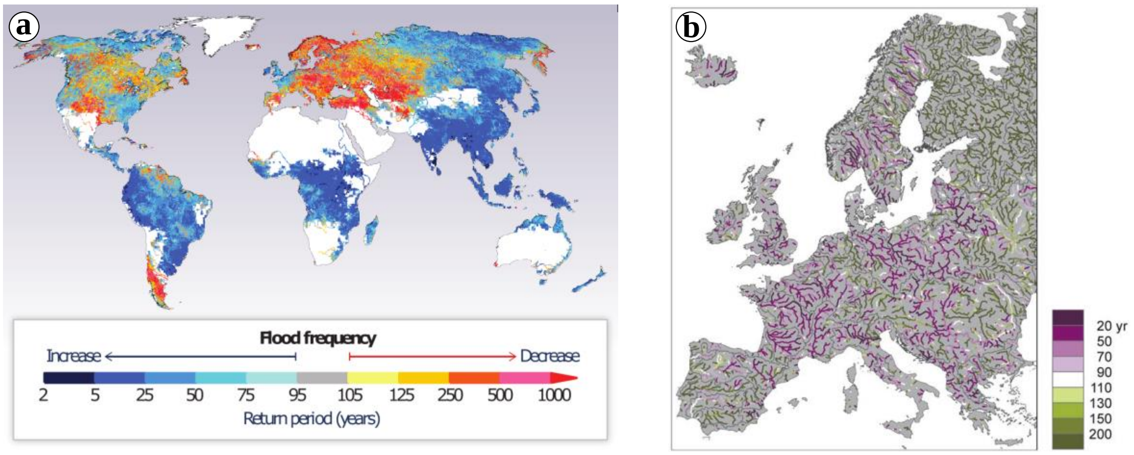

Figure 2-3. *(a) Multi-model median return period (years) in the 2080s for the 20th century 100-year flood based on one hydrological model driven by 11 GCMs under RCP8.5 (from Hirabayashi et al. (2013)). (b) Change in recurrence of a 100-year flood in Europe in the H12A2 scenario run using a Gumbel distribution (from Dankers and Feyen (2008)).*

More specific analyses require to rely on local effects on floods (at catchment-wide scale) rather than apply regional- or continental-scale findings. When no detailed information is available at the catchment level, site-specific analyses are required. Most studies use adapted global (GCMs) and regional (RCMs) climate models coupled with hydrological and land surface models to assess how floods are expected to change at the watershed level (Chernet et al. 2014; Duan et al. 2017; Khazaei et al. 2012). Climate models can be applied to present or historical climatic variables (mainly precipitation and temperature) in order to obtain projections of future climate series (preferably at daily or sub-daily time steps). These new series are then introduced as inputs to the hydrological model. The resulting flows are then statistically analyzed (the longer the simulation period, the more accuracy) to derive the flood frequency statistics.

In most cases climate change projections from GCMs cannot be directly used because their spatial resolution is too coarse for modelling the hydrological processes at the required regional or even local scale, and thus must be downscaled and eventually bias-corrected. A synthetic diagram of a common methodology for the frequency analysis of floods as used in Kay et al. (2006), Raff et al. (2009), Chernet et al. (2014), Shamir et al. (2015) or Duan et al. (2017), is presented in Figure 2-4. The possible downscaling techniques available can be divided into dynamical downscaling based on RCMs, statistical downscaling and a combination of both. Some techniques may be more appropriate than others to simulate precipitation and other extremes (Sarr et al. 2015; Sunyer et al. 2012).

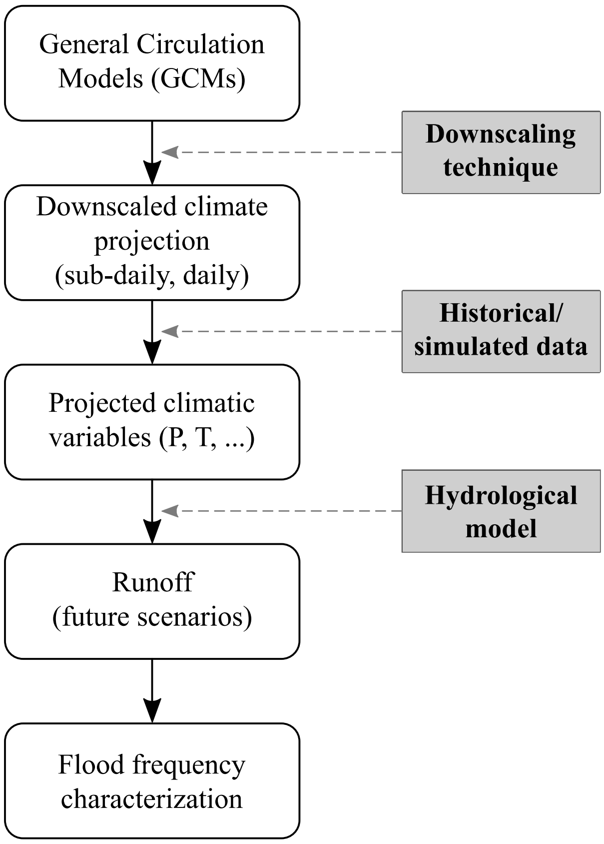

Figure 2-4. *Example methodology for the frequency analysis of floods under climate scenarios based on downscaled projections.*

Modelling extreme events remains a challenge, and still more research is needed for analyzing and refining the performance of downscaling techniques. Most downscaling techniques are designed to reproduce the mean of the climate signal, which could lead to underestimate the magnitude of the triggering precipitations, although some studies can be found that handle the projection of extreme events (Arnbjerg-Nielsen et al. 2013; Dobler et al. 2013; Pereira-Cardenal et al. 2014; Sarr et al. 2015; Willems 2012). Other limitations have been identified, for instance, in regions with a complex topography; in such cases, statistical downscaling perform more adequately to generate higher-resolution climate change scenarios (Dobler et al. 2013). Moreover, more attention must be paid to test the influence of non-stationarity in extreme events for flood frequency estimation (Kjeldsen et al. 2014), which is a major uncertainty when applying statistical downscaling techniques (Dixon et al. 2016; Lanzante et al. 2018). Traditionally, frequency analyses are based on the assumption of independency and stationarity of extreme events, which can eventually lead to a miscalculation of the resulting flood quantiles (Šraj et al. 2016; Zhang et al. 2015). Alternative approaches that incorporate the effects of non-independence and non-stationarity (for instance, by using time varying distribution parameters (Khaliq et al. 2006)) can improve the accuracy of the processes. Other attempts seek to reduce these uncertainties related to the statistical downscaling making use of stochastic weather generators (Wilks 2010) which produce synthetic time series of weather data for a location based on the statistical characteristics of observed weather at that location.

Additionally, impact assessment can benefit from deeper investigations. For instance, uncertainties are inherent to both climate and hydrological projections and should be incorporated to the analyses. These may come from the consideration of several climate models or scenarios (Knutti et al. 2010b), but also from the techniques used to obtain a specific projection (e.g., the downscaling method chosen), the hydrological model structure or the parameter identifiability (Chaney et al. 2015). In some cases it can be useful to apply several downscaling methods and compare the results (Willems 2013).

Studies might also consider the effects of time-varying watershed model parameters in extreme flood climate change studies. For instance, glacier retreat is expected to intensify, leading to an alteration of the flow regimes especially in high mountain regions (Huss et al. 2010). Also, potential evapotranspiration is very likely to increase in a warmer climate, therefore changing the soil conditions when flood events happen. These conditions can in turn influence the generation and propagation of flood hydrographs. Moreover, using flood information separately by seasons can be useful in basins or environments strongly influenced by snow precipitation and storage, where changes in melting of winter snow due to a global warming may play a significant role in peak river runoff (Lawrence et al. 2014).

2.3.1.2 Reservoir water levels

The distribution of the water storage in the reservoir, and thus of the pool levels, determines the loads to which the dam is subjected at the moment of arrival of a flood. A dam with a reservoir that is frequently full will be subjected to higher hydrostatic loads than one with larger fluctuations and less likely to be full. This is captured in the curves representing the relation between water pool level and probability of exceedance for two different cases (Figure 2-5): the continues curve represents the case of Reservoir A which is almost full (level above 540 m a.s.l.) almost 80% of the time; (b) while the discontinuous cure represents Reservoir B which is half empty more than 70 % of the time. Such distributions depend basically on the inflows, the demands, the reservoir management rules and the water losses (evaporation, infiltration, etc.), and can be obtained either by using the register of historic pool levels or through the simulation of the system of water resources management.

Under climate change, surface water availability is expected to fluctuate mainly due to increased precipitation variability (IPCC 2014) and potential evapotranspiration associated with global warming (Kingston et al. 2009; Seneviratne et al. 2010). However, other factors such as decreased snow and ice storage (Huss 2011) may have a significant influence. Changes in agricultural land uses, which accounts for about 90 % of global water consumption, are also expected to impact freshwater systems, affecting both the hydrological processes given in the catchment and the water irrigation needs. Moreover, water demand and allocation are strongly driven by demographic, socioeconomic, and technological changes, such as population growth, changes in land use or the adaptation of the reservoirs' exploitation strategies.

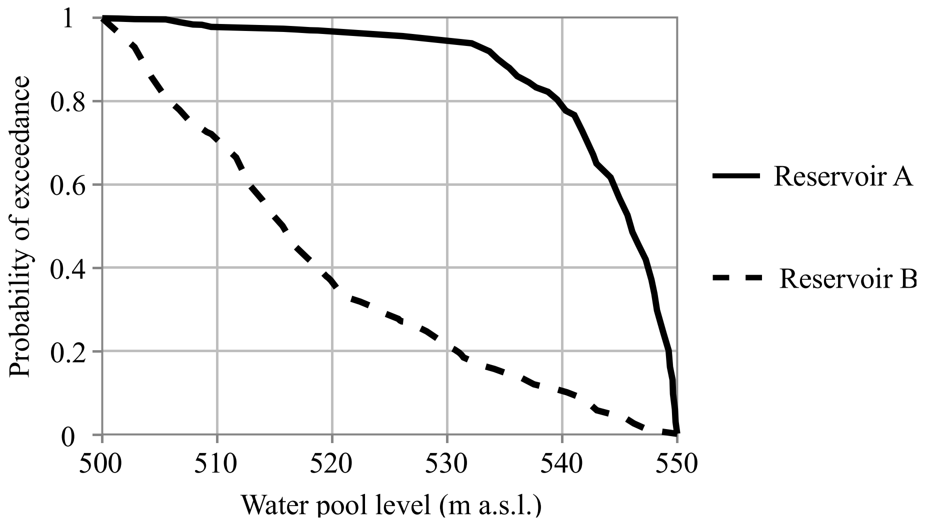

Figure 2-5. *Examples of the relation between water pool level and probability of exceedance.*

The combination of these factors is likely to alter the balance between water availability and supply, and thus will have a direct impact on the water levels in the reservoir. This impact does not only refer to the quantity, but also to the temporal distribution of the water stored, which has a key impact in the dam safety as stated before.

When assessing the effects of climate change on the distribution of the reservoir water levels, analyses must rely on the simulation of the system of water resources management. This allows reproducing the water balance in the reservoir under specific management rules and for future conditions. Firstly, the inflows are assessed, preferably using long updated climatic series obtained from specific climate models as inputs to a hydrological model. This in turn models the basin behavior and provides the inflow discharges at the reservoir. These results can be then coupled with the modelling of the system of water resources that computes the allocation and use of the water based on the reservoir's exploitation rules. For complex systems (e.g., the joint operation of several reservoirs), this can be done using simulation tools such as HEC-ResSim (Klipsch and Hurst 2007) or

AquaToolDMA (Andreu et al. 1996). The results of such models are the projected water storage evolution that can be transform in reservoir level series from which the previous pool levels curve can be obtained.

Here too the uncertainties inherent to climate and hydrological projections should be incorporated in the analysis. In this case, the conditions assumed for the water resources' exploitation modelling are also subjected to an uncertainty analysis. Additionally, non-climatic drivers affecting any component of the water balance computation (e.g., changes in land use, adaptation of reservoir's exploitation rules, etc.) can be significant and thus should be included in the analysis. However, the amount of information and work required, and the multiple determining factors involved can turn this procedure impracticable and must be envisaged only when the complexity of the system and the availability of data and time allow it.

2.3.1.3 Gate performance

Spillways and outlet works play a fundamental role in dam safety. They must ensure a certain discharge when required by the arrival of a certain flood. It is therefore important to assess any potential effect that could boost the failure of their regulating gates. Among the different causes that can induce a gates failure, it is worth mentioning (Lewin et al. 2003; SPANCOLD 2012): human failure, lack of access to the maneuver chamber, mechanical failure of the gate or of the civil works, electrical failure, blockage of the outlet works or spillway, or failure in the software controlling the gate or the valve.

An important aspect for their proper working is the good condition of the gates. Severe deficiencies and deterioration could render the outlet works or spillway useless. More intense rainfalls may lead to more soil erosion (Yang et al. 2003) which can be further fostered by changes in land use. Then, an increase in the sediment content of water can worsen the abrasion and erosion processes on the gates, their mechanical equipment or the spillways (British Columbia et al. 1998) thus compromising their reliability. Besides, if the water carries more and bigger suspended material (including trees, branches or debris) this could lead to a blockage of some gates, thus reducing the discharge capacity (Paxson et al. 2016). Changes in temperature can also affect the correct maneuvering of the gates. Hotter or colder conditions, or even greater fluctuations in temperature, can expose gates' mechanisms to additional stresses and/or deformations. This could eventually lead to blockages or malfunctioning of the gates.

The assessment of such impacts on the gates' reliability can be performed using the qualitative description of the gate system's condition. These descriptors are based on standard cases used in dam risk analysis and shown in Table 2-1, without being necessary to resort to detailed studies such as fault trees (Escuder-Bueno and González-Pérez 2014). The quantitative individual reliability of the gate (i.e.

the probability that it behaves properly) is related to a qualitative description of the condition of the gate system. By estimating the importance of new climatic conditions and stressors such as those mentioned above, one can assess if the gate's state must be updated and thus modify its reliability accordingly.

Table 2-1. *Standard individual reliabilities of the spillway gates.*

Case	Reliability
Non-gated	100 %
New / Very well maintained	95 %
Well maintained, some minor problem	85 %
Some problem	75 %
Unreliable	50 %
Not reliable at all / not used	0 %

For more detailed studies, a deeper analysis of the causes and of the assigned failure probabilities is required. The use of fault trees (not to be mistaken for event trees) is a good option to study them in detail (SPANCOLD 2012; Stamatelatos et al. 2002). Such tools include all the possible manners in which a gate can fail and disaggregate all the failure probabilities, however small they are (Lewin et al. 2003).

2.3.1.4 Flood routing strategy

This component defines how the dam–reservoir system should respond when This component defines how the dam-reservoir system should respond when confronted to a hydrological event. A correct operation of the reservoir allows maintaining adequate safety levels. Such safety levels will also depend on the characteristics of the dam-reservoir system: for some reservoirs the sufficient storage capacity to absorb the inflowing volumes will be determinant, while for others an adequate capacity of releasing peak inflows may be the dominant factor.

Indeed, the routing of the incoming floods reduces the loads to which the dam is subjected. The capability of the dam to perform such routing depends on the state of the outlet works needed to release the discharges as well as on adapted gates operation rules. Potential effects of climate change on these aspects should be checked.

The operation procedures of the regulated gates establish the desired outflow discharge at any given moment. These procedures will usually be defined depending on a variety of factors, such as the reservoir's water level and its evolution, the inflow discharge, time, etc. Under changes in climate conditions, flood routing strategies are likely to adapt. For instance, the increase of transported sediments driven by soil erosion will accelerate their accumulation within the reservoir, thus impairing the reservoir operation and decreasing its routing capacity and even posing safety hazards to the dam infrastructure (Kondolf et al. 2014; USBR 2006). Also, changes in heavy rainfall patterns may induce variations in the flood hydrographs concentration time, thus reducing the response capacity. This may compel to re-evaluate operation criteria, especially when relying on methods based on the remaining routing volume such as the Volumetric Evaluation Method (Girón 1988).

Changes in the reservoir's operation criteria should be analyzed under deep analyses that rely on the possible evolution of these criteria attending to climatic and non-climatic drivers. When comparing present and future risk, it is recommended to adapt current operation rules. First, the drivers affecting the definition of the operation rules must be identified. Then, under the consideration of the climate change scenarios adopted, the analysis of the influence on such drivers is performed. Finally, the operation criteria are re-evaluated accordingly. Given the important uncertainty involved in the process, this must be treated carefully to avoid inefficiencies in the analyses; only the most relevant and clear aspects of the problem should be addressed.

2.3.2 System response

2.3.2.1 Failure modes

Failure modes represent the possible ways in which the dam may fail: overtopping, pipping, sliding, etc. Their definition is a key process in risk analysis (FEMA 2015) since if a relevant failure mode is not included in the analysis, this might lead to an important underestimation of the calculated risk. Different guidelines and tools (FERC 2005; García-Kabbabe et al. 2010) provide guidance for the identification, description and structuring of failure modes whenever necessary.

The vulnerability of the dam infrastructure to failure can be somehow affected by climate change. As the conditions of the dam-reservoir system deteriorate or as the climate factors worsen, an update of the failure modes considered may be required. In particular, failure modes are susceptible to arise or previous ones to become obsolete. For instance, in the context of geological hazards, studies have confirmed the influence of climate change on slope stability (Damiano and Mercogliano 2013; Dehn et al. 2000). A slope failure event nearby a dam site could eventually entail a part of the terrain falling into the reservoir or impacting on the dam, which could trigger an overtopping of the dam and eventually a dam failure.

A similar hazard arises in glacial and periglacial environments where the increasing temperatures will likely cause a decrease in thickness and area of glaciers and progressive permafrost degradation. This thermal perturbation would entail stress redistributions and fast modification of the mechanical conditions at depth (Schneider et al. 2011), which could lead to rock-ice avalanches or Glacial Lake Outburst Floods (GLOFs) entering the reservoir (Evans and Delaney 2015; Huggel et al. 2008; Stoffel and Huggel 2012).

2.3.2.2 Probability of failure

Whether different failure modes are taken into account or not, the conditional probability of failure of the dam may also vary under new climatic conditions. To assess such probability and how it is impacted, one can disaggregate each failure mode into its failure mechanisms and then assess the probability of each of them by using different tools (e.g., reliability tools or expert judgment). The objective is to study whether, subject to the same loads, the dam is responding differently under different conditions.

The potential casuistry of climate change effects is large but, for simplicity's sake, in this study only the typical failure modes are examined: overtopping, sliding and internal erosion (piping). For instance, the structural behavior of concrete dams, and especially arch dams, is directly influenced by temperature (Malm 2016) and solar exposure (FERC 1999). Under future climate change, average temperature is expected to increase in all climate scenarios, and may have greater fluctuations during certain periods and reach more frequent extreme values (IPCC 2013). Moreover, the potential variation of the water storage in the reservoir (cf. Section 2.3.1.2) can increase the exposition of the body of the dam to sun radiation (both in duration and surface), increasing the temperature difference and causing temperature peaks in the surface of the concrete. These factors can eventually expose the dam to additional mechanical stresses due to the temperature variations, thus turning it more fragile to hydrostatic loads. In these cases, conventional stability analyses may be not sufficient to assess whether the failure probabilities related to dam sliding are influenced by increasing temperatures and solar radiation and then should be adapted. It could thus be of help performing mechanical and structural analyses, for instance using numerical tools such as finite element or finite difference methods. Similar studies can be applied in case other failure modes (e.g., overtopping or internal erosion) are found influenced by climate change.

In some cases, drier soil conditions are expected due to increasing temperatures and precipitation pattern’s variations. Moreover, as stated above, water pool levels may significantly vary and leave the dam at lower levels during long periods. This could reduce the soil moisture, thus changing the vulnerability of embankment dams to processes such as internal erosion. Indeed, moisture content (and even soil temperature) plays a key role on the internal erosion characteristics (Briaud 2008). The decrease of water content decreases the critical shear stress and increases the coefficient of piping erosion, thus worsening the soil resistance against erosion (Wan and Fell 2004). Besides, in dams with vegetated downstream faces, the loss of plants due to the change in soil moisture may on the one hand leave more or less deep holes that could turn the soil more susceptible to internal erosion processes, and on the other hand present less resistance to surface flow in case of an overtopping event.

Whenever necessary, the assignation of failure probabilities should be complemented with expert consultancy and participatory workshops where results from the models serve as relevant support for the understanding of the problem. More information about probability elicitation through expert judgment can be consulted in different guidelines (ANCOLD 2003; Ayyub 2001; SPANCOLD 2012).

2.3.3 Consequences

Damage produced by a dam failure or an abnormal discharge release is in general very important, causing serious socio-economic consequences. Their analysis is based on two parts: estimation of the outflow hydrographs and their routing downstream, and calculation of the consequences.

2.3.3.1 Outflow hydrographs

An important aspect in the definition of the consequences is the routing of the non-failure and the failure outflow hydrographs. The first one results from the spills released by the outlet works and spillways during the flood routing; the latter one is due to the dam failure. Even if the outflow hydrograph originated by the dam break may be many times greater than in the non-failure case, the impact of climate change is considered analogous and can be analyzed jointly.

The study of downstream hydrographs can be split in two stages: estimation of the reservoir outflow hydrograph (through the dam breach or through the outlet works), and routing of the resulting hydrograph throughout the downstream inundation area.

On the one hand, the first stage can be characterized using curves that generally relate the maximum water level reached in the reservoir and the peak discharge (Figure 2-6 (a)). These relationships may include other variables depending on the specificities of each case: duration of the hydrograph, speed of the flood wave, etc. According to the hydraulic behavior of the outflow hydrographs, there are no funded evidences that suggest relevant impacts of climate conditions on this aspect.

On the other hand, these outflow hydrographs are routed to estimate the resulting inundation maps downstream. This information is used to calculate the consequences curve in case of peak discharge (Figure 2-6 (b)).

Land use changes can affect substantially the progression of the downstream inundation wave depending on the type of surface (e.g., urbanized or vegetation), its slope, etc. (Bornschein and Pohl 2018; De Roo et al. 2001). Some studies have applied different techniques and models to forecast future land uses, which can be found in the literature (cf. Section 2.3.3.2). Furthermore, climatic factors such as temperature, precipitation or carbon dioxide concentration are likely to influence plant growth (Morison and Morecroft 2007; Peñuelas et al. 2004) with a high variability in time and space. This will not only induce a transformation of soil cover (upstream and downstream the dam) but will also affect the amount of sediment contained in the reservoir at the time of the flow release (Braud et al. 2001; Liu et al. 2014). In addition, some studies demonstrate that vegetation cover (Anderson et al. 2006; Järvelä 2002) and incoming flood sediment concentration (Carrivick 2010) may influence the propagation of downstream hydrographs. The flow resistance of vegetation increases the roughness of floodplains and then attenuates wave celerity and dispersion of hydrographs, while suspended sediment concentration changes fluid viscosity thus affecting the acceleration and/or deceleration of the flow.

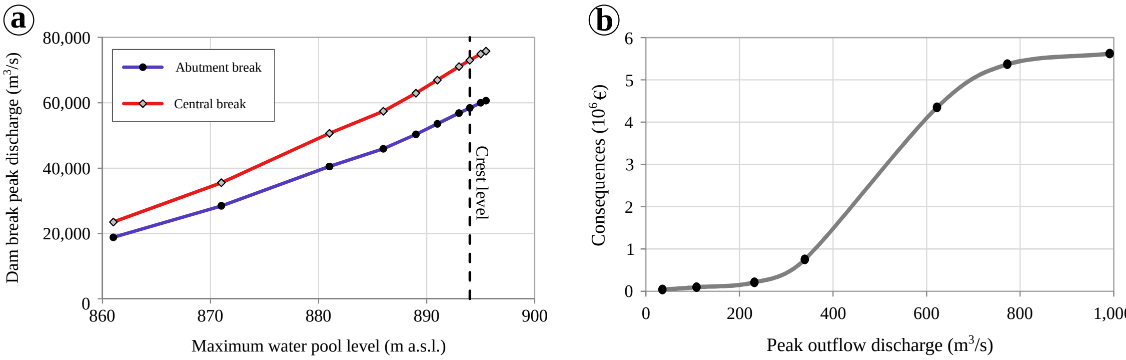

Figure 2-6. *(a) Example of the relation between the maximum water level attained in the reservoir and failure peak discharge, depending on the failure mode considered (abutment or central break). (b) Example of discharge–consequences curve.*

These two main factors —surface roughness and water viscosity— are typically used in floodplain models for the definition of inundation maps (Bladé et al. 2014; DHI 2014; USACE 2011b). By updating these inundation models with the projected values of the factors it is possible to analyze their effect on the outflow hydrographs.

2.3.3.2 <u>Socio-economic consequences</u>

Once the downstream hydrographs are defined, it is possible to assess their consequences. A distinction can be made between the direct consequences – those created directly by the impact of the inundation wave –, and the indirect consequences – induced by the direct impacts and which may occur outside the inundation event – (Merz et al. 2004).

Direct consequences

On the one hand, the calculation of direct consequences due to inundations relies on two factors: exposure, which reflects the presence of people, livelihoods, infrastructure or assets in an at-risk area; and vulnerability, which refers to their propensity to be adversely affected (Cardona et al. 2012; IPCC 2012). For the assessment of the impact on direct consequences, changes in exposure and vulnerability are analyzed.

According to long-term disaster records, some studies have revealed an increase in the losses due to extreme weather events (Mechler and Kundzewicz 2010; Peduzzi et al. 2009; Swiss Re 2016; UNISDR 2009). The long-term trends in these losses are attributed to the increasing exposure of people and economic assets in at-risk areas due to population and economic growth (Bouwer 2011; Changnon et al. 2000; Miller et al. 2008; Pielke Jr. et al. 2005) rather than to climatic drivers (Choi and Fischer 2003; Crompton and McAneney 2008; Neumayer and Barthel 2011). This can be extrapolated to inundations (Barredo 2009; Hilker et al. 2009; Pielke Jr. and Downton 2000) and hence to the dam risk framework. Indeed, potential increases in the socio-economic losses are directly influenced by the enhancing presence of people and economic assets in at-risk areas due to population and economic growth (Handmer et al. 2012).

It is also expected that vulnerability facing flooding events will be affected, especially when referring to population vulnerability in poor or underdeveloped environments. Indeed, the capacity to anticipate and respond to inundation risk depends on the existence of public education on risk, warning systems, or coordination between emergency agencies and authorities (Escuder-Bueno et al. 2012a). In a changing world, these capacities may vary with the socio-economic development. For example, a potential reduction of economic support for population training or for the maintenance of warning systems may entail a reduced capacity of response, thus increasing its vulnerability.

The assessment of the change in the exposure and vulnerability of the at-risk population and assets due to non-climatic drivers depends on the population and economic growth and should be based on socioeconomic development, urbanization, and infrastructure construction information. Few works have studied jointly both factors when assessing losses from climate change (Hall 2003; Pielke Jr. 2007; Schmidt et al. 2009).

Regarding population growth, a simple approach could be considering the past demographic evolution at the affected areas and extrapolating it to future scenarios. Another option is using existing projections at regional or national scale such as those available at the online publication Our World in Data (2018), extracted from the UN database (United Nations 2017). If no specific data are available and due to the complexity of proceeding otherwise, it can be considered that the same current assets and services at risk remain in the future. Only the update of their economic value (cost) is to be applied. Bouwer et al. (2010) propose the application of a factor reflecting the estimate of the increase in value of the at-risk assets based on the index for annual change in gross domestic product (GDP). Results of long term forecasts for the GDP for different countries (up to 2060) can be found in (OECD 2018), which are based on an assessment of the economic climate in individual countries and the world economy.

More detailed projections (population, land use and value of assets) can be achieved based on quantitative indicators of societal and economical changes and on the application of specific land use and population growth models. For instance, Maaskant et al. (2009) use projections and spatial distribution of population extracted from a land use model (Schotten et al. 2001) under a high economic growth scenario. Although this scenario was specifically developed for the Netherlands, useful indications can be obtained from other work or guides for the definition and application of socio-economic scenarios (Riahi et al. 2017; UK Climate Impacts Programme 2000). These practices are often complex and seldom applied (Feyen et al. 2008). Indeed, results of the application of such scenarios are highly dependent on the chosen scenario(s) and must include the corresponding uncertainty. Moreover, land use and economic models can be based on individual behavior and microeconomic trends that are difficult to capture.

Regarding changes in the population vulnerability, there are different methodologies to assess the inundation severity levels according to the socio-economic context. Escuder-Bueno et al. (2011) propose a classification to assess potential loss of life in urban areas in case of river flooding depending on several factors. Once a socio-economic scenario has been chosen, it is possible (although not always easy) to study how these factors will evolve and then update the vulnerability accordingly.

Indirect consequences

On the other hand, climate change may have an influence in the indirect consequences. In particular, services and products related to water are of special importance in the context of climate change. Indeed, the value of water allocated to irrigation or hydropower production is likely to vary due to the expected alteration of the distribution, volume and timing of water resources in the future (Fischer et al. 2007; Rodríguez Díaz et al. 2007; Solaun and Cerdá 2017; U.S. Department of Energy 2013). Dams are a key component when assessing socio-economic scenarios and their importance may even increase under future climatic conditions (more frequent droughts and extreme events, for instance). Thus, in case of dam failure or serious malfunctioning, the absence of the structure would indeed induce some consequences caused by the fact of being unable to manage part of the water volume.

The assessment of how climate change may impact the indirect consequences is often very complex given the number of components involved and their interrelations. When a deep analysis may be impracticable, indirect costs can be estimated as a fix percentage of direct cost (James and Lee 1970; SPANCOLD 2012). This fix percentage could be simply applied to the direct costs that must be re-evaluated under the new climate change scenarios. When the application of a fixed percentage may lead to important errors (e.g., in the case of an airport, for which the indirect costs involved by the interruption of the aerial traffic are much more important than the direct ones), a more detailed work is advised.

Deeper analyses require complex modelling of the economic system to assess how it would be affected by the impact of climate change. First, if it is not yet carried out, an identification of the potentially affected services and economic activities is required (e.g., electric or telecommunications supply, industrial production). Then, specific models are to be used to assess the indirect costs induced by the interruption of these services and/or activities due to a dam failure or disruption event. Different methodologies, such as the Input-Output or the Computable General Equilibrium analyses (U.S. Department of Homeland Security 2011), can be applied to study the variations of the economic flows after the flood. An analysis of how each component used in these models is susceptible to change in the future must be done. In order to simplify the work, one can study only the impact in the most relevant activities affected (e.g., services and products related to water such as irrigation or hydropower production). Different works and methodologies have been developed to analyze how climate change may affect the resulting damage on the water resources systems (Hutton et al. 2007; Kazem et al. 2016; Quiroga et al. 2011).

2.3.4 Summary

A succinct summary of the main impacts identified for each dam risk component is presented in Table 2-2 along with some recommended techniques and methods for their assessment.

Table 2-2. *Summary of climate change impacts on the different dam safety components and suggested methods for their assessment.*

Risk component	Climate change impacts	Assessment methods
Flood	Variations in local floods are expected due to changes in: - Heavy rainfall patterns. - Snow cover and snowmelt processes. - Vegetation or soil moisture.	- Direct application of previous analyses. - Combination of climate projections, downscaling techniques and hydro-meteorological modelling (Figure 2-4). - Uncertainties inherent to climate and hydrological projections and changes in watershed model.
Reservoir water levels	Fluctuations of water storage due to: - Precipitation variability, potential evapotranspiration or decreased snow and ice storage. - Changes and adaptations in agricultural land uses and water demand.	- Combination of climate projections, downscaling techniques and simulation of the system of water resources management. - Importance of non-climatic drivers (e.g., changes in land use, adaptation of reservoir's exploitation rules).
Gate performance	- Abrasion processes due to increase in the sediment content of the water. - Blockage of the gates due to suspended material. - Changes in temperature causing stresses and/or deformations.	- Qualitative assessment of the impacts of new climatic conditions and stressors (Table 2-1). - Use of fault trees.
Flood routing	Operation rules are likely to adapt under certain climate conditions (e.g., changes in heavy rainfalls inducing variations in the flood hydrographs concentration time).	Re-evaluation of the flood routing criteria.
Failure modes	Additional failure modes are susceptible to arise, in particular in the context of glacier melt and slope stability or GLOFs occurrence directly impacting the dam structure.	Guidelines and tools to identify, describe and structure additional failure modes or remove obsolete ones.
Probability of failure	- Temperature fluctuations may induce to additional mechanical stresses in concrete dams. - Drier soil conditions and water level fluctuations can increase processes such as internal erosion in embankment dams.	Probability elicitation through expert judgment in different guidelines.
Outflow hydrographs	The outflow hydrograph routing is affected by: - Surface roughness of the surface. - Water viscosity related to flood sediment concentration.	Use of inundation models to assess the sensitivity of the outflow hydrographs to these factors.
Socio-economic consequences	Direct consequences: - Exposure changes due to population growth. - Update of the assets' economic value. Indirect consequences: - The value of water for irrigation or hydropower production is likely to vary, which implies changes in the cost of interruption of services and/or activities.	Direct consequences: - Application of demographic projections. - Detailed land use and population growth models based on socio-economic scenarios. - Assessment of flood severity levels according to the socio-economic context. Indirect consequences: - Estimation as a fix percentage of direct costs. - Complex modelling of the economic system and assessment of costs induced by the interruption of services and/or activities.

2.4 Conclusions

This work presents an interdisciplinary review of the state-of-the-art research on projected climate change impacts on dam safety attending to both climatic and non-climatic drivers. The structure followed for such review is based on the risk analysis approach where all the variables concerning dam safety – from the hydrological loads to the consequences of failure – and their interdependencies are included in a comprehensive way. The extent of the analysis to be performed should depend on the detail level chosen. Paired with the impacts identified, the paper also presents the useful techniques for their direct application to provide information for dam owners and dam safety practitioners in their decision-making process. Although the information collected in this work is mainly based on existing works, there is still some novelty or innovation in its processing since usually the global effects of climate change on dam risk are studied separately. The authors introduce a more comprehensive and structured approach to take them into account, which can be used to apply this same risk analysis to other critical infrastructures.

The purpose of this review is to serve as a dam safety management supporting tool to assess the vulnerability of the dam to climate change, i.e. the additional risk imposed by climate change effects, and to define adaptation strategies for new climate scenarios under an evolutive dam risk management framework (Figure 2-7). Under this approach, dam risk models must be updated following to the effects of climate change on each of the risk components, which will later help define the adaptation strategies to be followed. As climate projections evolve with new scenarios of models, the process must be replicated iteratively.

With this information, long-term investments can be planned more efficiently. Indeed, the application of such tool may prevent investing in measures that would no longer be necessary in the future, or missing some measures that could reduce the future risk. As such, it is addressed to dam owners and dam safety practitioners, but also to the research community that can help improving it and filling the gaps that still remain in some aspects of the risk assessment.

The present work is based on available data sources and information at current levels of knowledge. However, this filed of research is highly dynamic and advances in science and techniques for the assessment of these climate change effects are expected over time. Therefore, climate change impacts can then be iteratively actualized along with the forthcoming innovations and advances in science and techniques for the assessment of these effects. In particular, climate modelers as well as dam engineers face significant uncertainties when proposing and assessing climate scenarios and their impact on the different components involved in dam safety. The assignation of probabilities to uncertain future conditions and scenarios remains a major challenge and thus the management of dam safety based on climate change impacts must take into account these limitations.

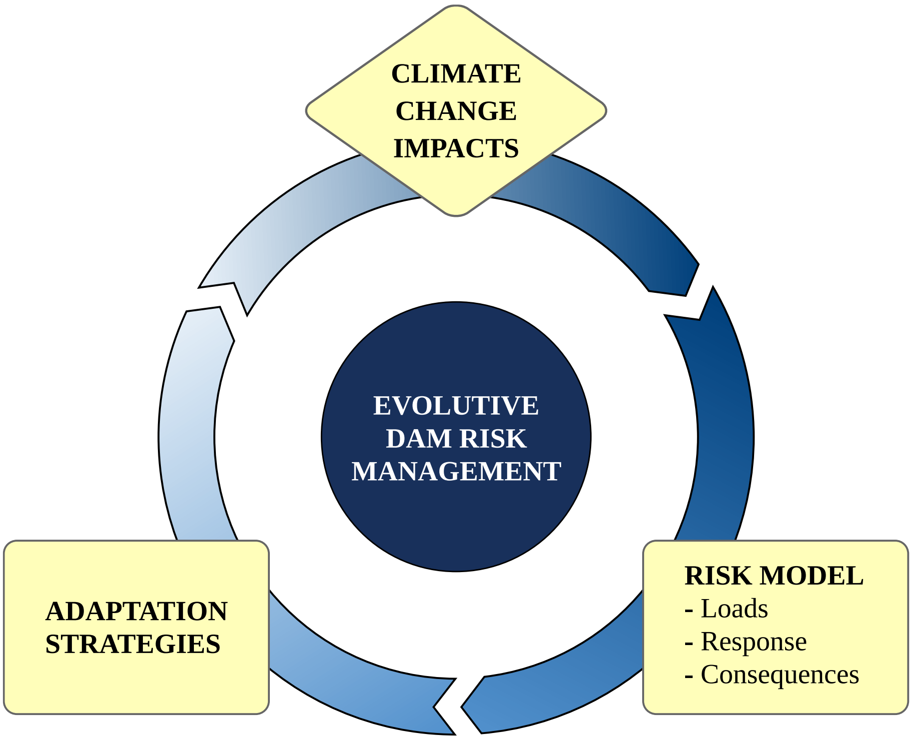

Figure 2-7. *Evolutive dam risk management driven by climate change impacts on risk components, including adaptation strategies.*

Chapter 3

Quantification of climate change impact on dam failure risk under hydrological scenarios: a case study from a Spanish dam

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Abstract

Dam safety is increasingly subjected to the influence of climate change. Its impacts must be assessed through the integration of the various effects acting on each aspect, considering their interdependencies, rather than just a simple accumulation of separate impacts. This serves as a dam safety management supporting tool to assess the vulnerability of the dam to climate change and to define adaptation strategies under an evolutive dam failure risk management framework.

This article presents a comprehensive quantitative assessment of the impacts of climate change on the safety of a Spanish dam under hydrological scenarios, integrating the various projected effects acting on each component of the risk, from the input hydrology to the consequences of the outflow hydrograph. In particular, the results of 21 regional climate models encompassing three Representative Concentration Pathways (RCP2.6, RCP4.5 and RCP8.5) have been used to calculate the risk evolution of the dam until the end of the 21st century. Results show a progressive deterioration of the dam failure risk, for most of the cases contemplated, especially for the RCP2.6 and RCP4.5 scenarios. Moreover, the individual analysis of each risk component shows that the alteration of the expected inflows has the greater influence on the final risk. The approach followed in this paper can serve as a useful guidebook for dam owners and dam safety practitioners in the analysis of other study cases.

3.1 Introduction

Dams are critical infrastructures whose associated failure risk must be properly managed in a continuous and updated process (Fluixá-Sanmartín et al. 2018). When assessing their safety levels, most dam risk assessments in the past assumed a stationary condition in the variability of climate phenomena. However, climate change is likely to affect the different factors driving dam failure risks (USBR 2014). The assumptions of stationary climatic baselines are no longer appropriate for long-term dam safety adaptation and decision-making support (USBR 2016). Therefore, the way risk analyses are envisaged on the long term has to be revisited in order to incorporate the new climate change scenarios.

In this context, some efforts have been done in the evaluation of climate change impacts on dam safety surveillance (OFEV 2014; USACE 2014; USBR 2014, 2016). However, the assessment of these impacts is usually applied separately and tend to focus on specific aspects such as the hydrological loads (Bahls and Holman 2014; Chernet et al. 2014; Novembre et al. 2015) relegating or ignoring other aspects.

The global effect of climate change on dam safety must be quantitatively assessed through the integration of the various projected effects acting on each aspect. In (Fluixá-Sanmartín et al. 2018), a dam safety management supporting tool is defined to assess projected climate change impacts based on the risk analysis approach where all the variables concerning dam safety and their interdependencies could be included in a comprehensive way. In this context, risk analysis is a useful approach encompassing traditional and state-of-the-art methodologies to manage dam safety in an accountable and comprehensive way (Bowles 2000; Serrano-Lombillo et al. 2013) that represents a useful basis on which such assessments can be structured. With this quantitative information, long-term investments can be planned more efficiently taking into account the potential evolution with time of risk and of the efficiency of measures.

In this work the authors seek a comprehensive quantitative assessment of the climate change impacts on the failure risk of a Spanish dam. The key innovative aspect of this methodology is the use of very different models and data sources, and their combination for the assessment of the overall effect of climate change in the resulting dam safety risk. The analysis has been elaborated under hydrological scenarios, where the floods are the main loads to which the dam is subjected. In order to decompose such impacts on the different risk aspects, a risk analysis scheme has been adopted. First, the methodological approach proposed is presented. Then the study case of the Santa Teresa dam to which the methodology will be applied is described. The different data sources and existing models employed on this study are presented. Using this information, the methodology is applied to the study case, explaining the treatment of raw climate projections, the elaboration of auxiliary models and the adaptation of the risk model components. Finally, the output risks are presented and the resulting effects on the dam safety analyzed.

3.2 Methodology

This section describes the methodology proposed in this paper for the calculation of climate changes impacts on the safety of dams. The goal is to analyze its effects on the different dam failure risk components involved. It is worth noting that, within the context of dam safety, failure risk can be defined as the combination of three concepts: what can happen (dam failure), how likely it is to happen (failure probability), and what its consequences are (failure consequences) (Kaplan 1997). Risk is obtained through the following formula:

$$risk = \sum_{e} p(e) \cdot p(f|e) \cdot C(f|e) \tag{3.1}$$

where the risk is expressed in consequences per year (social or economic), the summation is defined for all events *e* under study, *p(e)* is the probability of an event, *p(f|e)* is the probability of failure due to event *e* and *C(f|e)* represents the consequences produced as a result of each failure *f* and event *e*.

As stated in (Fluixá-Sanmartín et al. 2018), changes in climate such as variations in extreme temperatures or frequency of heavy precipitation events (IPCC 2012; Walsh et al. 2014) are likely to affect the different risk components driving dam failure. Hence, the proposed methodology intends to establish a framework for the evaluation of projected climate change impacts on dam safety attending to both climatic and non-climatic drivers. This is based on the risk analysis approach where the effects on all the variables concerning dam safety – from the hydrological loads to the consequences of failure – and their interdependencies are evaluated jointly. The cornerstone of the methodology is the application of a dam risk modelling approach which encompasses the information issued from different models and data sources.

Moreover, since climate change is a non-stationary process, it is expected that its effects will change with time. Therefore, it is not only important to assess the global impact of climate change on the dam failure risk but also how this risk is expected to evolve with time. For this purpose, the methodology should be applied on one hand to the present situation (to which the *future* results will be compared) and on the other hand to different time horizons in the future. Given that the climate projections used in this study include results until the end of the 21st century, the following four different periods are proposed in this study:

- **Historical**: 1970–2005. It corresponds to the period for which hydro-meteorological observations are available, as well as to the reference historical period of the climate projections (see Section 3.4.2). This allows us to perform the downscaling of the climate projections. Such a period will be referred to as the base case.
- **Period 1**: 2010–2039.
- **Period 2**: 2040–2069.
- **Period 3**: 2070–2099.

The methodology proposed is based on the following main steps. A synthetic scheme of this methodology is presented in Figure 3-1.

a. **Extraction and correction of climate projections.** First, the raw climate projections issued from the available climate models must be bias corrected using the climate observations. Assessing the impacts of climate change on future runoff generation and on water resources availability require high-resolution climate scenarios. Global Climate Models (GCM) provide valuable prediction information but at a spatial resolution too coarse (around 1000 by 1000 km) to be directly used for modelling the hydrological processes at the required scale (Akhtar et al. 2008; Fujihara et al. 2008; Orlowsky et al. 2008). Therefore, downscaling is required to describe the consequences of climate change, which can be done using empirical-statistical downscaling or dynamical downscaling by means of regional climate models (RCMs). RCMs are commonly used in regional studies of climate projection and climate change impacts to downscale GCM simulations (Gao et al. 2006; Gu et al. 2012; Yira et al. 2017). They use the GCM outputs as lateral boundary conditions and thus their results depend to some extend on its driving GCM (Benestad 2016). However, the meteorological projections issued from RCMs are usually biased and hence need to be post processed before being used for climate impact assessment (Gudmundsson et al. 2012).

b. **Hydrological modelling.** Then, a hydrological model is set up based on the physical characteristics of the basin and on the hydro-meteorological observations. On one hand, such model allows performing the simulation of the system of water resources management to obtain the relation between previous pool level and probability at the reservoir, at the present situation and for future scenarios. On the other hand, the hydrological model is also used for the calculation of the flood hydrographs arriving into the reservoir.

c. **Risk modelling.** The quantitative assessment of climate change impacts on dam failure risk is conducted using a quantitative risk model of the dam. As explained, such models are commonly used to inform dam safety management and they integrate and connect most variables concerning dam failure risk to analyze the different ways in which a dam can fail (failure modes) resulting from a loading event, calculating their probabilities and consequences (Ardiles et al. 2011; Serrano-Lombillo et al. 2011, 2012b; c; SPANCOLD 2012). The model must be adapted following the effects of climate change on each of the risk components (Fluixá-Sanmartín et al. 2018).

d. **Correction of resulting risks.** In order to consistently assess and compare modelled risks, a change signal correction (likewise the delta change approach) must be applied to the results by scaling the outputs based on the difference between climate model and Base Case risks for the historical reference period. This correction is computed as the relative variation between raw risk output for a future scenario and risk of its corresponding historical reference period. Then, the future scenario risk is adjusted by multiplying this delta to the Base Case risk.

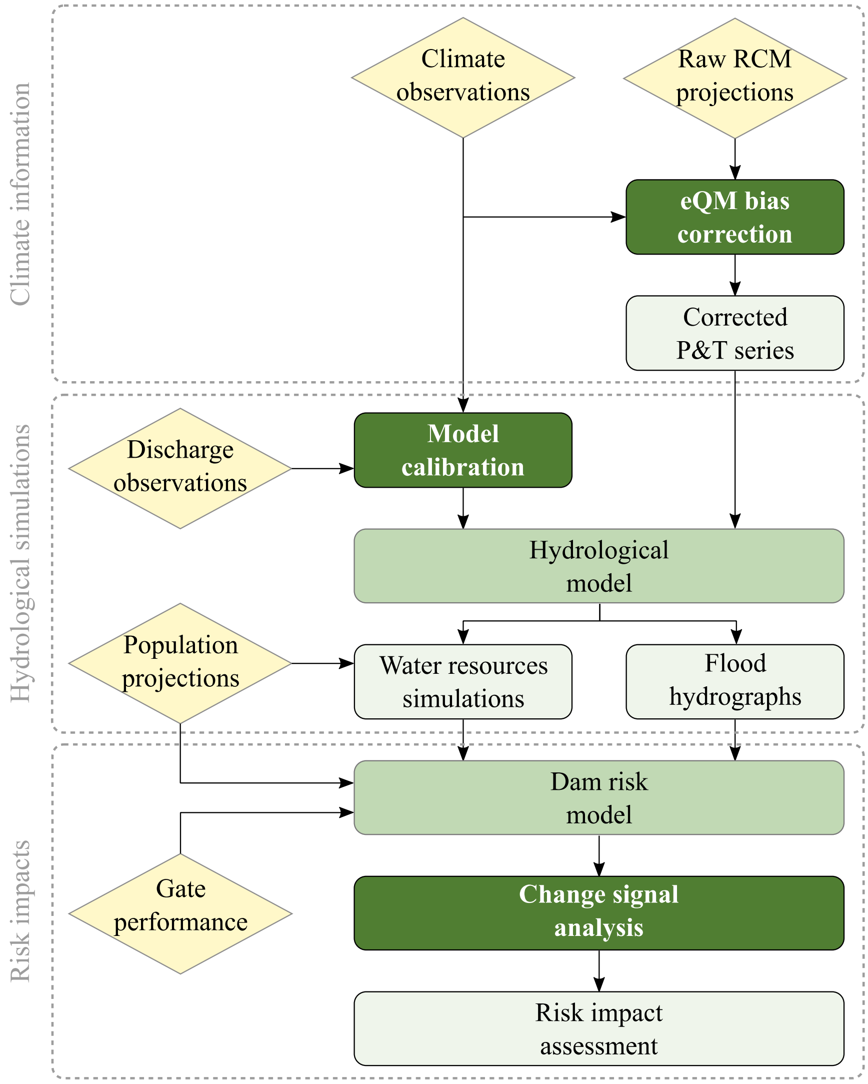

Figure 3-1. *Workflow of the methodology followed to assess climate change impacts on dam failure risk.*

3.3 Study case

The Santa Teresa dam is located in the upper part of the Tormes River, in the Province of Salamanca (Spain), and is managed by the Duero River Basin Authority. The Santa Teresa reservoir is bounded by the Santa Teresa dam and a smaller auxiliary dike. The Santa Teresa dam is a concrete gravity dam built in 1960 and has a height of 60 m with its crest level at 887.20 m a.s.l. and a length of 517 m. It is equipped with a spillway regulated by five gates capable of relieving, altogether, 2,017 m^3/s, as well as with two bottom outlets with a release capacity of 88 m^3/s each. The auxiliary dike is a 165 m long and 15 m high concrete gravity dam with its crest level at 886.90 m a.s.l.

The Santa Teresa reservoir has a capacity of 496 hm^3 at its normal operating level (885.70 m a.s.l.). The catchment that pours into the reservoir has a total surface of 1,853 km^2 and is part of the Tormes Water Exploitation System, being the Santa Teresa reservoir the first and uppermost infrastructure of the basin to regulate the Tormes River (Figure 3-2). The main uses for the Santa Teresa dam-reservoir system are hydropower production, flood protection, irrigation and water supply to the demands located between the Santa Teresa and the Almendra dams, including Salamanca city.

A risk analysis was already applied to the Santa Teresa dam in a previous study (Ardiles et al. 2011; Morales-Torres et al. 2016). Results from this analysis showed that, although the dam didn't require urgent correction measures, its risk was important enough to be carefully monitored. Therefore, it is interesting to evaluate whether its risk is expected to evolve up to the point of requiring correction measures.

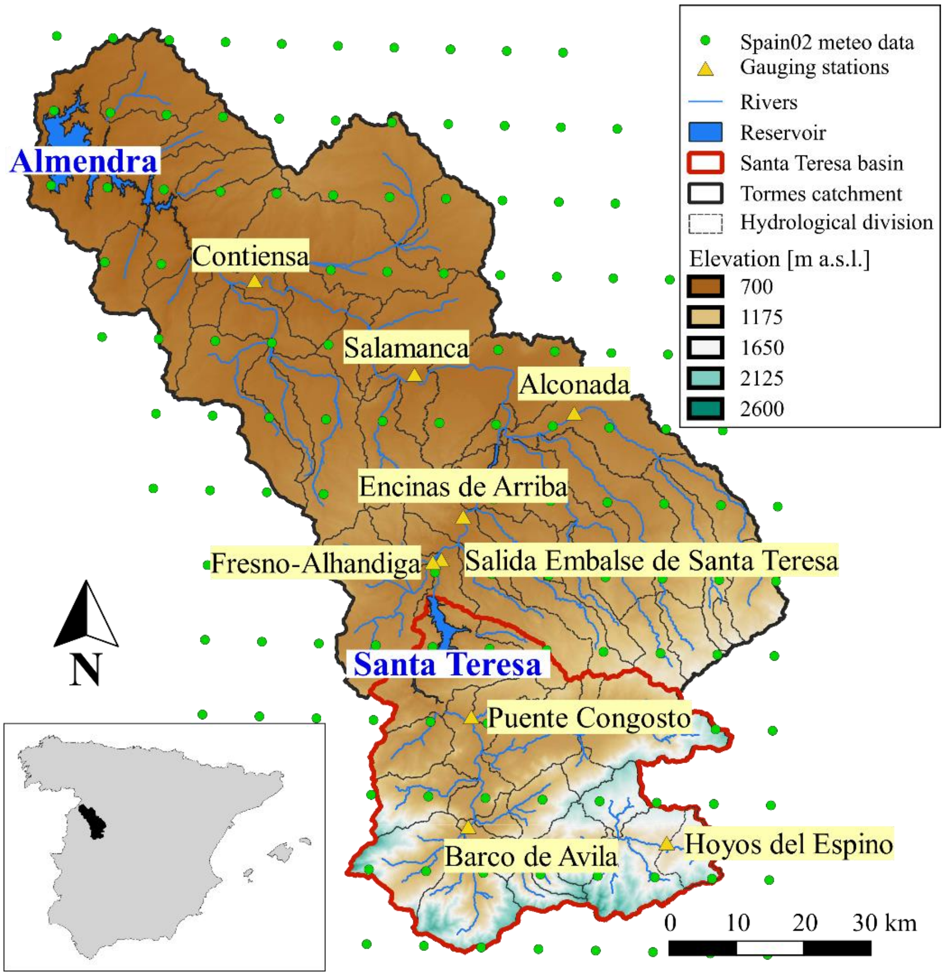

Figure 3-2. Location of the Santa Teresa and Tormes catchments, hydrological subdivision of the basin, reservoirs, gauging stations and the Spain02 gridded meteorological dataset.

3.4 Data and models

3.4.1 Hydro-meteorological data

The meteorological inputs used for the definition of the present situation are based on the observed data collected by the Spanish Meteorological Agency (AEMET). For this study, the Spain02 products have been employed. Spain02 is a series of high-resolution daily precipitation and mean temperature gridded datasets developed for peninsular Spain and the Balearic Islands. A dense network of over 2000 quality-controlled stations was selected from the AEMET and the Santander Meteorology Group (University of Cantabria 2020) in order to build the gridded products for the different dataset versions. The latest version of the dataset (Spain02 v5) provides daily data from 1951 to 2015 in a 0.1° interpolated regular grid (Herrera et al. 2016; Kotlarski et al. 2017). The full dataset is available at the AEMET climate services portal (AEMET 2020).

For the calibration of the hydrometeorological model, the daily historical discharge records at nine different hydrometric stations within the catchment are used (Figure 3-2): Hoyos Del Espino, Barco De Ávila, Puente Congosto, Salida Embalse de Santa Teresa, Fresno-Alhandiga, Encinas de Arriba, Alconada, Salamanca and Contiensa. These are part of the Integrated Network of Gauging Stations (SAIH-ROEA). The information of discharges was extracted from the CEDEX (Center for Research and Experimentation of Public Works) platform (CEDEX 2020). More information on the characteristics of these stations can be accessed in SAIH-ROEA (2020). Moreover, the historical water levels at the Santa Teresa reservoir from 1958 to 2015 is also available in this same platform.

3.4.2 Climate projections

The World Climate Research Programme (WCRP) Coordinated Regional Downscaling Experiment (CORDEX) project provides high-resolution regional climate projections and presents an interface for users of climate simulations in climate change impact, adaptation, and mitigation studies (Giorgi et al. 2009). As part of the CORDEX framework, the EURO-CORDEX initiative provides regional climate projections for Europe at 0.11° resolution (about 12 km) up to the year 2100 (Jacob et al. 2014). The regional simulations result from the downscaling of the Coupled Model Intercomparison Project Phase 5 (CMIP5) global climate projections (Taylor et al. 2012) and the Representative Concentration Pathways (RCPs) (IPCC 2013; Moss et al. 2010).

In the present study, the projections from the EURO-CORDEX project are used. These daily projections are available at the Earth System Grid Federation (ESGF) archiving system and accessible through one of its index nodes (e.g., ESGF Node IPSL (2019). In order to cover a large bandwidth of future climate evolutions, three different RCPs have been considered:

- RCP2.6: peak in radiative forcing at ~ 3 W/m^2 before 2100 and decline (van Vuuren et al. 2007, 2011).
- RCP4.5: stabilization without overshoot pathway to 4.5 W/m^2 at stabilization after 2100 (Thomson et al. 2011).
- RCP8.5: rising radiative forcing pathway leading to 8.5 W/m^2 in 2100 (Riahi et al. 2007, 2011).

Moreover, the uncertainties inherent to the modelled temporal evolution of future climate will be tackled by using ensemble simulations that combine different RCMs with different GCMs, as it is done within the CORDEX framework.

Each projection also has a reference period or *Historical* simulation (1970-2005) needed to evaluate and eventually correct results based on the comparison against observed climatological data sets. Table 3-1 summarizes the 21 climate projections used in this study, indicating the driving GCM, the ensemble member, the institute that conducted the projection and the RCM for each of them, as well as the scenarios (Historical and RCP) available.

3.4.3 Dam risk model

As part of a quantitative risk analysis performed on 27 dams located in Spain (Ardiles et al. 2011; Morales-Torres et al. 2016), the individual risk model of the Santa Teresa dam was set up with iPresas software (iPresas 2019) for hydrological loading scenarios. Such modelling was performed using event trees, an exhaustive representation of all the possible chains of events represented by nodes that can produce the dam failure (Serrano-Lombillo et al. 2011). The tree's branches represent all the possible outcomes of their event of origin and have an assigned probability. Any path between the initiating node and each of the nodes of the tree represent one of the possible outcomes that might result from the original event and can be calculated as the product of the probabilities associated with each branch (Fluixá-Sanmartín et al. 2019a).

The model used can be represented using the influence diagram presented in Figure 3-3. As suggested in Fluixá-Sanmartín et al. (2018), this risk modelling approach is used in this work to structure and organize the assessment of the potential impacts of climate change on the different components of risk.

Table 3-1. *List of climatic projections (CP) used in the study, indicating the driving GCM, ensemble member, institute and RCM for each of them, and which scenario is available.*

ID	Driving GCM	Ensemble	Institute	RCM	Historical	RCP2.6	RCP4.5	RCP8.5
CP1	CNRM-CERFACS-CNRM-CM5	r1i1p1	CLMcom	CCLM4-8-17	x		x	x
CP2	CNRM-CERFACS-CNRM-CM5	r1i1p1	SMHI	RCA4	x		x	x
CP3	ICHEC-EC-EARTH	r12i1p1	CLMcom	CCLM4-8-17	x	x	x	x
CP4	ICHEC-EC-EARTH	r12i1p1	KNMI	RACMO22E	x	x	x	x
CP5	ICHEC-EC-EARTH	r12i1p1	SMHI	RCA4	x	x	x	x
CP6	ICHEC-EC-EARTH	r1i1p1	KNMI	RACMO22E	x		x	x
CP7	ICHEC-EC-EARTH	r3i1p1	DMI	HIRHAM5	x	x	x	x
CP8	IPSL-IPSL-CM5A-LR	r1i1p1	GERICS	REMO2015	x	x		
CP9	IPSL-IPSL-CM5A-MR	r1i1p1	IPSL-INERIS	WRF331F	x		x	x
CP10	IPSL-IPSL-CM5A-MR	r1i1p1	SMHI	RCA4	x		x	x
CP11	MOHC-HadGEM2-ES	r1i1p1	CLMcom	CCLM4-8-17	x		x	x
CP12	MOHC-HadGEM2-ES	r1i1p1	DMI	HIRHAM5	x			x
CP13	MOHC-HadGEM2-ES	r1i1p1	KNMI	RACMO22E	x	x	x	x
CP14	MOHC-HadGEM2-ES	r1i1p1	SMHI	RCA4	x	x	x	x
CP15	MPI-M-MPI-ESM-LR	r1i1p1	CLMcom	CCLM4-8-17	x		x	x
CP16	MPI-M-MPI-ESM-LR	r1i1p1	MPI-CSC	REMO2009	x	x	x	x
CP17	MPI-M-MPI-ESM-LR	r1i1p1	SMHI	RCA4	x	x	x	x
CP18	MPI-M-MPI-ESM-LR	r2i1p1	MPI-CSC	REMO2009	x	x	x	x
CP19	NCC-NorESM1-M	r1i1p1	DMI	HIRHAM5	x		x	x
CP20	NCC-NorESM1-M	r1i1p1	SMHI	RCA4	x			x
CP21	NOAA-GFDL-GFDL-ESM2G	r1i1p1	GERICS	REMO2015	x	x		

In the first five nodes the model defines the probability of different dam-reservoir system scenarios prior to the arrival of the largest flood of the year. This encompasses the probability of falling in a specific period of the year (*Season*), whether its day or night time (*Day/Night*), the annual exceedance probability curve of the water pool level of the reservoir (*Previous pool level*) and the probability of the bottom outlet works and spillways gates functioning properly (or not) when a flood arrives (*Spillway Av.* and *Outlet Av.*). The next node (*Floods*) introduces the flood entering the reservoir; a probabilistic hydrologic analysis is necessary to obtain the annual exceedance probability of potential incoming floods. The following node (*Flood routing*) includes the maximum pool levels and peak outflows resulting from the flood routing for each possible combination of previous pool level, inflow flood and gate availability.

The node *Failure modes* contemplates the four possible ways in which the Santa Teresa dam is supposed to fail: due to the overtopping of the dam or of the dike, or due to the sliding of the dam or of the dike. For each branch the model relates the maximum water level reached in the reservoir in each flood event with the conditional failure probability. It is worth noting that the sliding failure mode is decomposed in two nodes: the probability of being in different uplift pressures hypothesis (*Dam/Dike uplift pressures*) and the existing capacity to detect and to avoid high uplift pressures (*No detection*).

Finally, the following nodes are used to compute consequences in order to estimate risk, following Equation (3.1). The nodes *Q fail* characterize the failure hydrograph for each failure mode by introducing a relation between the water pool level and the peak failure discharge. This relation was previously computed using hydraulic models of the dam breach.

Last nodes introduce the relation between the outflow hydrographs and the economic (*Econ. conseq. (failure)*) and loss of life consequences (*Social conseq. (failure)*). A common practice in dam safety is working with incremental consequences, obtained by subtracting the consequences for the non-failure case to the consequences for the failure case (Serrano-Lombillo et al. 2011; SPANCOLD 2012; USACE 2011a) in order to consider only the part of the incremental risk produced by the dam failure. Therefore, the consequences of the non-failure case (*Econ. conseq. (no failure)* and *Social conseq. (failure)*) must also be calculated to obtain incremental consequences.

3.4.4 Water resource management model

Risk modelling requires the analysis of the probability of occurrence of a certain water level in the reservoir at the moment of arrival of the flood. It defines the starting situation in the reservoir when studying the loads induced by the flood (SPANCOLD 2012). Such analysis can be usually done by using the register of historic pool levels. However, the effects of climate change are expected to affect the future water availability mainly due to increased precipitation variability and potential evapotranspiration (IPCC 2014). Therefore, the simulation of the system of water resources management under future conditions is necessary to obtain the relation between water pool level and probability of exceedance.

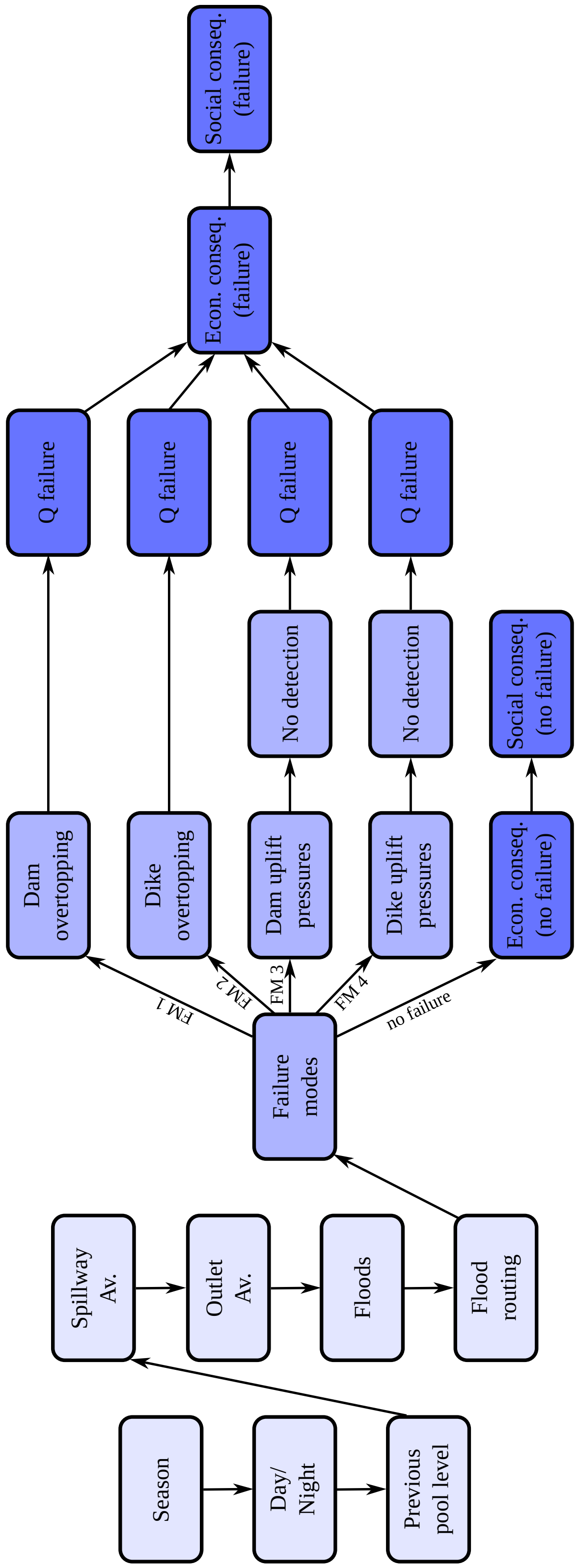

Figure 3-3. *Diagram of the quantitative risk model for the Santa Teresa dam.*

The simulation consists of a sequential calculation of the allocation and use of the water resources based on the reservoir's exploitation rules. Apart from the evaluation of the future inflows of the system, this analysis requires as inputs the basin management strategy and the water demand that depends on the reservoir's supply. Such information is contained in the Hydrological Plan of the Duero River Basin (Confederación Hidrográfica del Duero 2015) that describes the exploitation rules of the 13 systems of the basin.

In particular, the Tormes system is composed of the Santa Teresa and the Almendra reservoirs of 496 hm^3 and 2,649 hm^3 of volume capacity, respectively. The above-mentioned Hydrological Plan describes the water demands according to their category: agricultural (7), fish farming (5), urban (1) and industrial demands (1). The different demands of the Tormes system are mainly satisfied using the Santa Teresa reservoir according to the assignation rules established. It also specifies the minimum ecological discharges at different points of the river that must be guaranteed through reservoir's releases. Figure 3-4 shows a schematic diagram with the distribution to each water demand and its return to the system according to the Hydrological Plan.

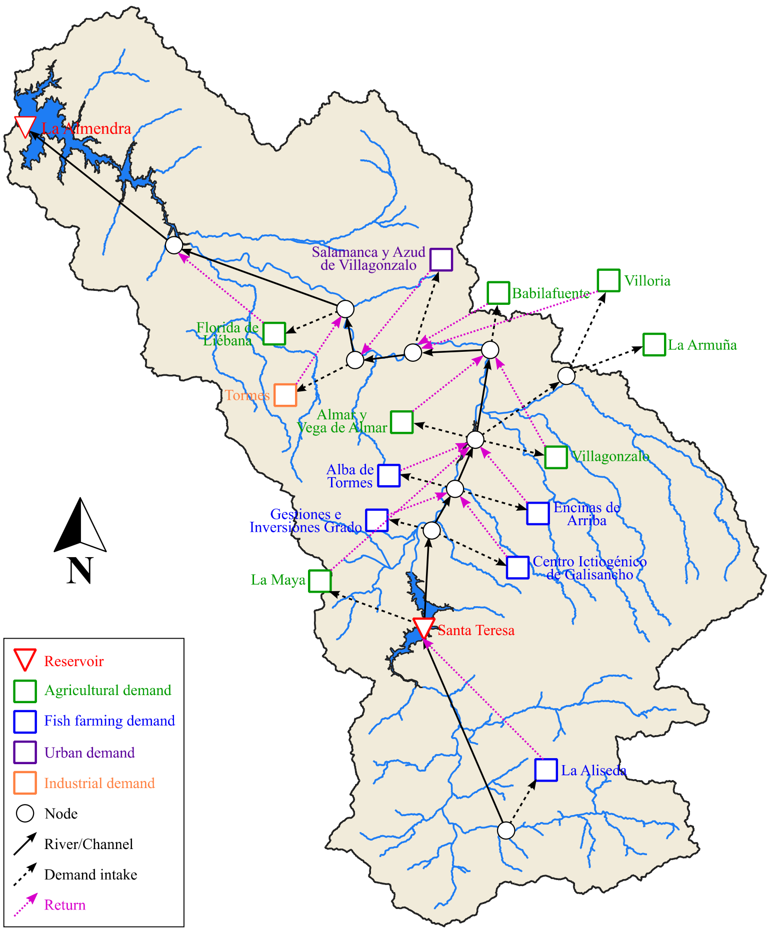

Figure 3-4. *Scheme of the main elements of the Tormes water resource system.*

Another aspect considered is the limitation of water storage in the Santa Teresa reservoir. Given the seasonality of high flows entering the reservoir, the Hydrological Plan considers freeboard volumes that vary throughout the year to adapt to the expected incoming floods. The minimum and maximum volumes and their corresponding water levels to be ensured each month in normal exploitation conditions are detailed in Table 3-2. These limitations are important for estimating water pool levels (Section 3.5.3.1). For this study, five periods of the year have been established from these specifications, coded as follows: *Dec-Feb* (December, January and February), *Mar* (March), *Apr* (April), *May-Nov* (May, June, October and November), and *Summer* (July, August and September).

Table 3-2. *Seasonal minimum and maximum volumes (hm^3) and water levels (m a.s.l.) for the Santa Teresa reservoir.*

Month	Minimum volume (hm^3)	Maximum volume (hm^3)	Minimum level (m a.s.l.)	Maximum level (m a.s.l.)
January	80	396	861.26	881.31
February	80	396	861.26	881.31
March	80	436	861.26	883.13
April	80	461	861.26	884.20
May	80	496	861.26	885.70
June	80	496	861.26	885.70
July	80	496	861.26	885.70
August	80	496	861.26	885.70
September	80	496	861.26	885.70
October	80	496	861.26	885.70
November	80	496	861.26	885.70
December	80	396	861.26	881.31

3.5 Application of the methodology to the Santa Teresa dam

3.5.1 Correction of the RCM projections

Each precipitation and temperature projection described in Section 3.4.2 has been bias-corrected using a statistical transformation. In particular, an empirical non-parametric quantile mapping (eQM) approach (Boé et al. 2007; Panofsky and Brier 1968) has been applied in this study using the R Software (R Development Core Team 2008). This method has been widely applied in climatology and more detailed information can be found in the extensive literature (Cannon et al. 2015; Gudmundsson et al. 2012; Gutjahr and Heinemann 2013; Maraun 2016).

The goal is to define the transformation function for a modelled variable x_{mod} so that its new distribution equals the distribution of the observed variable x_{obs} corresponding to the reference period, as defined in Equation (3.2):

$$x_{obs} = F_{obs}^{-1}\left(F_{mod}(x_{mod})\right) \tag{3.2}$$

where F_{mod} is the empirical cumulative distribution functions (ECDFs) of x_{mod} and F_{obs}^{-1} is the inverse ECDF (also named quantile function) corresponding to x_{obs}. In this case, the RCM-derived daily outputs represent the modelled variables while the daily data issued from the Spain02 v5 correspond to the observed variable.

Once this transformation function has been defined, it is afterwards used to translate a simulated projection time series into a bias-corrected series. This procedure is applied separately for each climate projection (CP) described in Section 3.4.2 (Table 3-1) and for each of the three future *Periods* (1, 2 and 3), using the *Historical* period 1970-2005 as the calibration period of the correction function.

Corrected values in between fitted transformed values has been approximated using a linear interpolation. When model values from climate projections are larger than the training values used to estimate the ECDF, the correction found for the highest quantile of the training period is used (Boé et al. 2007; Jakob Themeßl et al. 2011).

In order to account for seasonally varying bias characteristics of the precipitation and temperature variables, the correction function itself has been determined separately for each season. Moreover, when correcting the precipitation projections, the number of wet days in the RCM time series of the *Historical* period has also been adjusted to fit the number of wet days in the observed time series of the same period.

Figure 3-5(a) shows an example of the empirical cumulative distribution functions (ECDF) corresponding to the Observed and the modelled CP3 Historical time series of daily temperature, for the grid cell with coordinates 40°05'60.0"N 5°48'00.0"W. The required shift towards the right (increase) of the CP3 series for an ECDF of 0.4 to match the observations has been highlighted with arrows. Figure 3-5(b) displays the bias-corrected temperatures (green line) from the original CP3 modelled time series (red line), compared to the observed series (blue line), for the year 1979.

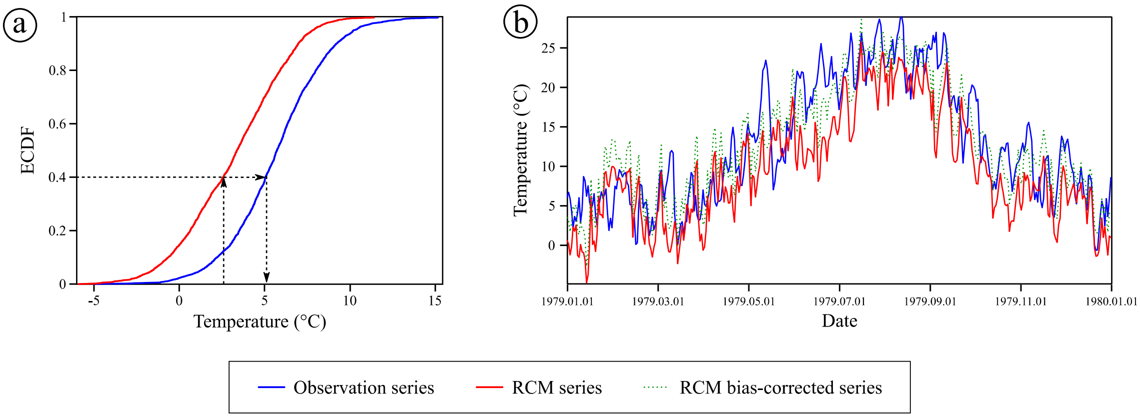

Figure 3-5. *(a) Example of ECDF of the observed (blue) and the modelled CP3 (red) daily temperature series and bias correction using the eQM technique: the ECDF of the simulated series (red) is shifted to match with the observed ECDF (blue). (b) Time series of daily temperatures for the observed (blue) and the CP3 modelled (red) datasets and bias-corrected series (green, doted line) for the year 1979.*

3.5.2 Hydrological modelling

3.5.2.1 <u>Setting and calibration of the model</u>

A hydrological model of the Santa Teresa and the Tormes catchments has been elaborated with the hydrological-hydraulic modelling software RS MINERVE (Foehn et al. 2019; García Hernández et al. 2019), a freeware models complex hydrological and hydraulic networks based on a semi-distributed concept and downstream propagation of discharges. In addition to particular hydrological processes such as snowmelt, glacier melt, surface and underground flow, RS MINERVE also includes hydraulic control elements (e.g. reservoir, gates, spillways, water consumptions, etc.).

First, the basin has been divided in sub-basins according to the hydrographic network and to the location of the gauging stations, as shown in Figure 3-2. For this study, the GSM-SOCONT model (Schaefli et al. 2005) has been applied to each resulting sub-basin. Simulated natural processes use precipitation and temperature inputs to model surface and subsurface flow, infiltration, evapotranspiration, snow accumulation and melting. Channel routing of the rivers has been solved with the kinematic wave model, also available in RS MINERVE.

Finally, the model's calibration has been performed using the calibration module of the RS MINERVE software based on the observed records of the gauging stations described in Section 3.4.1. Calibrated parameters are: the reference degree-day snowmelt coefficient (S); the maximum height of the infiltration reservoir (HGR3Max); the release coefficient of the infiltration reservoir (KGR3); and the runoff slope (J0) and Strickler coefficient (Kr) for the runoff surface as well as for the river reaches. The performance indicators used to assess the quality of the fit are Nash-Sutcliffe (Nash and Sutcliffe 1970) and the Kling-Gupta efficiency (Gupta et al. 2009; Kling et al. 2012).

Periods with available discharge data are heterogeneous and thus calibration/validation processes have been adapted accordingly. It has been decided to use the period 01.10.2010-30.09.2015 as the calibration period, while the validation period depends on each gauging station. Results of the calibration/validation process for the gauging stations upstream of the Santa Teresa dam (Hoyos del Espino, Barco de Ávila and Puente Congosto) are presented in Table 3-3. Figure 3-6 shows the observed and modelled flows for these stations. For visualization purposes, only the period 01.10.2010-30.09.2015 is displayed. It is considered that the calibration presents adequate results for the purpose of the study.

Table 3-3. *Calibration and validation results for the gauging stations upstream of the Santa Teresa dam.*

Station	Calibration			Validation		
	Period	Nash	Kling-Gupta	Period	Nash	Kling-Gupta
Hoyos del Espino	1 Oct 2010–30 Sep 2015	0.612	0.749	1 Oct 1983–1 Oct 1995	0.570	0.726
Barco de Ávila	1 Oct 2010–30 Sep 2015	0.679	0.766	1 Oct 1971–30 Sep 1987	0.667	0.589
Puente Congosto	1 Oct 2010–30 Sep 2015	0.939	0.768	1 Oct 1997–30 Sep 2010	0.670	0.709

3.5.2.1 Water management model simulation

The first purpose of the hydrological model of the Santa Teresa and Tormes catchments is the simulation of the water resources and its evolution with time. The basic inputs required are: (i) the reservoir's exploitation rules; (ii) the water demands; and (iii) the expected discharges at different points of the basin.

The first two inputs are extracted from the Hydrological Plan of the Duero River Basin (Confederación Hidrográfica del Duero 2015) described in Section 3.4.4. For this study, the only demand that is considered variable with time is the urban demand, which corresponds to the supply to the city of Salamanca. This is a direct consequence of the population variation expected at this city which is further described in Section 3.5.3.4. For that, the individual consumption has been maintained and only the number of consumers has been adapted. In the absence of more detailed information, the rest of the demands (agricultural, industrial and fish farming) and the prioritization of the water supply for each demand (the importance and order in which each demand is satisfied) are assumed unaltered in future scenarios.

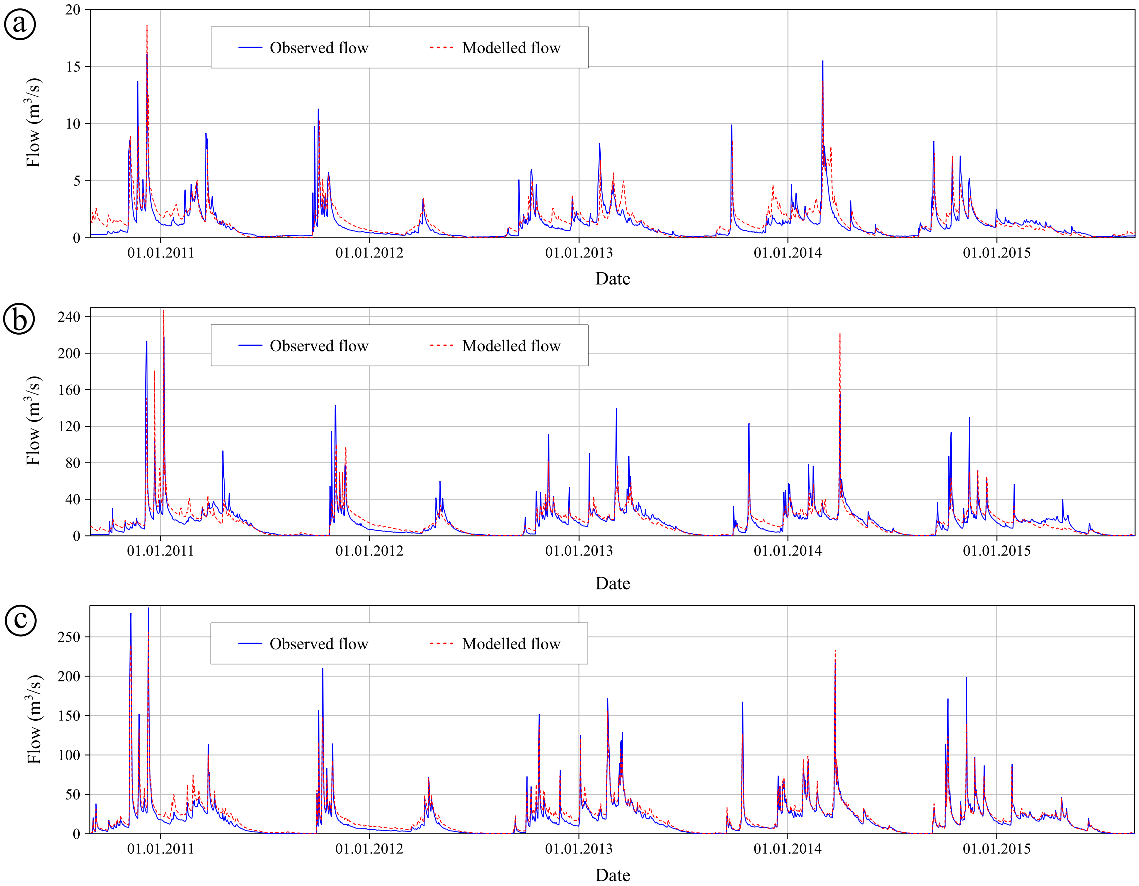

Figure 3-6. *Comparison between observed (blue) and modelled (red) flows for the gauging stations (a) Hoyos del Espino, (b) Barco de Ávila and (c) Puente Congosto.*

Concerning basin discharges, the hydrological model elaborated with RS MINERVE is able to simulate the rainfall-runoff processes at a daily resolution. Thus, the meteorological data issued from the Spain02 grid observations as well as from the climate projections are used as inputs to the model in order to obtain the consequent discharges at each sub-basin (Figure 3-2).

The simulation of the reservoir's response has been modelled including to the hydrological model different hydraulic elements available in RS MINERVE. On one hand, the water consumption has been modelled with *Consumer* objects which allow defining the flow abstraction series of each water demand (including the minimum ecological discharges) at each timestep. The order of preference defined in the Hydrological Plan guidelines for the supply to each demand has been respected. On the other hand, the outflows from the reservoir are managed using

Planner objects: these models permit to create different rules that rest on the hydrological and hydraulic conditions of the basin. That is, the supply to a specific point depends on the demand at this point, the water level at the reservoir or the satisfaction of preferential demands. At this point, it is worth mentioning that the seasonal minimum and maximum levels contemplated by the Hydrological Plan (Table 3-2) have been incorporated to the model within these *Planner* objects. More detailed descriptions on the use of such models can be found in García Hernández et al. (2019).

The validation of this water resources model is conducted by comparing its results with a reference record. Figure 3-7 displays the observed water levels recorded at the Santa Teresa reservoir and the simulated series obtained with the RS MINERVE model, for the period 1990-2015. As shown in the figure, results performance is moderate at the beginning of the period (1990-2000) and then increases notably from 2000 to 2015. This is mainly due to the fact that the reservoir's exploitation rules used in the model are based on the last Hydrological Plan of the basin (Confederación Hidrográfica del Duero 2015), which is relatively recent. It is likely that before 2000 the operational rules were different and thus the model is not capable of capturing the real fluctuations of the water resources. For the purposes of the study, it is considered that the overall performance of the hydrological model is adequate to simulate the water resources at the Santa Teresa reservoir. Once the model is validated, the different simulations have been processed for the *Historical* and the future periods.

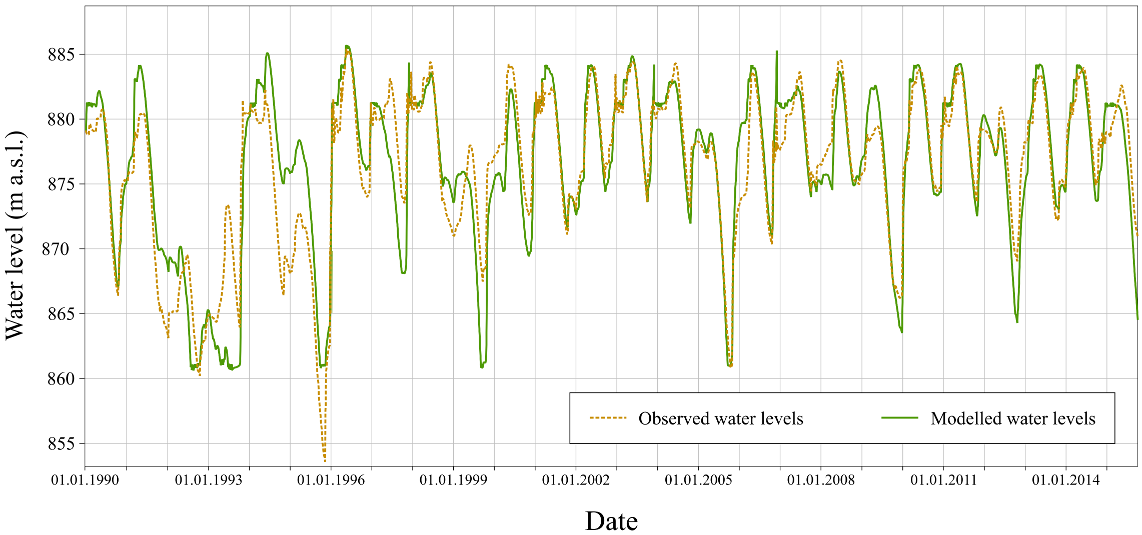

Figure 3-7. *Observed and simulated water levels at the Santa Teresa reservoir, between 1990 and 2015.*

3.5.2.2 Design flood hydrographs

Additionally, the hydrological model has been employed for the definition of the design flood hydrographs entering the Santa Teresa reservoir. A deterministic approach based on the design storm method (ASCE 1996; Reed et al. 1999) has been followed. In this method, a design storm is defined based on the intensity duration frequency (IDF) curve of rainfall and applied to an event-based hydrological model to calculate the hydrographs. Statistical methods have been discarded mainly due to a lack of representative flood records, in particular for the characterization of future floods.

The process consists of three main parts: the generation of synthetic storms, the definition of the initial conditions of the basin, and the simulation of the flood hydrographs. What follows is a detailed description of these steps. It is worth mentioning that the process has been individually applied to the different periods considered (*Historical*, *1*, *2* and *3*) in order to assess the changes in the resulting floods from the Base Case until the end of the 21st century.

Generation of design storm hyetographs

The definition of the design storm hyetograph first requires the statistical analysis of the annual maxima of storm rainfall, extracted from the daily precipitation data of the observation and climate projection series for each point of the Spain02 grid. This allows obtaining the maximum daily precipitation for any return period considered. Each annual maxima series has been fitted to a Gumbel distribution, a widely used option in the Spanish territory. Once the distribution fitted, the daily precipitations corresponding to the following return periods have been calculated: 2, 5, 10, 25, 50, 100, 200, 500, 1 000, 2 000, 5 000, 10 000, 20 000, 50 000 and 100 000 years. In order to evaluate the sensitivity of risk results to the fitted Gumbel distribution, a complementary sensitivity analysis is included in Appendix A.

Then, a predefined IDF curve has been used to estimate the rainfall depth for any given duration and for the selected return periods. The formulation of the IDF curve is taken from the document of Ministerio de Fomento (2016) and is expressed as:

$$\frac{I_t}{I_d} = \left(\frac{I_1}{I_d}\right)^{\frac{28^{0.1}-t^{0.1}}{28^{0.1}-1}} \tag{3.3}$$

where I_t is the average intensity (in mm/h) corresponding to the time interval of duration t; I_d is the daily average intensity (in mm/h) corresponding to the return period considered, and equal to $P_d/24$; P_d is the total daily precipitation (in mm) corresponding to the return period considered; I_1/I_d is the ratio between the hourly and daily intensity, obtained from Ministerio de Fomento (2016) and equal to 10.2 for the study case.

It is worth mentioning that this formula is climate- and location-dependent since it has been extracted from an analysis based on historical records. However, in this study the formula has also been applied for future climatic conditions. The difficulty to establish IDF relations with no sub-daily precipitation data available is one of the limitations of the present work. Thus, in order to deal with this issue, the option chosen was to rely on pre-defined formulations such as the one presented in Equation (3.3).

Temporal rainfall distribution is obtained using the alternating block method (Chow et al. 2008), where the intensity of each time interval is read from the previous IDF curve. Subsequently, the rainfall depths for each interval (P1, P2, …) are obtained taking the difference between successive rainfall depth values, with $\Delta t = 0.5$ h. The blocks P1, P2, … are reordered with the maximum intensity at the center of the hyetograph and the other blocks alternating to the right and left. In the absence of more detailed, it has been considered that the duration of the storm events is 24 hours.

Given that rainfall is never evenly distributed over the area of study due to the topographic variability of the catchment areas, the use of an Areal Reduction Factor (ARF) is required to correct each grid point rainfall and avoid an overestimation of the rainfall input. The ARF adopted follows the empirical formulation proposed in (Témez 1991) for the Spanish territory:

$$ARF = 1 - \frac{logA}{15} \tag{3.4}$$

where A is the area of the catchment (in km^2). In this case, the drainage area of the Santa Teresa reservoir is 1,853 km^2.

Initial basin conditions

Francés et al. (2012) and Rogger et al. (2012) highlighted an important drawback when applying the design storm method. It is generally assumed that the rainfall and the discharge return periods are equal, and no other factors such as the initial conditions of the basin are generally considered. Indeed, the proper selection of basin antecedent conditions is of paramount importance for the runoff definition.

To address such limitation, an analysis of three different state variables of the hydrological model was performed: the level in the infiltration reservoir (HGR3), the runoff water level downstream of the surface (Hr) and the river discharge (Q). The goal was to define a characteristic initial state of the basin prior to the occurrence of each storm.

Once the hydrological model set, it was used to run the rainfall-runoff simulations corresponding to the different scenarios (observations and projections) and for all the periods considered (*Historical*, *Period 1*, *Period 2* and *Period 3*). For each simulation, the dates on which the annual maximum rainfalls occurred were identified, making it possible to extract the state variables of the model corresponding to the precedent day. This resulted in a set of state variables per year for each simulation. From each of these series of state variables, an ECDF curve was generated. In this way, the initial conditions matching with the storm hyetograph of return period T can be obtained reading from the ECDF curve the value for a non-exceedance probability equal to 1-1/T. Figure 3-8 illustrates the extraction of the soil saturation (calculated as *HGR3/HGR3Max*100* for the SOCONT model) corresponding to a non-exceedance probability of 0.9 or a return period of 10 years.

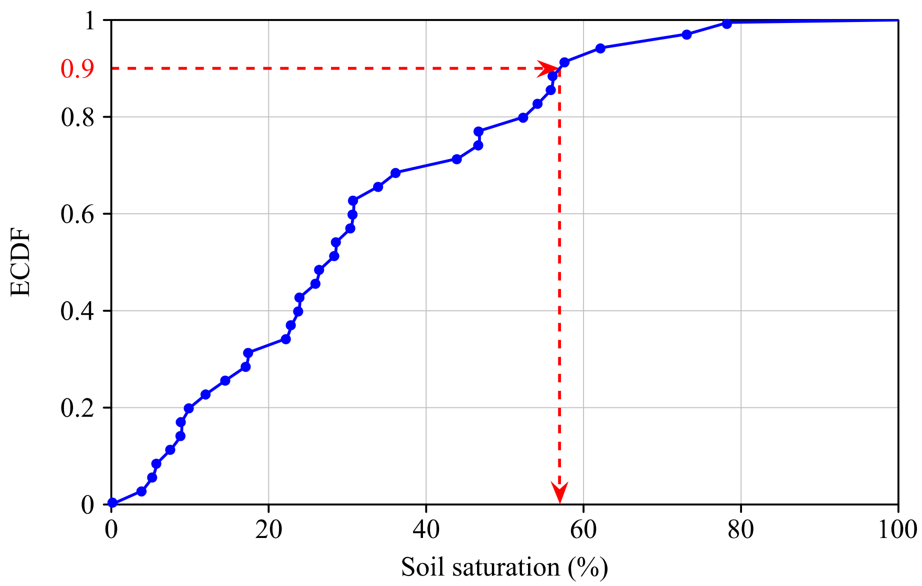

Figure 3-8. *Example of ECDF curve for the soil saturation (relative HGR3 state variable) and extraction of the value corresponding to a non-exceedance probability of 0.9.*

Hydrograph calculation

The model developed with RS MINERVE and described above was used as the event-based hydrological model to simulate the behavior of the Santa Teresa basin. In this case, the simulation timestep was set at 10 minutes in order to better capture the hydrological processes occurring in the basin. Once each storm hyetograph and set of initial conditions corresponding to a return period between 2 and 100,000 years has been defined, the model was run, and the flood hydrographs are obtained.

Resulting floods for the Base Case are presented in Figure 3-9 (a). Peak discharge by return period is displayed in Figure 3-9 (b).

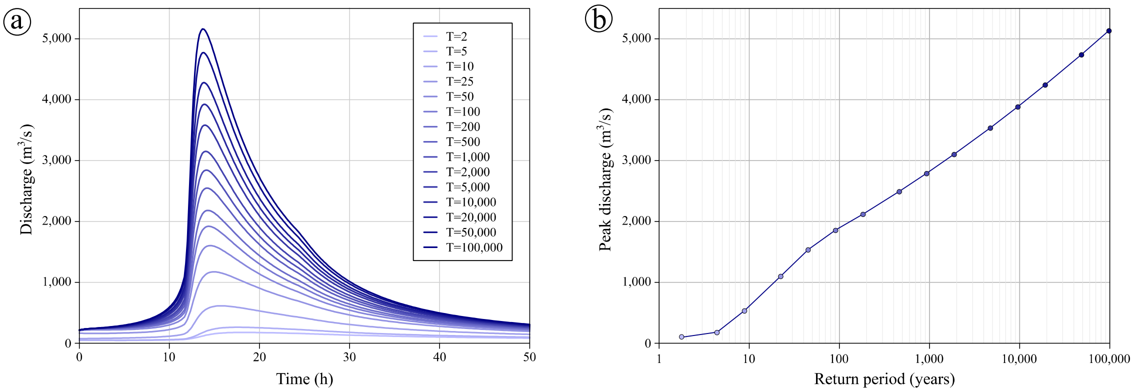

Figure 3-9. *(a) Resulting flood hydrographs for return periods between 2 and 100,000 years, for the base case. (b) Flood frequency characterization of the maximum values of peak discharges.*

3.5.3 Risk modelling

Considering the exposure of the dam to climate change, the risk model of the Santa Teresa dam (Figure 3-3) is updated following the effects of climate change on each of the risk components. Among these components, mainly four have been identified as susceptible to be altered: previous pool levels in the reservoir, spillway gate and bottom outlet performance, floods entering the reservoir and social consequences used to compute the social risk. In the absence of more detailed analyses, in this study other risk model components are assumed unaltered.

3.5.3.1 Previous pool level

Based on the reservoir levels obtained from the water resources simulation of each scenario defined in Section 3.5.2.1, the empiric exceedance probability curve of the pool levels is obtained by ordering all the data in an increasing order (SPANCOLD 2012) and applying Equation (3.5):

$$PE_n = 1 - \frac{i_n - 1}{N - 1} \tag{3.5}$$

where PE_n is the probability of exceedance for a pool level n, i_n is the number of order of pool level n within the series of sorted levels and N is the length of the series.

The resulting curve is discretized in different not equidistant intervals to be included within the risk model event tree. In the event tree, the probability of each branch is the probability of falling within any of the values of the interval considering a representative value of each interval - usually the average value of the interval -. Since the risk model used in this study considers the specific period of the year in which the flood occurs, the reservoir's exploitation rules differ depending on this period (Section 3.4.4) and thus imply different exceedance probability curves of the pool levels. The analysis of the previous pool level must therefore be done for each of the periods considered. Figure 3-10 shows the comparison of the exceedance probability curves corresponding to the Base Case and to the climate scenario CP1 (RCP45 and *Period 1*), both computed for the *Summer* season. As can be appreciate, the results of the CP1 projection present lower water levels than for the Base Case. This is mainly due to the reduction in the discharge contributions to the reservoir and the enhanced evapotranspiration directly related to the increase of temperatures.

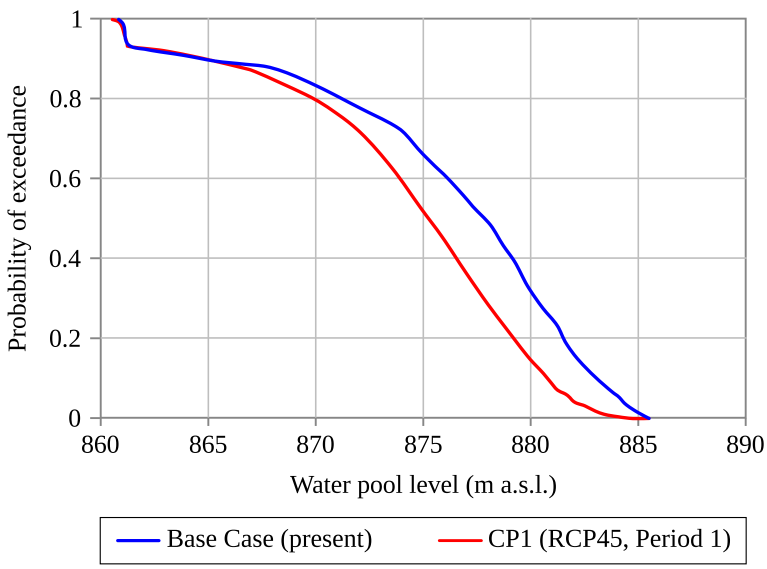

Figure 3-10*. Relation between water pool level and probability of exceedance for the base case (present situation) and the climate projection CP1 (RCP45 and period 1), for the summer season.*

3.5.3.2 Gate performance

In the context of dam safety, spillways and outlet works play a fundamental role. The estimation of their reliability, i.e., that in the moment of the arrival of the flood they can be used, makes part of the studies required to feed a risk model. In a basic analysis, individual reliability can be estimated directly for each gate using the qualitative description of the gate system's condition. (Escuder-Bueno and

González-Pérez 2014) propose a classification based on these descriptors that avoids resorting to detailed studies such as fault trees:

- *95%*. The outlet is new or has been very well maintained.
- *85%*. The outlet is well maintained but has had some minor problems.
- *75%*. The outlet has some problems.
- *50%*. The outlet is unreliable for flood routing.
- *0%*. The outlet is not reliable at all or it has never been used.

In this analysis, gates can be considered independent and thus the probability of each availability gate case can be estimated with a binomial distribution (Equation (3.6)):

$$P(x) = \frac{n!}{x! \cdot (n-x)!} \cdot p^x \cdot (1-p)^{n-x} \tag{3.6}$$

where *P(x)* is the probability that *x* number of gates work properly, *n* is the total number of gates and *p* is the individual reliability of gates.

As part of the quantitative risk analysis performed on the Santa Teresa dam, the state of the spillway gates and the bottom outlet was estimated as well maintained. Their individual reliabilities were thus established as 85% for the present situation. However, the conditions of the gates can deteriorate with time and with changing hydro-meteorological conditions. As mentioned in (Fluixá-Sanmartín et al. 2018), certain factors as increased soil erosion due to more intense rainfalls or greater fluctuations in temperature could eventually lead to a decreased reliability of the gates. In this study, the state of both the spillway and the bottom outlet gates is assumed to progressively deteriorate until the end of the 21st century. Following a simple approach, it is considered that some problems may appear and thus the individual reliability will vary from 85% to 75%, corresponding to the *Period 3* (2070-2099). For the intermediate scenarios a linear interpolation is applied to obtain the individual reliability, that is 81.5% for the *Period 1* (2010-2039) and 78.5% for the *Period 2* (2040-2069).

3.5.3.3 Floods

Since the present study analyses the risk of the dam under a hydrological scenario, it is supposed that the floods are the main loads to which the dam is subjected. Therefore, the resulting flood hydrographs obtained in Section 3.5.2.2 have been incorporated to update the risk model of the dam. As described above, each hydrograph is characterized by its return period or annual exceedance probability which defines the probability associated to each branch of the risk model emerging from the *Floods* node (Figure 3-3). This also has an impact on the outcomes of the dam's flood routing, in particular the maximum pool levels and the peak outflows.

It has been considered however that the flood routing strategy remains unchanged as defined in the Operation Rules document of the dam.

3.5.3.4 Social consequences

The dam risk model used in this study considers the social consequences resulting from the dam failure (Figure 3-3) which rely on the exposure of people in the at-risk area to the dam output hydrograph. These consequences correspond to the number of fatalities among the inhabitants of the different population nucleus between the Santa Teresa and the Almendra dams.

Under future scenarios, the evolution of population at risk is thus expected to affect the potential casualties and needs to be considered to adequately assess the social risk. This does not account for a direct effect of climate change; however, this non-climatic factor has been considered in this study in order to contemplate a more realistic situation in future scenarios.

For this analysis, the long-term population projections at national scale available in the online publication Our World in Data (2018) extracted from the UN database (United Nations 2017) were used. According to these projections, population is expected to slightly decrease until 2040 and will follow a substantial diminution until the end of the century. It has been supposed that the same pattern at the national level can be replicated at the regional and local levels. Therefore, in order to adapt the dam risk model used, the population at risk at the different cities and settlements has been proportionally reduced under the three future scenarios envisaged. Hence, the relative variation compared to the population in 2010 is as follows: -2.52% for the *Period 1* (2010-2039); -14.37% for the *Period 2* (2040-2069); and -22.25% for the *Period 3* (2070-2099).

It is worth mentioning that, for the assessment of the economic consequences, the same current assets and services at risk remain so in the future and no new services are considered. Moreover, their economic cost has not been updated in order to work only with present values independently of the future scenario considered.

3.6 Results and discussion

Once the dam risk model is adapted following the effects of climate change on each of the risk components, the social and economic risks [consequences/year] are calculated for the Base Case and for all the CP-period-RCP combinations. For the Base Case (present situation), the failure probability is 2.91×10^{-6}/year, while the social and economic risks are 2.56×10^{-4} lives/year and 7.53×10^{-4} M€/year respectively.

The evolution of social and economic risks for each RCP, from the present situation until the end of the 21st century, is presented in Figure 3-11. For illustrative purposes, the y-axis is plotted on a logarithmic scale to better appreciate the order of magnitude of its values. The dashed black line indicates the present risk and helps to highlight whether the future risk of a particular CP is above or under such reference risk level. In general, these results indicate that in most future scenarios a deterioration of both the social and economic risks occurs. Indeed, the risk tends to increase in comparison to the present risk level and a certain dispersion of the risk appears with time. However, the RCP8.5 cases present a wider dispersion of results and no homogeneous effects can be extracted from it.

In order to deepen in the analysis, the resulting risks have been decomposed in its associated probability of failure and average consequences. Figure 3-12 represents this disaggregation of social and economic risks for each period considered. In such graph, risk is the dimension that combines both axes and is smaller in the lower left corner and grows towards the upper right corner. This is a widely used type of representation, used for instance by the US Bureau of Reclamation (USBR 2011) to propose tolerability recommendations for incremental risk. Logarithmic scales are used in both axes and the same legend as in Figure 3-11 is applied for the points. The present risk level has been represented as a black point and its probability of failure and consequences are highlighted with two dashed black lines. These lines divide the graph in four quarters labelled as:

- Type I: cases where the failure probability is greater, and the consequences are lower than in the Base Case.
- Type II: cases where both the failure probability and the consequences are greater than in the Base Case.
- Type III: cases where both the failure probability and the consequences are lower than in the Base Case.
- Type IV: cases where the failure probability is lower, and the consequences are greater than in the Base Case.

Moreover, Table 3-4 and Table 3-5 present the percent of cases falling in each of these situations, grouped by period and RCP. These results exhibit a tendency of the cases analyzed to be in the Type I, and a lower proportion in the Type III situation, for all the periods analyzed. Therefore, most cases indicate a reduction in the average consequences (not only due to the diminished exposure of people in the at-risk area) as well as an increase of the probability of failure of the dam.

Since in this study the different components of the risk model have been adapted and analyzed concurrently (Section 3.5.3), risk results do not highlight the individual contribution of each component to the final risk state. However, the use of risk models allows decomposing the contribution of each node in the final risk. For this purpose, a sensitivity analysis has been performed on the different risk components (*Previous pool level*, *Gate performance*, *Floods* and *Social consequences*) and their effect on the final dam failure risk, comparing to the overall effects combined. Results are presented in Figure 3-13. According to these results, the *Floods* component has the larger influence on increasing the final risk. Furthermore, for its part the *Previous pool level* component tends in general to lower the risk in all cases. And as expected, deterioration in gate performance makes both risks to increase, mainly due to an increase in the failure probability. Therefore, the effects of climate change on the dam failure risk are mainly explained by the changes in the flood loads and the changes in the reservoir water levels regime. This explains the differences between each RCP scenario. Indeed, as the emission scenario worsens (from RCP2.6 to RCP8.5) the discharge contributions and especially the higher evapotranspiration related to the increase of temperatures are expected to reduce the water levels in the reservoir. This will ultimately cause a more marked worsening of the risk for the RCP2.6 scenario than for the RCP8.5 scenario.

Although a general increase of the risk can be extracted from the results, it is difficult to directly define unequivocal recommendations for dam owners and managers. Different factors play important roles when assessing risk management action plans: Are risk acceptable in present situation? Are they acceptable in future scenarios? What are the risk reduction measures envisaged? How long should we wait before implementing them? What is the efficiency of each of these measures? What criteria should we follow to prioritize them? In order to exploit these results in the context of decision-making support, further efforts to address the non-stationarity nature of risk as well as its intrinsic uncertainties are needed. Such issues impose a deeper evaluation of the recommendations to make for the development of long-term adaptation strategies. This line of research is in progress and still has the potential for improving comprehensive decision-making support based on future changes in dam risk.

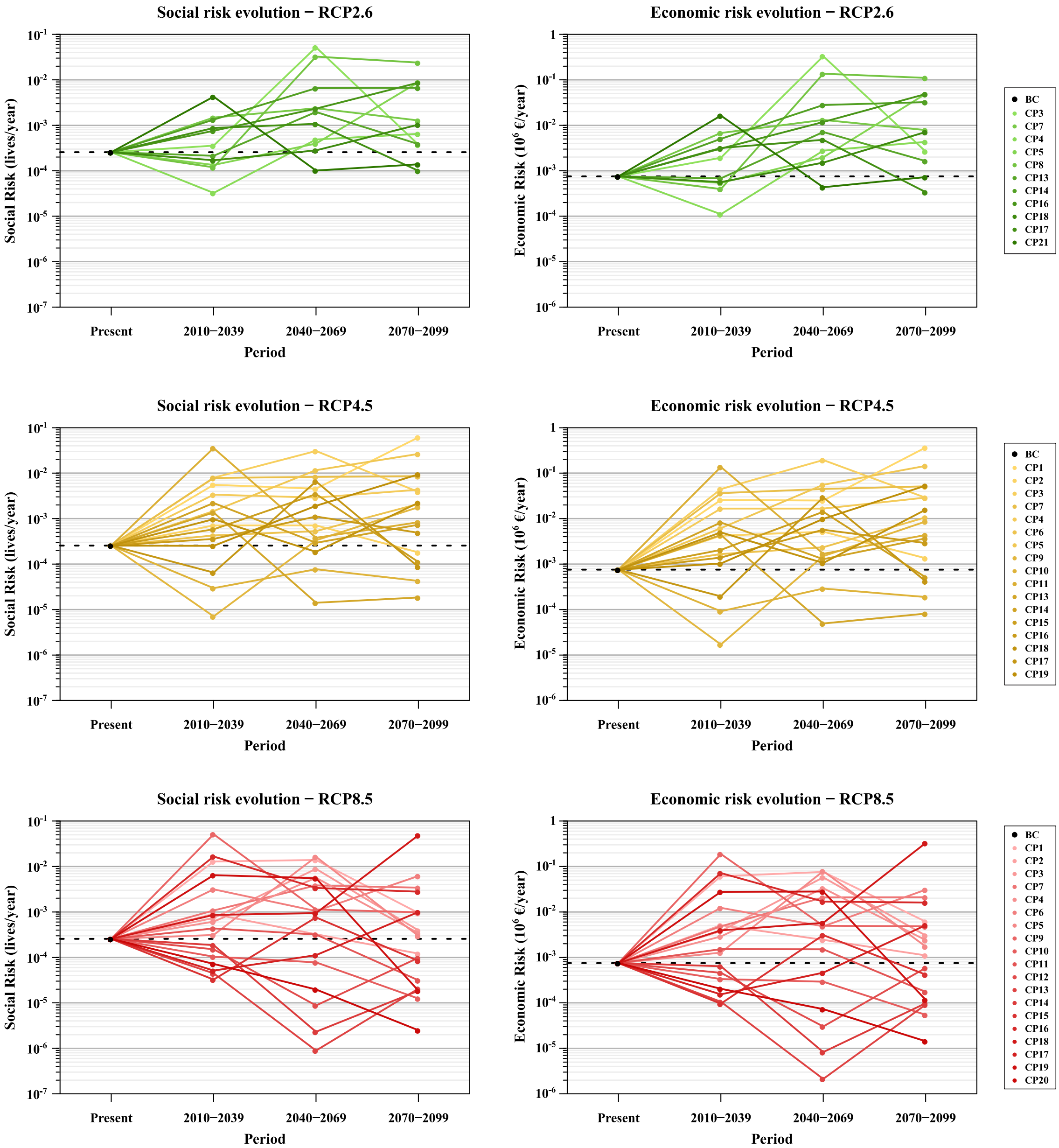

Figure 3-11. Social and economic risk results, classified by RCP. The base case (BC) situation is highlighted with a black point and a dashed line.

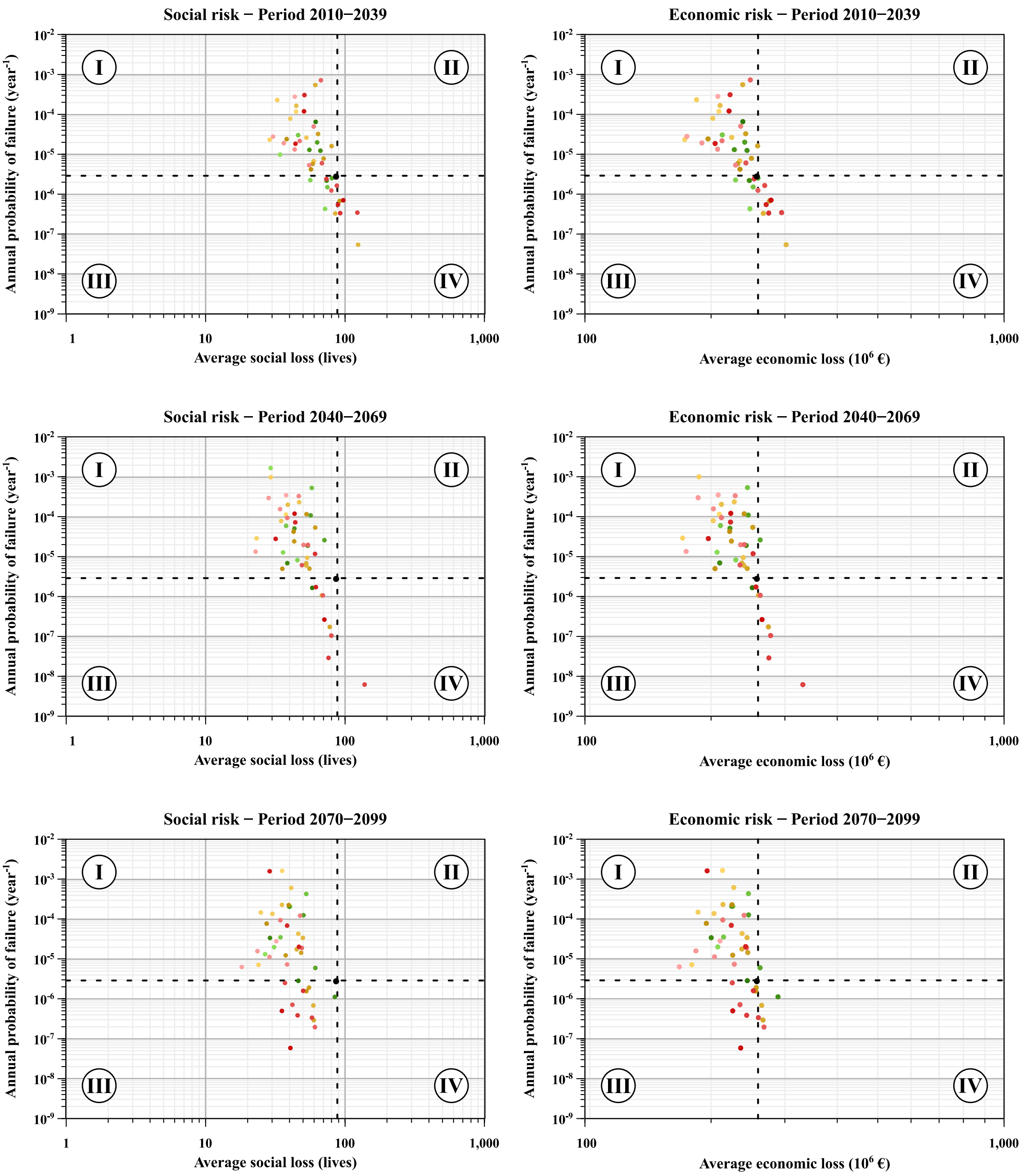

Figure 3-12. *Disaggregation of social and economic risks in annual probability of failure and average consequences, classified by simulation period. The same legend as in Figure 3-11 is applied here for the points. The base case situation is highlighted with a black point and two dashed lines.*

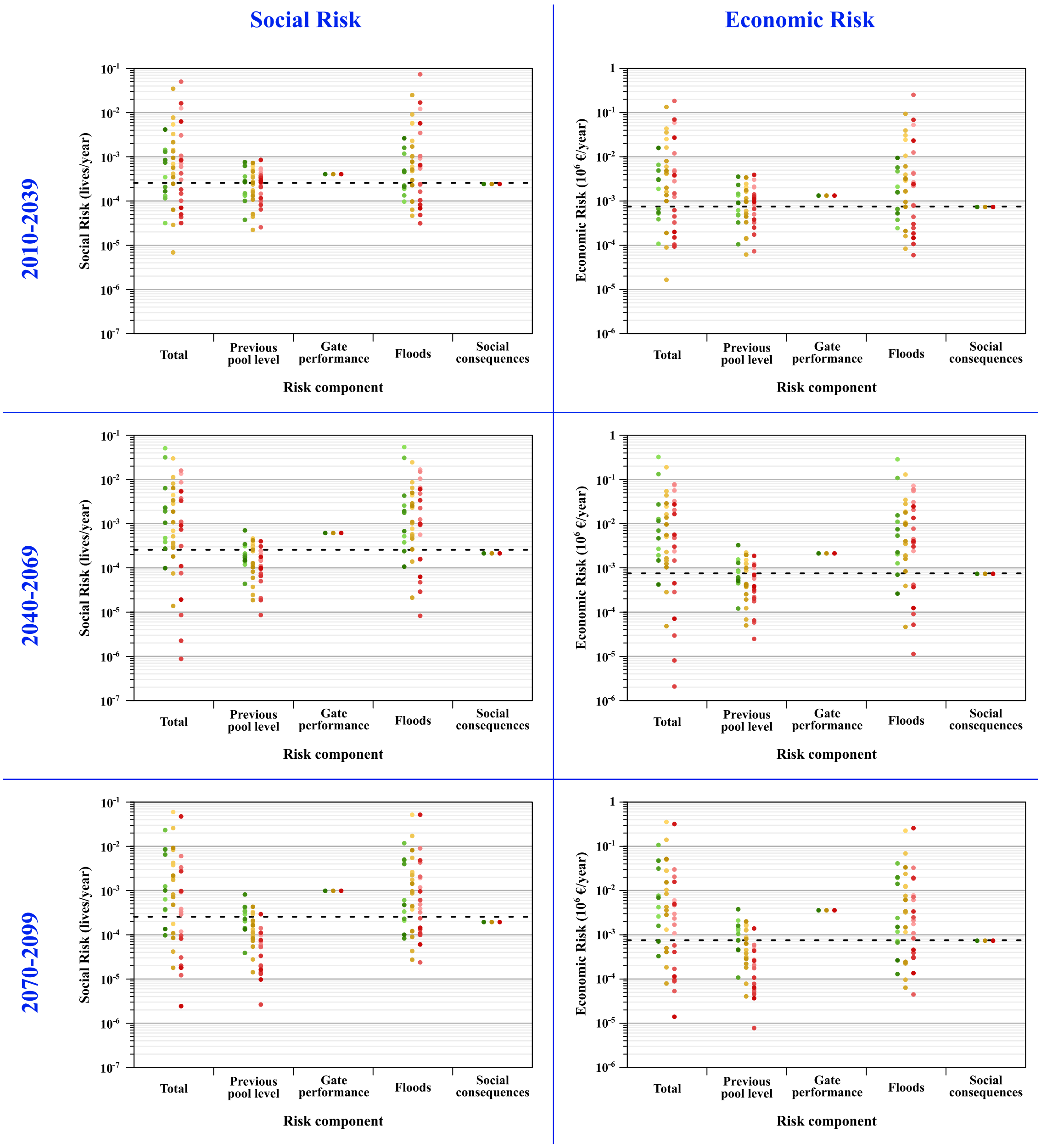

__Figure 3-13.__ Individual effects of each risk model component on the total social and economic risk computed, classified by period. The same legend as in Figure 3-11 is applied here for the points. The base case situation is highlighted with a black dashed line.

Table 3-4. *Percent of social risk cases falling in each type (I, II, III or IV) grouped by period and RCP.*

Period	RCP	Type I	Type II	Type III	Type IV
2010-2039	RCP2.6	55 %	0 %	45 %	0 %
	RCP4.5	82 %	0 %	6 %	12 %
	RCP8.5	63 %	0 %	11 %	26 %
2040-2069	RCP2.6	91 %	0 %	9 %	0 %
	RCP4.5	88 %	0 %	12 %	0 %
	RCP8.5	68 %	0 %	26 %	5 %
2070-2099	RCP2.6	91 %	0 %	9 %	0 %
	RCP4.5	76 %	0 %	24 %	0 %
	RCP8.5	58 %	0 %	42 %	0 %

Table 3-5. *Percent of economic risk cases falling in each type (I, II, III or IV) grouped by period and RCP.*

Period	RCP	Type I	Type II	Type III	Type IV
2010-2039	RCP2.6	55 %	0 %	36 %	9 %
	RCP4.5	76 %	6 %	0 %	18 %
	RCP8.5	63 %	0 %	5 %	32 %
2040-2069	RCP2.6	82 %	9 %	9 %	0 %
	RCP4.5	88 %	0 %	0 %	12 %
	RCP8.5	68 %	0 %	5 %	26 %
2070-2099	RCP2.6	82 %	9 %	0 %	9 %
	RCP4.5	76 %	0 %	12 %	12 %
	RCP8.5	58 %	0 %	32 %	11 %

3.7 Conclusions

This article presents a comprehensive quantitative assessment of the effects of This article presents a comprehensive quantitative assessment of the effects of climate change on the failure risk of the Santa Teresa dam under hydrological scenarios, i.e. where the floods are the main loads to which the dam is subjected. The analysis integrates the various projected effects acting on each component of the risk, and how the dam failure risk evolves until the end of the 21st century.

The analysis is based on existing data and models from different sources. In particular, the climate projections (CPs) extracted from the CORDEX project have been treated and adapted for the study case. In order to deal with the associated uncertainty of climate modelling issued from the dispersion of their projection, the analysis is applied to the 21 available CPs. Additionally, a hydrometeorological model have been elaborated to simulate the response of the studied basin to present and future climatic conditions. Finally, the risk model of the dam has been adapted to the new components issued from the climate change impacts. Figure 3-1 summarizes the methodology proposed.

Results show a significant uncertainty of risk given by the dispersion of climate projection inputs and by the sensitivity to the hydrological modelling. In general, results show in most future scenarios an increase of both the social and economic risks in comparison to the present risk level, especially for the RCP2.6 and RCP4.5 scenarios. Moreover, most cases indicate a reduction in the average consequences as well as an increase of the probability of failure of the dam.

The use of a dam risk model allowed integrating the expected effects of climate change on the different components of the dam risk. The sensitivity analysis performed has shown that the effects of climate change on the dam failure risk are mainly explained by the changes in the flood loads and the changes in the reservoir water levels regime.

The methodology presented in this paper can serve as a useful guidance for dam owners and dam safety practitioners in the analysis of other study cases by entailing different models and data sources. This would eventually allow a more efficient planning of dam safety investments on the long term and even the adaptation of existing dam exploitation rules. New approaches that take into account the evolution with time of risk and of the efficiency of measures are thus needed. Furthermore, it is important to highlight that, without the use of risk models, the integration of the various projected effects of climate change on each dam safety aspect would not have been possible.

In conclusion, the methodology proposed in this paper allows a detailed quantification of the effect of climate change on dam safety, which is one of the main concerns of managers and technicians of these critical infrastructures for water supply and energy production worldwide. However, in order to exploit such results in the context of decision-making support, further efforts to address the non-stationarity nature of risk as well as its intrinsic uncertainties are needed. Such issues impose a deeper evaluation of the recommendations to make for the development of long-term adaptation strategies.

Appendix A: Sensitivity analysis for precipitation Gumbel distribution

The use of precipitation data from the observation and climate projection series induces sampling errors in estimating the Gumbel probability distribution parameters applied in Section 3.5.2.2, which induces uncertainty to the estimated quantile-frequency relationship. This will eventually impact on the estimated dam failure risk, as a result of the methodology proposed above. In this Appendix, the influence of the Gumbel distribution fitting uncertainty on the estimated dam risks is investigated. A sensitivity analysis has been applied to the Base Case (present situation); this would give an idea on how the rest of cases would react under the same uncertainty.

It can be assumed that, due to the sampling error, the T year quantile estimator x_T of daily precipitation can be treated as a random variable (Su and Tung 2013), as shown in Figure 3-14. In this paper, the maximum likelihood method proposed by Kite (1988) is applied to calculate the sampling error of the Gumbel-based quantile estimator. According to such method, the variance for the Gumbel T year quantile estimator (x_T) can be expressed as:

$$s_e{}^2(x_T) = \frac{\beta^2}{n} \cdot (1.1087 + 0.5140 \cdot Y + 0.6079 \cdot Y^2) \tag{3.7}$$

where β is the scale parameter of the fitted Gumbel distribution, n is the sample size and Y=-ln(-ln(1-1/T)).

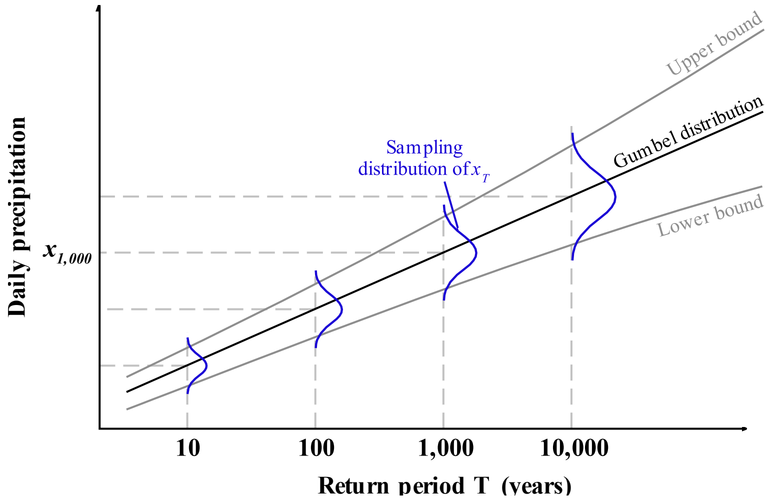

Figure 3-14. *Uncertainty of estimated T year daily precipitation quantile due to sampling error (adapted from Kite (1975)).*

Then, assuming the sampling distribution of the T year quantile estimator to be normal (Kite 1975; Su and Tung 2013) with mean x_T and variance s_e^2, 200 random quantiles are generated for the observation series (Base Case) for each return period T. Thenceforward, the corresponding hydrographs are obtained by replicating the process described in Section 3.5.2.2, this time using the new quantile-frequency relationships to determine the daily precipitations corresponding to return periods between 2 and 100,000 years. Finally, the risk model is applied, and social and economic risks are obtained for each of the 200 aleatory cases.

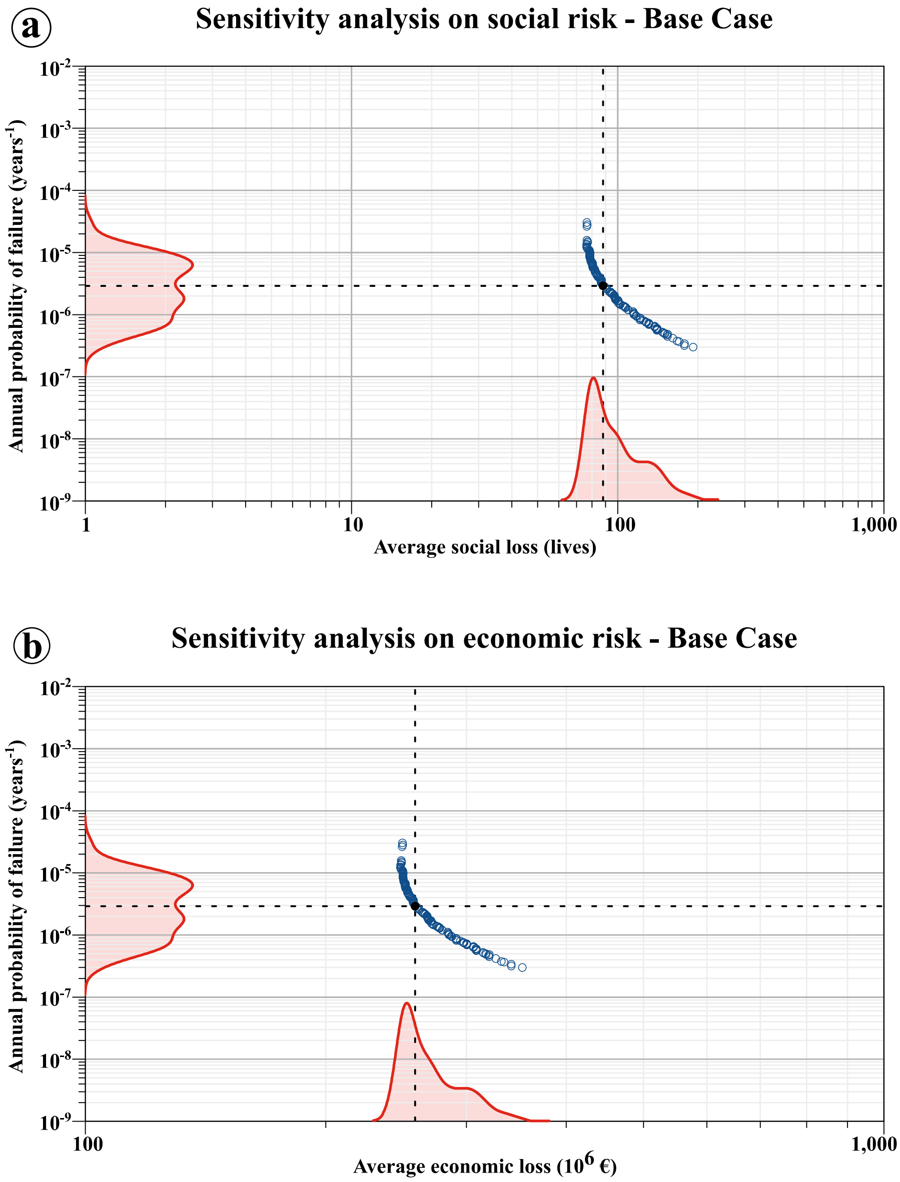

Figure 3-15. *Effect of precipitation sampling uncertainty on (a) social and (b) economic risk. The kernel density plot is displayed in red on the x and y axes. The base case situation is highlighted with a black point and two dashed lines.*

Results are displayed in Figure 3-15. Risks have been decomposed in its associated probability of failure and average (a) social and (b) economic consequences. Moreover, the point densities for consequences (x-axis) and failure probability (y-axis) are obtained by applying the kernel density estimation technique (Parzen 1962; Rosenblatt 1956) and displayed in red. The Base Case risk is represented as a black point and its probability of failure and consequences are highlighted with two dashed black lines.

Results show a significant sensitivity of risks to the meteorological modelling, and in particular to the statistical distribution fitting used to obtain maximum daily precipitations. Failure probability varies from 3×10^{-7}/year to 3×10^{-5}/year (being 2.91×10^{-6}/year the probability of the Base Case), that is two magnitude orders. Social and economic risks fluctuate between 5.64×10^{-5} and 2.33×10^{-3} lives/year, and between 1.06×10^{-4} and 7.59×10^{-3} M€/year, respectively. It is worth noting that the peak density for both the social and economic consequences is approximately coincident with the corresponding to the Base Case.

Data availability

We thank AEMET and the University of Cantabria for the data provided for this work (Spain02 v5 dataset, available on AEMET (2019)). The hydrological information used in this study is available at the CEDEX platform (CEDEX 2020).

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Chapter 4

Comprehensive decision-making approach for managing time dependent dam risks

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Abstract

Dams are critical infrastructures whose safety must be properly managed. Traditional decision-making approaches often assume the stationarity of factors defining risk. However, dam risks are susceptible to evolve with time. Risk can no longer be considered a static but a time-dependent concept which cumulative value must be reduced for different timescales. A broader perspective to dynamically evaluate time issues in the prioritization of measures is thus required.

A new approach is proposed for dam risk management on the long term that considers the potential evolution of risk. A new time-dependent risk indicator that allows assessing the efficiency of adaptation measures in optimally reducing dam risks has been defined: the Aggregated Adjusted Cost per Statistical Life Saved (AACSLS). Its use helps to better design risk reduction measures and to plan the implementation sequence that maximize their effectiveness.

The methodology has been applied to the case study of a Spanish dam under the effects of climate change. Different risk reduction measures have been proposed and their effects have been analyzed for a specific time horizon. The use of the AACSLS indicator has allowed identifying the prioritization of measures that optimizes the allocation of economic resources in the long term.

4.1 Introduction

Dams are critical infrastructures whose associated risk must be properly managed in a continuous and updated process (Fluixá-Sanmartín et al. 2018). Risk can be estimated by the combined impact of a given scenario, probability of occurrence, and associated consequences (ICOLD 2003). Risk Analysis techniques are being used worldwide to inform dam safety management and assess the efficiency of adaptation measures (Benjamin 1982; Bowles 2000; Escuder-Bueno et al. 2012b) with which decision-making is justifiable, objective and clear.

In the dam safety context, most dam risk management strategies are often applied assuming the stationarity of factors defining risk (Milly et al. 2008). However, risks are thus susceptible to evolve with time due to changes in their components and can no longer be assumed as a static but rather as a time-dependent concept. Among others, factors affecting risk evolution are:

- Effects of climate change on dam safety. Changes in climate factors such as variations in extreme temperatures or frequency of heavy precipitation events are likely to affect the different factors driving dam risk (CH2014-Impacts 2014; Fluixá-Sanmartín et al. 2018; IPCC 2012; Lee and You 2013; Walsh et al. 2014).

- The increasing exposure of people and economic assets in at-risk areas due to population and economic growth (Bouwer 2011; Changnon et al. 2000), which augment the potential socio-economic losses.
- Changes in the value of water as a resource. The value of water allocated to irrigation or hydropower production is likely to vary due to the expected alteration of the distribution, volume, and timing of water resources in the future (Fischer et al. 2007; Rodríguez Díaz et al. 2007; Solaun and Cerdá 2017; U.S. Department of Energy 2013). Thus, in the case of dam failure or serious malfunctioning, the absence of the structure would induce changes in the consequences caused by being unable to manage water resources as required.
- The degradation of the dam-reservoir system, due to the aging of the infrastructure, lack of maintenance or to reservoir sedimentation processes (White 2005).
- Moreover, within the dam safety management context, the implementation of risk reduction measures can be planned in the short-, mid- or long-term, which will have a direct impact on the variation of the associated risks (SPANCOLD 2012).

Usually, decision-making processes use criteria for prioritizing infrastructure investment based on current management priorities, safety standards and/or recent climate conditions. Under this new dynamic context, traditional approaches are no longer enough and should be updated to consider risks and costs as time series rather than fixed values (Lind 2002a). In this context, adaptation planning is of critical importance to ensure that relevant information is incorporated early on when developing long-term adaptation strategies, such as infrastructure investments or policy and operational changes (USBR 2014). Decision-makers must provide themselves with robust tools to manage future risks by anticipating the application of resilient mitigation measures.

Some efforts have been taken to address the non-stationary nature of risk. For instance, the US Bureau of Reclamation (USBR) has defined a Climate Change Adaptation Strategy (USBR 2014, 2016) to consider climate change information in agency decision making. This Strategy proposes qualitative methods that help identify actions to be implemented in the short term and in the long term. The US Army Corps of Engineers (USACE) describes in its Climate Change Adaptation Plan (USACE 2014) the actions that are undertaken to manage climate change related risks and vulnerabilities at the basin level. Among other guiding principles identified, the Adaptation Plan recommends incorporating risk-management methods and tools (such as Risk Analysis techniques) to help identify, assess, and prioritize options to reduce vulnerability to potential implications of climate change. In a more specific scenario, Lee and You (2013) proposed a framework to investigate the risk of dam overtopping resulting from time-variant climatic factors and to determine the optimal termination time of dam retirement based exclusively on economic criteria. These same principles are being undertaken in other fields of work, for instance for the definition of maintenance strategies for flood and coastal flood defenses (Buijs et al. 2009; Chen and Mehrabani 2019).

Existing initiatives in the field of dam safety management can however benefit from a comprehensive and quantitative approach based on Cost-Benefit Analysis. This has the advantages that it is transparent, sets clear standards of methodology, and allows meaningful debate and comparison between alternatives (Lind 2002b). This approach should use information about future risks in order to make decisions about how to manage dam-reservoir systems or prioritize investments for operations and maintenance in a wide range of scenarios. In this paper, the authors present an approach to tackle dam safety management on the long term considering both human-induced and natural variation of risk as well as considering their economic and social components (Hall et al. 2012). Moreover, a new risk indicator is proposed for the quantitative assessment of the long-term efficiency of risk reduction measures designed to reduce the cumulative risk value for a range of timescales, denoted as AACSLS (Aggregated Adjusted Cost per Statistical Life Saved). With this new approach, long-term investments can be planned and prioritized more efficiently in the decision-making process. This will prevent selecting measures that would no longer be necessary in the future or missing some measures that could efficiently reduce future risk.

4.2 Review of dam risk management approaches based on risk indicators

Risk analysis techniques are increasingly gaining importance as decision support tools in civil engineering applications (Faber and Stewart 2003) and in particular in the field of dam safety management. They allow the integration of all the relevant aspects of dam safety and help to optimize the existing resources and to point at the most efficient ways of using them (ANCOLD 2003; ICOLD 2005; SPANCOLD 2012; USACE 2011a).

4.2.1 Concepts of failure probability and risks

In the context of dam safety, risk can be defined as the combination of three concepts: what can happen (dam failure), how likely it is to happen (failure probability), and what its consequences are (failure consequences, including but not restricted to economic damages and loss of life) (Kaplan 1997). In this case, the concept of *failure* is not limited exclusively to the catastrophic breakage of the dam but includes any event that might produce adverse consequences, e.g.

mission disruption (SPANCOLD 2012). The associated failure probability can be defined as:

$$p(f) = \sum_{e} p(e) \cdot p(f|e) \tag{4.1}$$

where the summation is defined over all events e under study, $p(f)$ is the dam failure probability, $p(e)$ is the probability of an event that originates failure and $p(f|e)$ is the probability of failure due to event e. As the equation reflects, failure probability has two components: one corresponding to the loads ($p(e)$) and one corresponding to the system response ($p(f|e)$). In Risk Analysis, failure probability is usually expressed as an annual probability, that is, the probability that in any given year the dam fails. Hence, the term $p(e)$ in Equation (4.1) refers to the probability of the event occurring in any given year.

Based on the previous definition, risk can be computed in a single value by combining failure probabilities and the consequences as a result of that failure, including economic consequences and loss of life, among others. Risk is expressed through the following formula:

$$R = \sum_{e} p(e) \cdot p(f|e) \cdot C(f|e) \tag{4.2}$$

where $C(f|e)$ are the consequences produced as a result of each failure f and event e. When $C(f|e)$ expresses the loss of life, the risk is referred as social risk (R_s); when $C(f|e)$ expresses the economic consequences, the risk is referred as economic risk (R_e).

Following these formulas, failure probabilities, consequences and risks can be calculated, usually with risk models (SPANCOLD 2012; USBR and USACE 2011). A common practice in dam safety is working with incremental consequences (ANCOLD 2003; Serrano-Lombillo et al. 2011; USACE 2011a). Incremental consequences are incremental losses or damage, which dam failure might inflict over and above any losses which might have occurred for the same natural event or conditions, had the dam not failed (Canadian Dam Association 2013). They are obtained by subtracting the consequences in the non-failure case to the consequences in the failure case. This allows considering only the part of the risk produced by the dam failure. Risk is then known as incremental risk.

It is worth mentioning that, although environmental damage (as well as social disturbing, loss of reputation, damages to historical or cultural heritage, etc.) can also be part of the negative consequences due to a dam failure, they are difficult to quantify and so are usually treated in a qualitative way. Therefore, in this work only the economic and social consequences have been quantitative assessed and included in the analysis.

4.2.2 Risk evaluation and management

Once the risk for the current situation (base case) has been calculated, its importance must be evaluated to determine whether mitigation measures are required. Judgments and values are introduced in the process (ICOLD 2005) and risk is generally classified as unacceptable, tolerable or broadly acceptable (HSE 2001). Different organizations have proposed risk tolerability recommendations to evaluate whether a dam risk is tolerable or not (ANCOLD 2003; Li et al. 2015; SPANCOLD 2012; USACE 2011a; USBR 2011). It is worth mentioning that such recommendations do not include yet the temporal dimension in their criteria, and thus do not account for climate change influence. In the light of climate change influence and its expected evolution with time, a re-definition of such recommendations seems worthwhile. Based on changes in these criteria, the proposed methodology could be re-defined, or techniques for updating its application could be established.

Based on the classification of the estimated risk for the base case, a key stage of the risk analysis process relies on the definition of risk reduction measures. Decisions should be made based on the comparison of risk for the current situation and for the situation after the measure is implemented. Such comparison can be conducted using risk indicators, as described below.

4.2.3 Risk reduction indicators

As shown in (Morales-Torres et al. 2016; Serrano-Lombillo et al. 2017), risk reduction indicators are a useful tool to obtain prioritization sequences from a set of risk reduction measures by analyzing the efficiency in risk reduction of each proposed action. These indicators are obtained using the cost of each measure and the risk results for the base case and the situation with the measure implemented. This is done by applying the principles of Cost-Benefit analyses, where the total expected cost of each measure is compared with their total expected benefits (Baecher et al. 1980; Palmieri et al. 2001), in this case, in terms of risk reduction. Such techniques can be applied to inform and evaluate a range of interventions that can address disaster risks (Hugenbusch and Neumann 2016; Paté-Cornell and Tagaras 1986). In this case, the risk can be recognized as a real cost that can be expressed both in monetary and social terms. Several indicators can be used in the evaluation of dam risk reduction measures, including one or both terms of risk. In this paper, three key indicators are explained:

- **CBR (Cost-Benefit Ratio)**. This indicator (Bowles 2004; Parker et al. 1987) arises from the comparison of the cost of measure with the economic risk reduction benefit resulting from its implementation:

$$CBR = \frac{C_{meas} - \left(C_{op(base)} - C_{op(meas)}\right)}{R_{e(base)} - R_{e(meas)}} \tag{4.3}$$

  where C_{meas} is the annualized cost of the measure; $C_{op(base)}$ is the present annual operation cost of the dam; $C_{op(meas)}$ is the operation cost assuming the implementation of the measure; $R_{e(base)}$ is the economic risk in the base case; and $R_{e(meas)}$ is the economic risk in the situation with the measure implemented.

- **CSLS (Cost per Statistical Life Saved)**. This indicator is used to analyze risk management measures in very different fields such as aerospace (Stewart and Mueller 2008), health science (Lutter et al. 1999; Ramsberg and Sjoberg 1997), soil pollution (Khadam and Kaluarachchi 2003), dam safety (ANCOLD 2003) and road traffic safety (de Blaeij et al. 2003). It shows how much it costs to avoid each potential loss of life as a result of a dam failure by implementing a measure:

$$CSLS = \frac{C_{meas} - \left(C_{op(base)} - C_{op(meas)}\right)}{R_{s(base)} - R_{s(meas)}} \tag{4.4}$$

  where $R_{s(base)}$ is the social risk in the base case; and $R_{s(meas)}$ is the social risk in the situation with the measure implemented. The CSLS has economic units per life.

- **ACSLS (Adjusted Cost per Statistical Life Saved)**. This indicator (ANCOLD 2003; Bowles 2000) is calculated as the previous CSLS but adjusting the cost to consider the benefit due to the economic risk reduction:

$$ACSLS = \frac{C_{meas} - \left(C_{op(base)} - C_{op(meas)}\right) - \left(R_{e(base)} - R_{e(meas)}\right)}{R_{s(base)} - R_{s(meas)}} \tag{4.5}$$

  where $R_{e(base)}$ is the economic risk in the base case; and $R_{e(meas)}$ is the economic risk in the situation with the measure implemented. ACSLS is usually used to apply the ALARP (As Low as Reasonably Practicable) (Bowles 2004; HSE 2001) criterion, by indicating that a measure can be rejected in case the results show that it is not cost-efficient.

Intuitively, these indicators express how much it costs to avoid each potential loss of life as a result of a dam failure when applying a measure. They are based on efficiency and/or equity principles that rise from the need society has to distribute and use its available resources in such a way as to gain maximum benefit in the most efficient way (HSE 2001; Morales-Torres et al. 2016). In general, the measure that reduces the risk at the lowest cost and thus presents the higher efficiency will be prioritized, that is the measure with the lower value of the indicator.

4.3 Proposed strategy for long-term dam risk management

In general, the evaluation of the impact and efficiency of potential measures for risk reduction is performed taking the present situation as the base case (SPANCOLD 2012). This implies considering that the risk is stationary with time; indeed, the risk components of the previous formulas ($R_{e(base)}$, $R_{s(base)}$) are constant values. Under this traditional approach, risk evolution is considered affected only by the sequence of measures implemented. Conversely, in this work risk is rather treated as a time-dependent concept and must be tackled under a new perspective.

4.3.1 Re-evaluation of risk concepts

First, the concepts of failure probability as well as social and economic risk presented in Section 4.2.1 must be re-evaluated to incorporate their time-dependency.

The new approach proposed will be applied to a dam for a period [0,n] between the present time (year *0*) and a general time horizon (year *n*). As mentioned above, failure probability and risks are expressed in terms of annual probability and risks, respectively. That implies that the time step for the definition of these concepts is one year and that the analysis is applied to a period covering a total of n+1 time steps or states.

As the dam safety conditions evolve from year to year, the associated risks can be re-evaluated for each time step. For illustration, Figure 4-1 displays an event tree that models a risk system for the period [0,n]. For any year *i*, the state [i] can be represented as an event tree with 2 branches: non-failure (*nf[i]*), and failure (*f[i]*). For the period considered between the years *0* and *n*, the resulting risk system is composed of n+1 sequential event trees with 2 branches each, as shown in Figure 4-1. Each branch has an associated probability of $p_{nf[i]}$ and $p_{f[i]}$, respectively. Moreover, each state [i] has an associated risk $R_{[i]}$ based on the incremental consequences between the failure and the non-failure branches (cf. Section 4.2.1).

Failure cases are represented as black circles in Figure 4-1, while the non-failure cases are represented as white circles. It is considered that for each state [i], only two complementary possibilities exist: the failure and the non-failure of the dam; this means that in any given state:

$$p_{f[i]} + p_{nf[i]} = 1 \tag{4.6}$$

Moreover, it can be assumed that, once the dam has failed (*f[i]* branches), no more sub-cases arise from the resulting failure event. Indeed, the post-failure state of the dam-reservoir system is different from the analyzed situation: removal of the dam, partial rebuilding of the dam, or building of a completely new infrastructure. As the dam-reservoir system configuration changes, the methodology proposed must be re-applied from the beginning with another event tree with newly activated failure probabilities.

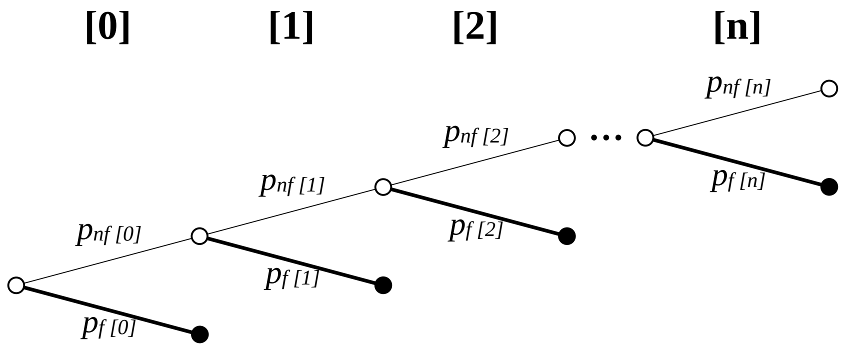

Figure 4-1. *Representation of an event tree modeling a risk system for the next n years.*

In this new context, the aggregated failure and non-failure probabilities and the aggregated risk for a given period [0,n] must be used to assess their representative future values at year n. On one hand, the aggregated failure probability is the sum of probabilities of all the tree branches corresponding to the dam failure between year *0* and year n, that is all the paths leading to the black circles in Figure 4-1. Based on Equation (4.6), this aggregated probability can be expressed depending of the failure probability of each branch as:

$$\begin{aligned} p_{f[0,n]} &= p_{f[0]} + p_{nf[0]} \cdot p_{f[1]} + \cdots + p_{nf[0]} \cdot p_{nf[1]} \cdot (\cdots) \cdot p_{nf[n-1]} \cdot p_{f[n]} \\ &= p_{f[0]} + \left(1 - p_{f[0]}\right) \cdot p_{f[1]} + \cdots + \left(1 - p_{f[0]}\right) \cdot \left(1 - p_{f[1]}\right) \\ &\cdot (\cdots) \cdot \left(1 - p_{f[n-1]}\right) \cdot p_{f[n]} \end{aligned} \tag{4.7}$$

On the other hand, the aggregated non-failure probability represents the probability of the dam not failing during the entire period [0,n]. Based on the event tree of Figure 4-1, this probability corresponds to the product of the probabilities of all the non-failure branches $p_{nf[i]}$ in the event tree:

$$\begin{aligned} p_{nf[0,n]} &= p_{nf[0]} \cdot p_{nf[1]} \cdot (\cdots) \cdot p_{nf[n]} \\ &= \left(1 - p_{f[0]}\right) \cdot \left(1 - p_{f[1]}\right) \cdots \left(1 - p_{f[n]}\right) \end{aligned} \tag{4.8}$$

Finally, the aggregated risk can be seen as the total economic cost or cost in lives resulting from the failure of the dam for the entire period [0,n]. This corresponds to the sum of all risks $R_{[i]}$ at each year i, where each risk value must be weighted by the probability of reaching the state [i]. Based on the previous equations, it can be expressed as:

$$\begin{aligned} R_{[0,n]} &= R_{[0]} + p_{nf[0]} \cdot R_{[1]} + \cdots + p_{nf[0]} \cdot p_{nf[1]} \cdot (\cdots) \cdot p_{nf[n-1]} \cdot R_{[n]} \\ &= R_{[0]} + R_{[1]} \cdot \left(1 - p_{f[0]}\right) + \cdots + R_{[n]} \cdot \left(1 - p_{f[0]}\right) \\ &\cdot \left(1 - p_{f[1]}\right) \cdot (\cdots) \cdot \left(1 - p_{f[n-1]}\right) \end{aligned} \tag{4.9}$$

The formulas of Equations (4.7), (4.8) and (4.9) can be generalized as:

$$p_{f[0,n]} = p_{f[0]} + \sum_{j=1}^{n} \left[p_{f[j]} \cdot \prod_{k=0}^{j-1} \left(1 - p_{f[k]}\right) \right] \tag{4.10}$$

$$p_{nf[0,n]} = \prod_{j=0}^{n} \left(1 - p_{f[j]}\right) \tag{4.11}$$

$$R_{[0,n]} = R_{[0]} + \sum_{j=1}^{n} \left[R_{[j]} \cdot \prod_{k=0}^{j-1} \left(1 - p_{f[k]}\right) \right] \tag{4.12}$$

The latter expression of $R_{[0,n]}$ is valid for both the social (R_s) and the economic risk (R_e). It is worth noting that, when referring to a future cost such as the economic risk and since the value of money changes with time, convention imposes that all amounts be translated in time to the same instant, e.g. by adding their net present values. This allows evaluating and comparing in a homogeneous way time-dependent risks. Therefore, the present value of the aggregated economic risk, noted R^*_e, is expressed as:

$$R^*_{e[0,n]} = R_{e[0]} + \sum_{j=1}^{n} \left[\frac{R_{e[j]}}{\prod_{t=1}^{j} (1 + i_t)} \cdot \prod_{k=0}^{j-1} \left(1 - p_{f[k]}\right) \right] \tag{4.13}$$

where i_t is the discount rate at year t. It is assumed that $i_0=0$.

4.3.2 *Definition of a new time-dependent indicator for the prioritization of risk reduction measures*

When assuming the stationarity of risk, the criteria used to prioritize different risk reduction measures are based on a direct comparison of the indicators' values (a unique value for each measure). Since the new approach is based on a time-dependent assumption, the indicator used must be adapted to consider time variability.

The criterion in which such indicator must be based consists on prioritizing those measures that presents a higher efficiency in the risk reduction throughout a predefined period [0,n]. The use of this risk reduction principle would prevent prioritizing measures that would no longer be necessary in the future or missing some measures that could efficiently reduce the future risk. For this, the ACSLS has been taken as the reference indicator since it combines social and economic efficiency principles.

Under this assumption, a new risk indicator is proposed in this paper: the Aggregated Adjusted Cost per Statistical Life Saved (AACSLS). The AACSLS indicator calculates the total cost of a statistical life saved during a given period. It is considered that measures may take a certain time to be fully implemented due to construction duration or administration processes among others, and that until completed they have no effects on the risk.

Thus, the components of Equation (4.5) (costs, economic and social risks) are evaluated cumulatively following the concepts presented in Section 4.3.1:

$$AACSLS_{[0,n]} = \frac{C^*_{meas[0,m]} - \left(C^*_{op(base)[0,n]} - C^*_{op(meas)[0,n]}\right) - \left(R^*_{e(base)[0,n]} - R^*_{e(meas)[0,n]}\right)}{R_{s(base)[0,n]} - R_{s(meas)[0,n]}} \quad (4.14)$$

where *AACSLS* is expressed in monetary units per life; $C^*_{meas[0,m]}$ is the total cost of the measure that may take a certain period to be fully implemented (m is the final year of the implementation of the measure, with $m \le n$); $C^*_{op[0,n]}$ are the operation costs computed for the period [0,n]; $R_e{}^*_{[0,n]}$ is the economic risk as expressed in Equation (4.13); and $R_s{}^*_{[0,n]}$ is the social risk, that is the average expected number of lost lives during the period [0,n] as expressed in Equation (4.12). As in Equation (4.13), the present value of the cost of the measure as well as of the operation costs must be used:

$$C^*_{meas[0,m]} = C_{meas[0]} + \sum_{j=1}^{m} \left[\frac{C_{meas}[j]}{\prod_{t=0}^{j}(1+i_t)} \cdot \prod_{k=0}^{j-1}\left(1 - p_{f[k]}\right) \right] \quad (4.15)$$

$$C^*_{op[0,n]} = C_{op[0]} + \sum_{j=1}^{m} \left[\frac{C_{op}[j]}{\prod_{t=0}^{j}(1+i_t)} \cdot \prod_{k=0}^{j-1}\left(1 - p_{f[k]}\right) \right] \tag{4.16}$$

4.3.3 New approach for the prioritization of risk reduction measures

The use of the proposed indicator requires a new approach that incorporates the evolution of risk with time and evaluates the impact of each measure for a defined period. The goal is to define a prioritization of risk reduction measures based on the AACSLS indicator.

Priority measures should correspond to those presenting a higher risk reduction throughout a specific time period, while assuming a lower accumulated cost calculated for this same period. That is, rank the different measures according to increasing AACSLS values.

A procedure is proposed in this work to evaluate risk and to assess the efficiency of the measures on the long term as follows (Figure 4-2):

a) The first step is the computation of risk. In this case, we calculate the risk in the present situation and its evolution with time. In particular, the values of the failure and non- failure probabilities ($p_{f[i]}$ and $p_{nf[i]}$) and both the social ($R_{s[i]}$) and the economic risk ($R_{e[i]}$) for any given state [i] within the analysis period are needed. For simplicity, it is suggested to calculate these values for a few time horizons and then interpolate them at an annual interval. Risk models are a basic tool used for the quantitative assessment of these components, integrating and connecting most variables concerning dam safety (Ardiles et al. 2011; Bowles et al. 2013a; Serrano-Lombillo et al. 2012a). Such models serve also as a supporting tool to assess the effects on risk imposed by climate change. Refer to Fluixá-Sanmartín et al. (2018, 2019c) for a theoretical and practical guidance on the use of risk models for the calculation of dam risk evolution under this approach.

b) Risk evaluation is needed to evaluate whether a risk is tolerable or not and, eventually, to justify the proposition and implementation of risk reduction measures. This must be done for the risk level at the current situation but also for future risks. Several reference organizations have proposed tolerability recommendations that can be used for this evaluation, as mentioned in Section 4.2.2.

c) Based on the tolerability of the computed present and future risk, a set of potential risk reduction measures are proposed. The implementation and operation costs of each measure must be also defined, considering the change in the value of money.

d) The next is the definition of the decision time horizon or financing horizon. This horizon T is the upper limit of the time interval [0,T] during which the investment is to be justifiably financed (Lind 2007). This is a key step prior to the assessment of the efficiency of each measure. Indeed, it implies that risks in the far future are to be counted as if they occurred at the financing horizon. This allows foreseeing the events to be expected during this period [0,T], to define the risk reduction measures and to plan the implementation that maximize their effectiveness. Criteria for setting the decision time horizon cover a wide range of possibilities. These are the basis for the widespread application in diverse domains of economic and financial analyses such as cost benefit analysis (CBA), cost effectiveness analysis (CEA) or multi-criteria analysis (MCA) (Annema et al. 2015; Beria et al. 2012; Diewert 1983; Rackwitz et al. 2005); among others:

   - Availability of funds.
   - Expected lifetime of the dam.
   - Applicability of the measures.
   - Factors affecting the evolution of the dam failure risk, such as changing climate or sedimentation phenomena in the reservoir (Lee and You 2013).

e) Risk is computed again considering each measure implemented, in current and future situations.

f) Based on the risk results, the AACSLS indicator defined in Section 4.3.2 is computed for all the measures proposed and for the entire analysis period.

g) The measures are ranked according to their risk reduction efficiency. We select first the measure that present a lower AACSLS indicator for the study period.

Finally, steps d) to g) can be iteratively repeated for the rest of the measures in order to define the implementation sequence of such measures. For this, the risk reduction resulting from the previously implemented measure(s) has to be taken into account before ranking the remaining measures. Moreover, the decision time horizon should be re-evaluated based on the efficiency of selected measures but also on other factors (e.g., remaining funding capacity).

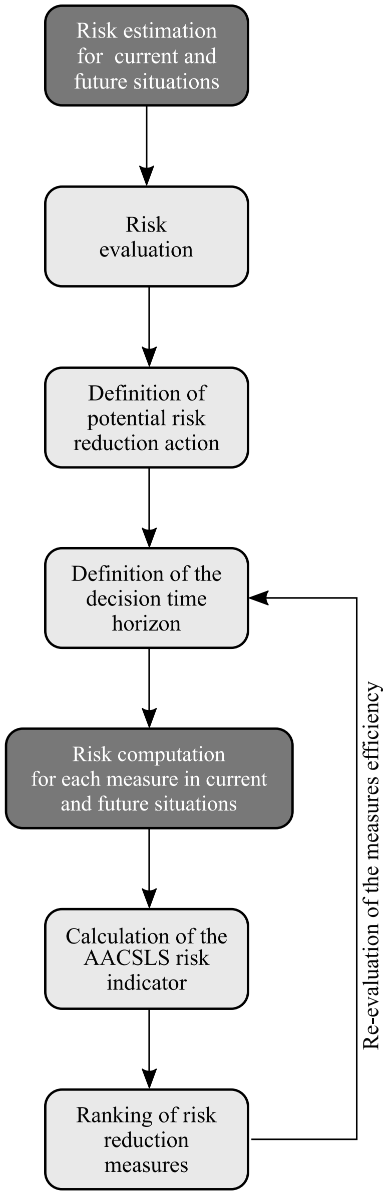

Figure 4-2. *Process to rank risk reduction measures based on long-term risk evaluation.*

4.4 Case study

A case study of a Spanish dam belonging to the Duero River Basin Authority is used in this work for the application of the proposed methodology. The Santa Teresa dam is located in the upper part of the Tormes River, in the province of Salamanca (Spain), and is managed by the Duero River Basin Authority. The Santa Teresa reservoir is bounded by the Santa Teresa dam and a smaller auxiliary dike.

The Santa Teresa dam is a concrete gravity dam built in 1960 and has a height of 60 m with its crest level at 887.20 m a.s.l. and a length of 517 m. It is equipped with a spillway (Figure 4-3) regulated by five gates capable of relieving, altogether, 2,017 m^3/s at its normal operating level (885.70 m a.s.l.), as well as with two bottom outlets with a release capacity of 88 m^3/s each. The dam is complemented with a 165 m long and 15 m high auxiliary gravity concrete saddle dam with its crest level at 886.90 m a.s.l.

Figure 4-3. *View of the Santa Teresa spillway from downstream.*

The Santa Teresa reservoir has a capacity of 496 hm^3 at its normal operating level (885.70 m a.s.l.). The catchment that pours into the reservoir has a total surface of 1,853 km^2 and is part of the Tormes Water Exploitation System, with the Santa Teresa reservoir being the first and uppermost infrastructure of the basin to regulate the Tormes River. The main uses for the Santa Teresa dam-reservoir system are hydropower production, flood protection, irrigation and water supply to the areas located between the Santa Teresa and Almendra dams, including Salamanca city.

An analysis published in Fluixá-Sanmartín et al. (2019c) showed a quantitative assessment of the future effects of climate change on the failure risk of the Santa Teresa dam. Such results are used in this work to assess how a long-term approach that takes into account the expected evolution of risk would improve the risk management of the dam.

4.4.1 Risk estimation

In Fluixá-Sanmartín et al. (2019c), a risk model of the dam was used to compute the associated failure risks for the present situation and for future climate scenarios. This risk model was set up with iPresas software (iPresas 2019), a tool for quantitative risk calculation based on event trees to compute failure probability and risk. The software integrates the probability of occurrence of loads, the system response and any type of consequences (loss of life, economic, total, incremental) through the use of influence diagrams.

The risk model used analyzes the different ways in which the dam can fail resulting from the loading events and calculating their probabilities, consequences and risks. Such model was elaborated for hydrological loading scenarios and included: (i) floods probability; (ii) probability of outlets availability; (iii) previous pool levels probability; (iv) results from flood routing; (v) fragility curves for different failure modes; and (vi) loss of life and economic consequences based on hydraulic models.

The climate projections of 21 regional climate models from the EURO-CORDEX project (Jacob et al. 2014) encompassing three Representative Concentration Pathways (RCP2.6, RCP4.5 and RCP8.5) were used. The risk model allowed calculating the evolution of risk and dam failure probability until the end of the 21st century. Results were then extracted for 4 periods: 1970-2005 (Base Case); 2010-2039; 2040-2069; and 2070-2099. These results serve as reference points (years 2005, 2039, 2069 and 2099, respectively) for the interpolation of risk and failure probability. Results in Fluixá-Sanmartín et al. (2019c) showed in most future scenarios an increase of both the social and economic risks in comparison to the present risk level. Most cases indicated an increase on the probability of failure of the dam as well a reduction in the average consequences. Such reduction is mainly due to the diminished exposure of people in the at-risk area; according to long-term projections, population is expected to slightly decrease until 2040 and will follow a substantial diminution until the end of the century.

Among the different climate models and RCPs available, in this study the climate projection coded as CP16 in Fluixá-Sanmartín et al. (2019c) (Global Climate Model: MPI-M-MPI-ESM-LR; Ensemble: r1i1p1; Institute: MPI-CSC; RCM: REMO2009) under the RCP2.6 is used for the study case analysis. This case has been selected since its results resemble the average situation resulting from the different cases studied in Fluixá-Sanmartín et al. (2019c). Table 4-1 shows the failure probability and the social and economic risks for each period for the selected climate projection as obtained in Fluixá-Sanmartín et al. (2019c). Probability and risks for intermediate years can be extracted with a linear interpolation of these values.

Table 4-1. *Results of failure probability, social risk and economic risk for the Base Case and future projections (from Fluixá-Sanmartín et al. (2019c)).*

Year	Failure probability [years^{-1}]	Social risk [lives/year]	Economic risk [M€/year]
2005	2.91×10^{-6}	2.56×10^{-4}	7.53×10^{-4}
2039	1.35×10^{-5}	7.60×10^{-4}	3.08×10^{-3}
2069	5.30×10^{-5}	2.33×10^{-3}	1.18×10^{-2}
2099	2.16×10^{-4}	8.69×10^{-3}	4.86×10^{-2}

At this point, it is important to mention that climate change uncertainties impose a great impact in risk assessment and decision-making. Although this work is focuses on a unique climate projection, consideration of uncertainty is therefore an essential element of decision-making as it is inherent in all evidence and in all decisions (Delenne et al. 2012; Morales-Torres et al. 2019). The difficulty remains on how to incorporate these uncertainties into the process of dam safety governance by defining adaptation strategies and prioritizing risk reduction investments. In the context of climate adaptation policy making, relevant approaches are Adaptive Policy Making (Walker et al. 2013, 2001), Adaptation Pathways (Haasnoot et al. 2012) or Real Options Analysis (Gersonius et al. 2012; Park et al. 2014). Such methods should be incorporated in a comprehensive approach to deal with climate-related uncertainties in long-term risk reduction strategies.

4.4.2 Risk evaluation

The previous results have been evaluated using the USBR tolerability criteria (USBR 2011) to estimate whether the risk are tolerable or not. This helps to determine the convenience of implementing mitigation measures. As can be seen in Figure 4-4, these tolerability guidelines can be represented on an f-N graph. The vertical axis represents failure probability and the horizontal axis represents average life loss, which can be obtained dividing social risk by failure probability.

A first limit is set at a failure probability of 10^{-4} years^{-1}; this value is related to individual risk, to the public responsibility of the dam owner and to protecting the image of the organization. A second limit is set for social risk, suggesting a maximum value of 10^{-3} lives/year. These limits define two areas. On the upper area, the further away you are from the limit lines, the more justified risk reduction measures will be. On the lower area, the further away you are from the limit lines, the less justified risk reduction measures will be. Moreover, a limit on consequences is placed on the value of 1,000 lives. If the risk is to the right of this line, risks should be evaluated carefully, ensuring ALARP (As-Low-As-Reasonably-

Practicable) considerations are addressed. ALARP means that tolerable risks should only be assumed if their reduction is impracticable or the cost of such reduction is disproportional to the safety gain it gives.

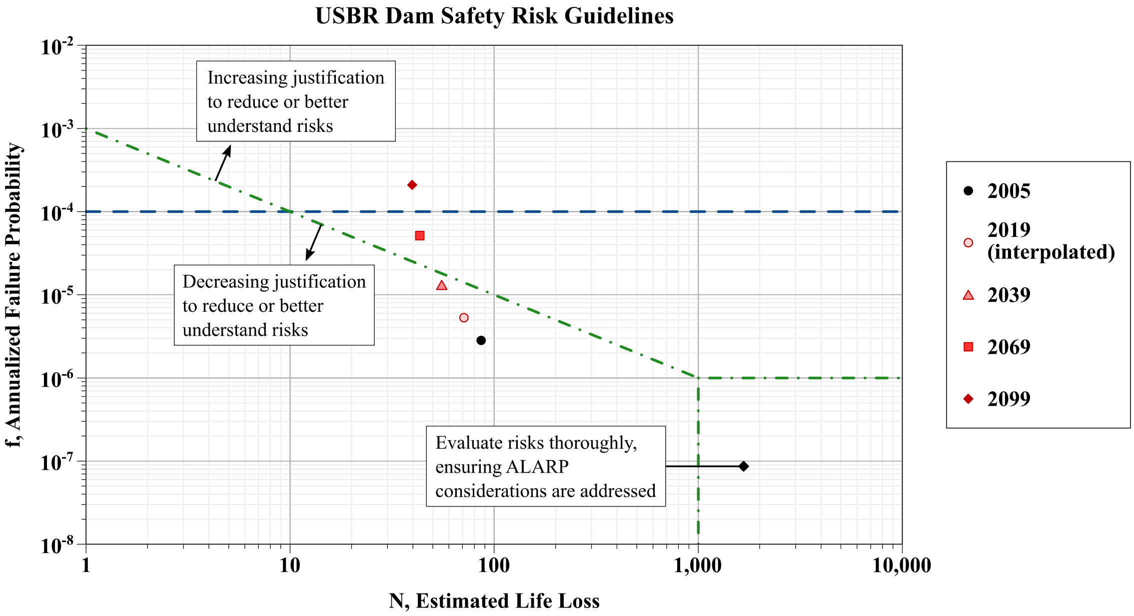

Figure 4-4. USBR tolerability criteria, and f-N points representing the estimation of failure probability and loss of life based on the risk results from 2005 to 2099.

Results obtained in the risk computation are plotted in Figure 4-4. Each point represents the risk situation at a certain time horizon. Moreover, interpolated values corresponding to the present scenario (year 2019) have been calculated using values from Table 4-1, as indicated above, and are also depicted in Figure 4-4. Based on these recommendations, the current situation does not present an urgent need for risk reduction measures. However, as the risk progresses, the need for risk mitigation becomes increasingly important. Finally, the situation at the end of the 21st century exceeds all the proposed tolerability criteria. Hence, the change of the situation from acceptable to unacceptable risk levels justifies not only the definition of risk reduction measures, but also the application of the approach proposed in this paper.

4.4.3 Analysis of risk reduction measures

Previous results justify the convenience of proposing risk reduction measures to be implemented in the Santa Teresa dam for the long term. Four measures have been defined in this work based on the quantitative risk analysis performed on 27 dams located in Spain (Ardiles et al. 2011; Morales-Torres et al. 2016) and considering the expected climate change impacts resulting from the risk analysis performed. The implementation costs and operation costs of Measure A were extracted from the "Implementation Project of the Emergency Plan of the Santa Teresa Dam and the Saddle Dam", while for Measures B, C and D costs were estimated using the Spanish recommendations published in Dirección General de Carreteras (2016). The description of each measure is presented below, and the corresponding costs are shown in Table 4-2:

- **Measure A**: implementation of an Emergency Action Plan (EAP). The Emergency Action Plan has a direct effect on the potential consequences of dam failure. The existence of adequate protocols and systems for warning and evacuating the population downstream means that in the event of a failure, the loss of human life will be reduced. The result on the dam risk is a reduction of the social risk but not of the failure probability or the potential economic consequences, although in some cases it might be considered.
- **Measure B**: construction of a continuous concrete parapet with height of 1.5 m along the dam and the auxiliary saddle dam. The parapet is supposed connected to the existing infrastructure and resistant enough to support the water pressure to which it is subjected. Its direct effect is an increase of freeboard of the dam (dam crest level), thus reducing the probability of overtopping of both the dam and the saddle dam.
- **Measure C**: increase of the spillway capacity by lowering 1.5 m its crest level. This implies a direct effect on the maximum discharge capacity through each gate, which increases from 403 m^3/s at its normal operating level (885.70 m a.s.l.) up to 588 m^3/s. The Tainter gates regulating the outflows would be replaced by new ones as well.
- **Measure D**: establishment of a better maintenance program for spillway gates. In Fluixá-Sanmartín et al. (2019c), a progressive deterioration in each of the 5 spillway gates was assumed, producing that their individual reliabilities vary from 85% at the present situation to 75% in 2099. With this measure, the individual reliabilities are maintained at 85% until the 2099 scenario, which will reduce dam failure risk in the future.

Table 4-2. *Implementation and maintenance costs for each analyzed risk reduction measure.*

Measure	Implementation cost	Operation cost (present value)
A	601,528.00 €	30,076.00 €/year
B	479,413.00 €	0 €/year
C	2,817,365.00 €	0 €/year
D	0 €	82,750.00 €/year

4.4.4 Computation of risk for each measure

Using the risk model described above and considering the effects of each measure on the different dam safety components, the resulting risks have been computed for the study period. Results in terms of failure probability as well as social and economic risks are presented in Figure 4-5. Each measure affects one or several of these three terms. It is worth mentioning that Measure A does not have any impact on failure probability or on economic risk, but only on social risk.

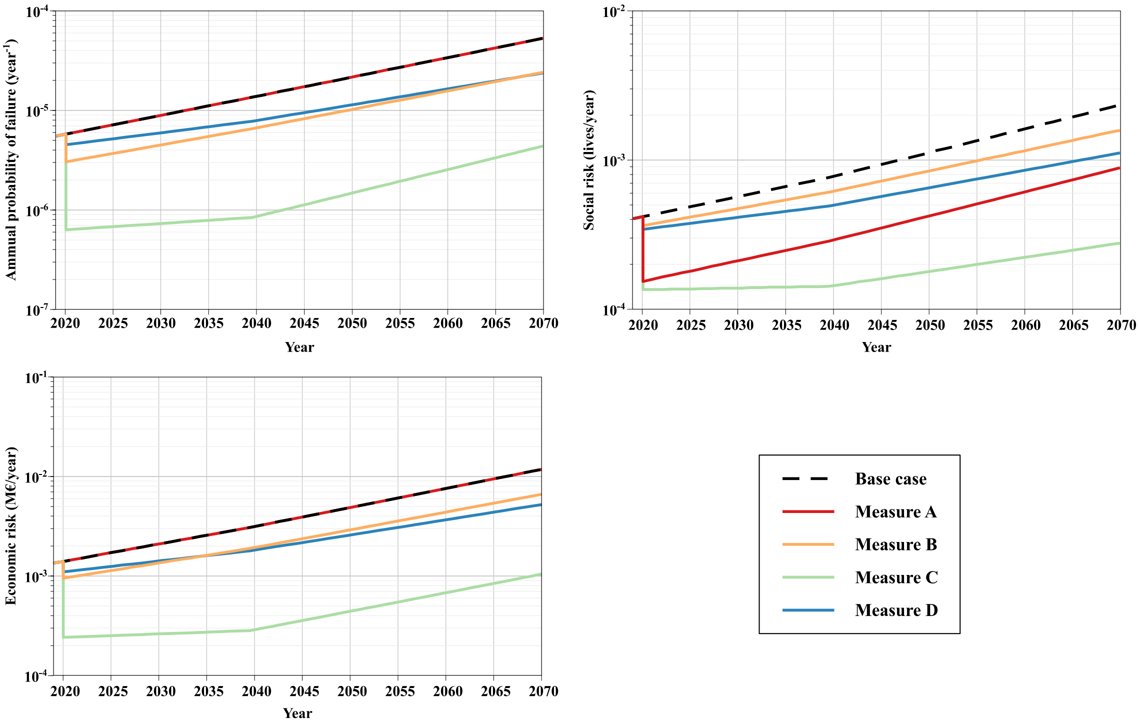

Figure 4-5. *Resulting evolution of failure probability (top-left), social risk (top-right), and economic risk (bottom-left) considering the implementation of each risk reduction measure.*

4.4.5 Estimation of the AACSLS indicator and ranking of measures

Once the resulting risks and failure probabilities have been obtained for the entire study period and for each risk reduction measure, it is possible to evaluate their efficiency. Following Equation (4.14), the AACSLS indicator has been calculated for the four measures proposed. Moreover, in order to assess the convenience of applying the proposed methodology, the ACSLS indicator (Equation (4.5)) has been calculated as well considering that risk and failure probabilities do not evolve with time. For its calculation, the annual maintenance and operation costs have been added to the implementation cost and the total cost of every measure has been expressed in monetary units (in this case, euros) per year.

According to the results obtained, a ranking of the measures based on both risk indicators has been applied. As stated before, priority measures correspond to those presenting a higher efficiency in risk reduction. That is, the measure with the lowest value of the indicator is chosen. Thus, the ranking depends on the risk reduction indicator used to define it.

Table 4-3 shows the values of the AACSLS and the ACSLS indicators for each risk reduction measure, as well as the position of each measure in the ranking based on both indicators. In particular, the priority of measures A, B and C are swapped. The ranking based on AACSLS reveals what are the higher efficiencies on the long term, while the ranking based on ACSLS gives a short-term perspective. Thus, according to the results it can be stated that Measure B has the greatest efficiency when considering its effect on dam safety and the evolution of the failure probability as well as the social and the economic risks. Without the application of the proposed approach, Measure A would have been prioritized over Measure B, thus lessening economic efficiency at the long-term. Moreover, the AACSLS present lower values than the ACSLS. This means that risk reduction measures are more justifiable economically when the risk evolution is taken into account.

Table 4-3. *Resulting AACSLS and ACSLS indicators for considered risk reduction measures, and their position in the prioritization order.*

Measure	AACSLS	Priority (based on AACSLS)	ACSLS	Priority (based on ACSLS)
A	62.25 M€/life	3	160.77 M€/life	1
B	27.55 M€/life	1	169.47 M€/life	2
C	57.32 M€/life	2	197.20 M€/life	3
D	175.42 M€/life	4	1,115.30 M€/life	4

4.4.6 Sensitivity analysis

In order to evaluate how the selection of the decision time horizon affects the AACSLS and consequently the prioritization of risk reduction measures, a sensitivity analysis has been performed. For this, the process described above has been replicated for different times, namely from 25 to 75 years. Results are shown in Figure 4-6, where for each time horizon the proposed measures are classified from priority 1 to 4.

These results highlight the importance of the decision time chosen. For instance, Measure A goes from being highly justified for short horizons (up to 28 years) to becoming less justifiable for longer horizons (from 48 years forward). The inverse can be stated for Measures B and C. In this case, Measure D remains the less priority option for all the decision times considered.

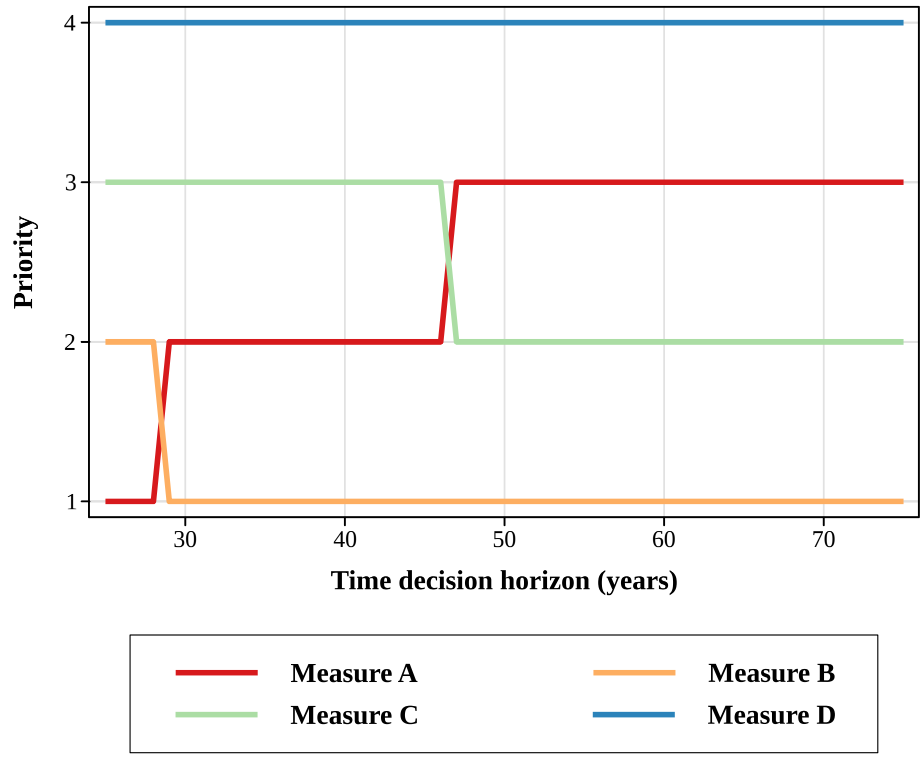

Figure 4-6. Variation of the priority of each measure depending on the time decision horizon.

4.5 Conclusions

In this paper, a new approach is proposed for long-term dam risk management that takes into account the potential evolution with time of risk and of the efficiency of risk reduction measures. The goal of this approach is to prevent selecting measures that would no longer be necessary in the future or missing some measures that could efficiently reduce future risk. This is of particular interest when adapting risk management strategies to future climate change impacts.

Although traditional decision-making approaches assume the stationarity of factors defining risk, dam risks are susceptible to evolve and can no longer be assumed as a static but rather as a time-dependent concept. For this, a re-evaluation of risk concepts has been made. In particular, risk components have been expressed in terms of aggregated values for a predefined time decision horizon. In order to adapt the methodology for risk adaptation, the authors propose a new risk indicator that encompasses both the social and economic risk: the Aggregated Adjusted Cost per Statistical Life Saved (AACSLS). This indicator defines the total cost of saving a statistical life computed for the entire studied period as a result of applying a certain risk reduction measure. Based on this indicator, different measures can be ranked according to their risk reduction efficiency where the main criterion to follow would be choosing first the measures that present a lower AACSLS value at the time decision horizon. This represents an innovative contribution since no other indicator that takes into account the changeable nature of risks has been proposed before.

The methodology proposed has been applied to the case study of a Spanish dam. This is the first documented application of a comprehensive analysis to define long-term adaptation strategies and assess their efficiency for a dam subjected to the effects of climate change. Four risk reduction measures have been proposed and their effects have been analyzed for a specific time horizon. The use of the AACSLS has proved to be useful to identify the measures that optimize the use of economic resources in the long term based on their effect on risk reduction, that is, those that reduce risk (social and economic) at the lowest cost for the entire period analyzed. The same analysis has been performed by applying a traditional approach commonly used in dam risk management that does not considers the evolution of risk with time. Differences between both approaches highlight the usefulness of the proposed methodology and provide a more accurate economic justification for the selection of risk reduction measures to be undertaken. Furthermore, a sensitivity analysis has revealed the importance of the decision time horizon employed in the prioritization of such measures, which becomes a key aspect of the proposed methodology.

It is worth mentioning that uncertainty remains a complex issue when dealing with climate information (Willows and Connell 2003). Some of these uncertainties have to do with incomplete knowledge while others relate to the intrinsic variability in climatic, economic, social and environmental systems. Therefore, adaptation strategies that cope with such uncertainty sources must be envisaged as an effective tool for risk management on the long term where there is not enough certainty to unambiguously establish the best solution (European Commission 2013b).

Chapter 5

Accounting for climate change uncertainty in long-term dam risk management

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Abstract

This paper presents a practical approach for adaptive management of dam risks based on robust decision-making strategies coupled with estimation of climate scenario probabilities. The proposed methodology, called *Multi-Prior Weighted Scenarios Ranking*, consists of a series of steps from risk estimation for current and future situations through the definition of the consensus sequence of risk reduction measures to be implemented. This represents a supporting tool for dam owners and safety practitioners to help making decisions for managing dams or prioritizing long-term investments using a cost-benefit approach. This methodology is applied to the case study of a Spanish dam under the effects of climate change. Several risk reduction measures are proposed and their impacts are analyzed. The application of the methodology allows identifying the optimal sequence of implementation measures that overcomes the uncertainty from the diversity of available climate scenarios by prioritizing measures that reduce future accumulated risks at lower costs. This work proves that such a methodology helps to address uncertainty that arises from the existence of multiple climate scenarios while adopting a cost-benefit approach that optimizes economic resources in dam risk management.

5.1 Introduction

Risk assessment techniques help to implement dam safety management as a comprehensive approach. Such techniques are applied worldwide in the dam sector (ANCOLD 2003; ICOLD 2005; SPANCOLD 2012; USACE 2011a) to support informed safety governance when adopting risk-reduction measures and their prioritization. Moreover, these approaches are often based on quantitative methods and models, which depend strongly on the quality and precision of the input data.

Climate change imposes new challenges to the application of risk analysis techniques. Dam risk management can no longer be envisioned by assuming risk stationarity over long-term operations (Fluixá-Sanmartín et al. 2019b; c; USACE 2016). Updating the risk components becomes imperative to consider new climate scenarios under a more robust approach. Efforts are currently focused on defining, analyzing, and managing climate change impacts on risks (Chernet et al. 2014; International Hydropower Association 2019; USACE 2016; USBR 2014, 2016; Willows and Connell 2003).

However, one issue remains challenging: climate-related uncertainties come on top of other uncertainty sources, which affects the results of risk analysis models and their effectiveness (Morales-Torres et al. 2019). This represents a major roadblock for adaptive decision-making and requires organizations and individuals to adapt their standard practices and decision procedures (National Research Council 2009). Under uncertain future climate conditions, response strategies that explicitly recognize these uncertainties are an essential element of decision-making (Khatri and Vairavamoorthy 2011; Street and Nilsson 2014).

The first aspect to consider is the incorporation of climate (and other) uncertainties into the dam safety assessment. That is, evaluating their effect on each component of risk, taking into account their interdependencies. This can be achieved using quantitative risk models, which are useful tools for the identification and structuration of climate change impacts and uncertainties for each dam risk component. These models have been recently applied in several studies (Fluixá-Sanmartín et al. 2019b; c; Morales-Torres et al. 2019).

Secondly, it is important to establish how to incorporate these uncertainties into the process of dam governance by defining so-called robust adaptation strategies and prioritizing risk reduction investments. Such strategies seek options to satisfy their purpose across a variety of futures by integrating a wide range of climate scenarios or model results (Haasnoot et al. 2013; Wilby and Dessai 2010). Recent efforts have been put in applying decision-making approaches to cope with uncertainty effects in water resources systems (Miao et al. 2014; Minville et al. 2010; Roach et al. 2016; Spence and Brown 2018), although more work needs to be done in the context of dam safety.

A common economic approach when modeling uncertainty is the use of the expected utility framework defined by von Neumann and Morgenstern (1944). This technique has been applied in different fields to make decisions without knowing what outcomes will result from a given decision (Chamberlain 2000; Danthine and Donaldson 2015; Levitan and Thomson 2009). The goal is to capture such uncertainty by characterizing the outcome likelihood with a given probability distribution and act accordingly. Knowing climate change probabilities would allow determining the plausibility of risk conditions, which leads to more informed decision-making (Dessai and Hulme 2004; Jones 2000).

Nevertheless, the struggle to assign probabilities makes it difficult to support informed decisions (New and Hulme 2000) since no probabilities have been attached to the future climate scenarios (IPCC 2013). Even though probabilities are needed for risk and adaptation studies (Pittock et al. 2001), the application of methods to assign these probabilities remains a controversial topic that requires further development (Knutti et al. 2010a). In addition, the expected utility is highly dependent on the selected configuration of probabilities and there is a risk of overweighing a particular climate scenario, leading to suboptimal decisions.

Since our knowledge about the climate system is not (yet) of enough quality to assign a unique probability distribution over states, an alternative to the expected utility framework is the application of a multiple priors approach. The idea is to use different distributions and assign a weight to each of them (Garlappi et al. 2004; Heal and Millner 2014). These distributions are then used to evaluate the convenience of a decision. This approach would help lessen the sensitivity of the expected utility evaluation to the probability configuration used.

This paper presents a practical approach to support robust decision-makings adapted to dam safety in the context of climate uncertainty. The goal is to define a complete procedure that allows defining and prioritizing risk reduction measures based on their efficiency on short- to long-term operations while establishing the consensus implementation sequence. The usefulness of the approach consists of aggregating multiple scenarios by applying and adapting the expected utility theory and the multiple priors approach, providing different results than simply considering a compilation of states. First, the primary uncertainty sources related to future climate change scenarios are presented. Secondly, a probabilistic approach is given as focused on evaluating the robustness of measures and on their prioritization strategy. Finally, the procedure is applied to a real case study of a Spanish dam based on previous risk results (Fluixá-Sanmartín et al. 2019c).

5.2 Climate change uncertainty in dam risk management

When evaluating the risk of dams as well as other complex structures, two types of uncertainty are generally distinguished as (Ferson and Ginzburg 1996; Hartford and Baecher 2004):

- Natural uncertainty: Arising from inherent variability in natural processes.
- Epistemic uncertainty: Resulting from not having complete knowledge or information about the analyzed system.

When studying dam risk management, natural uncertainties can arise from variability in potential flood magnitudes that occur. Epistemic uncertainties are related to the estimation of fragility curves, which represent a relationship between the conditional failure probabilities and the magnitude of loads that produce such failures. Fluixá-Sanmartín et al. (2019c) applied a sensitivity analysis to assess how uncertainty in meteorological modelling affects dam risks. An extract of these results is shown in Figure 5-1.

Specific sources of uncertainty can be identified when considering climate change projections. For example, (Hawkins and Sutton (2009) grouped the uncertainties into three major categories: (i) scenario, (ii) internal climate, and (iii) model uncertainties. Further detailed descriptions of the uncertainty sources can be found in other references (Eggleston et al. 2006; European Environment Agency 2017; Knutti et al. 2010a; Wilby and Dessai 2010). The ensemble of uncertainties is propagated through input data and models, which inherit prior uncertainties and expand at each step of the process. To address such uncertainties, it is typical to work with ensemble simulations that combine different regional climate models (RCMs), scenarios, and models.

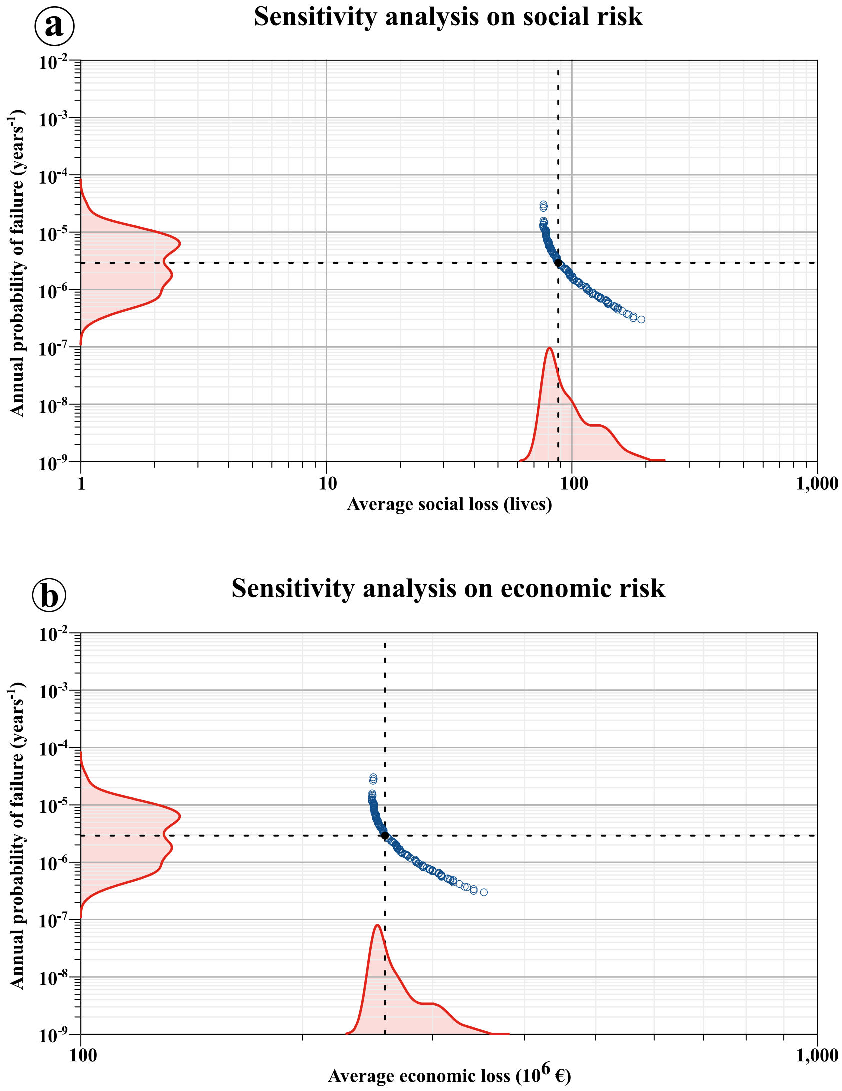

Figure 5-1. *Effects of precipitation sampling uncertainty on (a) social and (b) economic risks, where the kernel density plot for each variable is displayed in red on the x and y axes. The reference situation is highlighted with a black point and two dashed lines (source: Fluixá-Sanmartín et al. (2019c)).*

Dam failure risks are subjected to the impact of climate change uncertainties in different ways. The primary component that is affected by climatic drivers is the hydrology of river basins. Precipitation regimes play a key role in this component, as do other factors that are highly dependent on temperature, such as snowmelt and soil moistening/drying. Uncertainties related to these natural aspects will inevitably affect the evaluation of flood occurrence through its magnitude and frequency. The other component subjected to the uncertainty of meteorological scenarios is the distribution of water storage in reservoirs. This determines the loads a dam is subjected to at the moment of flood arrival, which influences its safety level (SPANCOLD 2012). Surface water availability is expected to fluctuate primarily from variability in precipitation (IPCC 2014) and evapotranspiration (Kingston et al. 2009; Seneviratne et al. 2010), which directly impacts reservoir water levels.

Besides natural uncertainty, the socio-economic dimension of climate change impacts must also be considered. For example, the evaluation of dam failure risks also includes the potential consequences downstream from the dam, which are directly related to the exposure and vulnerability of people, livelihoods, infrastructure, or assets in at-risk areas. The evolution of exposure is subjected to global socio-economic trends that are attributed to climatic drivers (Choi and Fischer 2003; Neumayer and Barthel 2011). Moreover, changes in freshwater needs, agricultural land use, water resource management strategies, and population growth are likely to modify the balance between water availability and supply, which then directly impact the reservoir water levels. However, such processes are still poorly known, and the unpredictability of future socio-economic scenarios also accentuates the uncertainty on the final consequences (Burke et al. 2011).

The aforementioned uncertainties influence the reliability of the results and the adopted adaptation strategies. This affects how decisions are made and the planning of long-term investments when future climatic conditions are only conjectured. However, while it is a challenging task, the incorporation of uncertainties must not prevent decisions from being made. Uncertainty should actually boost strategies that prevent the considered actions from being inadequate, inappropriate, or increase the vulnerability (Street and Nilsson 2014). When uncertainty cannot be reduced through data collection, research, or improved modeling, the incorporation of uncertainty into the decision-making process represents a suitable option (Schneider 2003).

In the context of climate adaptation in policy making, relevant approaches include adaptive policy making (Walker et al. 2013, 2001), adaptation pathways (Haasnoot et al. 2012), or real options analysis (Gersonius et al. 2012; Park et al. 2014). In addition, there are several other methodologies, tools, and techniques to handle uncertainties in general. A few examples are scenario planning (Swart et al. 2004), Monte Carlo analysis (Zhang and Babovic 2012), multi-layer decision analysis (Harvey et al. 2012), and safety margin strategies (Hallegatte 2009).

In this work, the treatment of climate uncertainty in adaptation decision-making relies on a combination of expected utility theory and a multi-prior approach, based on Cost-benefit analysis (CBA) techniques.

5.3 A decision-making approach incorporating climate change uncertainty

The approach proposed in this paper is called *Multi-Prior Weighted Scenarios Ranking* (MPWSR). It tries to overcome the above-mentioned limitations in the assignation of scenario probabilities by simultaneously using multiple probability configurations, which leads to lessen the sensitivity and increase the robustness of the results. The methodology is based on robust decision-making strategies coupled with climate scenario likelihoods where each climate projection is associated with a probability, even if it is only subjective. The ultimate results or recommendations are expressed in the form of a ranking of measures associated with a certain degree of confidence (or uncertainty). Thus, a 6-step iterative strategy is proposed in this paper to apply robust decision-making for dam risk management under climate change uncertainty (see Figure 5-2). When repeated, this approach ultimately allows identifying the most favorable sequence of implementable risk reduction measures.

5.3.1 Risk estimation for current and future situations

The first step of the proposed decision-making approach is to estimate risk for the current situation and its evolution with time. In this context, risk can be defined as the combination of three concepts: what can happen (dam failure), how likely it is to happen (failure probability), and what its consequences are (failure consequences including but not limited to economic damage and loss of life) (Kaplan 1997). Therefore, risk can be obtained through the following formula:

$$risk = \sum_{e} p(e) \cdot p(f|e) \cdot C(f|e) \tag{5.1}$$

where the summation is defined over all events *e* under the study, risk is expressed in consequences per year (social or economic), *p(e)* is the probability of an event that causes failure, *p(f|e)* is the probability of failure due to event *e* and *C(f|e)* are the consequences produced as a result of each failure *f* and event *e*. For simplicity, it is suggested to calculate future risks for a select number of time horizons and then interpolate between them for arbitrary times within the analysis period.

Risk models are the basic tool to quantitatively assess risk and integrate and connect most variables concerning dam safety (Ardiles et al. 2011; Bowles et al. 2013b; Serrano-Lombillo et al. 2012a). By applying such techniques, Fluixá-Sanmartín et al. (2018, 2019c) confirmed that changes in climate, such as variations in extreme temperatures or the frequency of heavy precipitation events (IPCC 2012; Walsh et al. 2014), are likely to affect the different components that drive dam risks. These works provide theoretical and practical guidance on the use of risk models to calculate the evolution of dam risks under this approach.

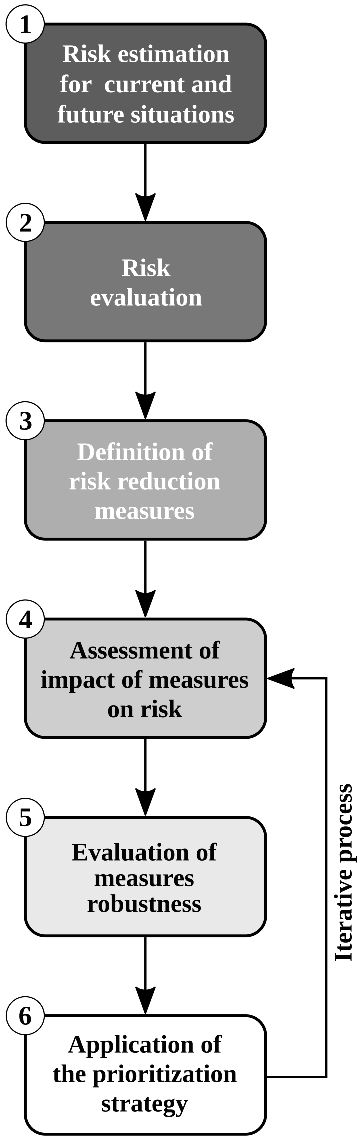

Figure 5-2. *Flow diagram of the decision-making strategy.*

5.3.2 Risk evaluation

Risks must be evaluated after they are calculated for current and future scenarios. That allows assessing whether a risk is tolerable and eventually justifies the proposal and implementation of the risk reduction measures. Judgments and tolerable risk thresholds are introduced in the process (ICOLD 2005), and risk is generally classified as either unacceptable, tolerable, or broadly acceptable (HSE 2001). Different organizations have proposed risk tolerability recommendations to evaluate whether dam risk levels are tolerable or not (ANCOLD 2003; SPANCOLD 2012; USACE 2011a; USBR 2011).

It is assumed that risks are likely to evolve with time primarily due to climate change impacts; thus, the results from risk evaluation evolve as well. Under such circumstances, it is convenient to compare the present and future situations of a dam in terms of its risk evaluation. The different combinations of dam evaluation cases based on present and future risks are proposed as presented in Table 5-1. This may help identify the sensitivity of dam failure risks to climate change. The more the dam risk tolerability changes between present and future conditions, the more the dam is susceptible to climate change impacts.

Table 5-1. *Different dam evaluation cases based on present and future risks.*

		Present risk		
		Broadly acceptable	Tolerable	Unacceptable
Future risk	Broadly acceptable	I	II	III
	Tolerable	IV	V	VI
	Unacceptable	VII	VIII	IX

5.3.3 Definition of potential risk reduction measures

The previous step defines the convenience of adopting a certain risk reduction strategy. A set of potential risk reduction measures is proposed based on the tolerability scenarios for the computed present and future risks. However, depending on the resulting classification of the dam from Section 5.3.2, measures that are justifiable in the present may not be necessary in the future (e.g., class III in Table 5-1) and vice versa (e.g., class VII). This greatly affects not only the type of measures to be applied but also the decision time horizon. This horizon is the upper limit of the time interval during which the investment is to be justifiably financed (Lind 2007). This implies that some measures will only be justifiable for long-term operations.

Moreover, under the uncertainties imposed by climate change scenarios, envisioned risk adaptation measures must fit the so-called robust approaches. This may help design more robust measures (i.e., no/low regret options) and discard those that do not perform well for different climate scenarios (Noble et al. 2014). The design of adopted measures depends on different factors, which include:

- Risk conditions in the present/future situations
- Decision time horizon
- Implementation and operation costs of each measure

- Availability of funds
- Expected lifetime of the dam
- Technical feasibility of the measure in the long term
- Socio-environmental factors.

Risk analysis techniques rely on the efficiency of measures to optimally reduce dam risks, which creates options that reduce risk at the lowest cost. To assess such an efficiency, the effects of implementing these measures on the risks must be evaluated, not only in the short term but also for the future. This is usually performed by applying the principles of cost-benefit analyses where the total expected cost of each measure is compared with their total expected benefit (Baecher et al. 1980; Palmieri et al. 2001), which is in terms of risk reduction here. Different indicators can be used to evaluate dam risk reduction measures, including social and/or economic terms for the risks (ANCOLD 2003; Bowles 2000, 2004; Serrano-Lombillo et al. 2013). In general, the measure that reduces the risk with the lowest cost consequently presents the highest efficiency will be prioritized, which is the measure with the lowest indicator value.

Fluixá-Sanmartín et al. (2020) presented a methodology to assess the effects of risk reduction measures in the long term using a proposed risk reduction indicator called the aggregated adjusted cost per statistical life saved (AACSLS). The AACSLS indicator is used to calculate the total cost of a statistical life saved over a given period to evaluate the long-term efficiency of the risk reduction strategy. The prioritization of risk reduction measures can then be defined using this indicator.

5.3.4 Evaluation of measures robustness

5.3.4.1 Considerations

In contrast with traditional decision analyses seeking strategies that perform best for a fixed set of assumptions about the future, under robust decision-making approaches the prioritized measures must perform well under a wide range of scenarios (Lempert et al. 2003). This work proposes applying the expected utility theory (von Neumann and Morgenstern 1944; Ramsey 1926; Savage 1972) combined with multi-prior approach to assess the robustness of measures and apply it to dam safety management.

Based on the expected utility theory, preference for a set of alternatives can be established using a quantitative valuation of their utility, which can be estimated as the sum of the utility of outcomes multiplied by their respective probabilities (Davis et al. 1998). The alternative with the highest expected utility should then be selected. In this case, each outcome measures the efficiency of a risk reduction measure under an expected climate scenario, and the respective probability designates the likelihood of such a scenario. Therefore, applying this method requires quantifying the outcome that results from implementing a specific measure and to assign probabilities to each climate scenario.

Despite the difficulty of finding quantitative methods to assess the preferences among different adaptive strategies (Lempert et al. 2006), risk reduction indicators in the context of dam safety can be used as they quantify the efficiency of each alternative (measure) envisioned. This paper proposes using the AACSLS to quantify the utility of each risk reduction measure under a certain future climate scenario; the core of the proposed methodology will therefore rely on a Cost-benefit analysis (CBA) approach.

It is necessary to determine which configuration(s) of probabilities are used to evaluate the adaptation measure suitability while also defining the likelihood of each projection. A practical methodology based on multi-prior approach is proposed in this work to lessen the sensitivity and increase the robustness of the process by performing simulations under different configurations. Such a methodology includes two levels.

First is the generation of a scheme of weighted probabilities configurations, each one describing the plausibility of the climate future, defined in a prior level or hyperprior. For each configuration, the different future states (in our case, the climate projections) are assumed having different probabilities of occurrence. The definition of these configurations thus depends on the knowledge of the climate system and the modelled projections.

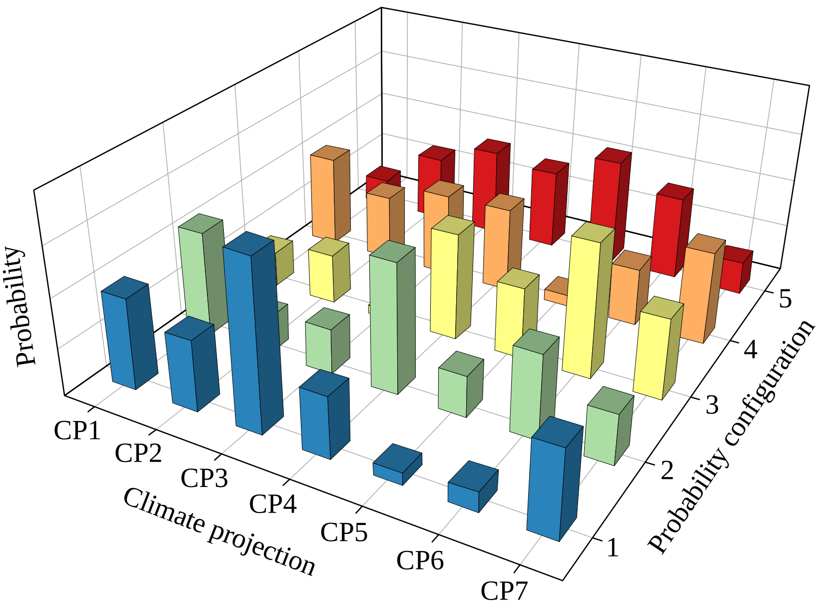

Figure 5-3. *Example of probability configurations (1 to 5) for different climate projections (CP1 to CP7).*

Second is to generate the probabilities assigned to each projection and for each configuration. The resulting ensemble of configurations are presented in the form of modulated probabilities, as shown in Figure 5-3.

5.3.4.2 Procedure

Suppose we have N risk reduction measures and P climate scenarios. The process to define the robustness of this set of measures is repeated M times using the following steps:

a) Calculate the AACSLS indicator (noted $x_{j,k}$) of each risk reduction measure j and for each climate scenario k.

b) Generate a configuration of probabilities p_k associated with each climate scenario k, verifying that:

$$\sum_{k=1}^{P} p_k = 1 \tag{5.2}$$

The ensemble of probabilities can be generated or modulated based on one of the scenario weighting schemes presented in Section 5.3.4.3.

c) Calculate the expected utility $E[u(x_j)]$ of each measure j as the weighted average of all possible outcomes of such a measure under the different envisioned scenarios. This is expressed as the sum of the products of probabilities (weights) and utilities (AACSLS values) over all possible scenarios as:

$$E[u(x_j)] = \sum_{k=1}^{P} (p_k \cdot x_{j,k}) \tag{5.3}$$

d) Rank the measures according to their expected utility. In expected utility theory, preferred actions are those that present a higher utility; however, the AACSLS presents lower values for more efficient options. Therefore, when applying this approach, the criterion to be followed in the expected utility formula is applied inversely and the measure with the lowest $E[u(x_j)]$ is prioritized. Thus, for each configuration, the M measures have the expected utilities $E[u(x_1)], E[u(x_2)], \ldots, E[u(x_N)]$ and associated prioritization order (PO).

e) Repeat M times steps b) to d), where probabilities p_k are redefined. At each repetition of the process, we assume a different plausibility of the climate futures projected.

The results are expressed in the form of a matrix with M rows and N columns, which define the ranking or priority order $PO_{i,j}$ of the N measures for each probability configuration (Table 5-2). Once this matrix is built, a prioritization strategy must be performed to define the most suitable measure.

Table 5-2. *Priority orders of the N risk reduction measures for each probability configuration.*

Probability configuration	Measures			
	1	2	…	N
1	$PO_{1,1}$	$PO_{1,2}$	…	$PO_{1,N}$
2	$PO_{2,1}$	$PO_{2,2}$	…	$PO_{2,N}$
…	…	…	…	…
M	$PO_{M,1}$	$PO_{M,2}$	…	$PO_{M,N}$

5.3.4.3 Scenario weighting scheme

As defined in step b) of Section 5.3.4.2, each considered climate scenario k must be weighted according to its relative importance through an associated probability p_k. This step is repeated M times.

According to IPCC (2013), no probabilities have been attached to the alternative RCP scenarios (as was the case for SRES scenarios) and each of them should be considered plausible, as no study has questioned their technical feasibility. However, in some cases evidences might show that one or several models are not performing adequately (e.g., unrealistic models for mountain regions in Switzerland detected in CH2018 (2018)) or that a given ranking of such models is of application. In order to pertinently apply this information to the analysis, a weighting scheme can be envisaged, although some critical aspects must be taken into account when assessing climate change model results for such purposes (Knutti et al. 2010a).

The different weighting schemes proposed in this work to apply the multi-model combination approach are presented here as:

a) **Equal weights.** This is the simplest way to construct the multi-model, and it is assumed that all models and climate scenarios perform similarly. The projections are then considered as equiprobable (i.e., $p_1=p_2=...=p_P=1/P$ in Equation (5.3)). It has been demonstrated that on average, an equally weighted multi-model consistently outperforms single models (Knutti et al. 2010b; Weigel et al. 2010). In this case, unless the subset of projections varies among each probability configuration, the procedure described in Section 5.3.4.2 consists of a unique configuration, and Table 5-2 would contain only a single row. This option may be adequate when all climate scenarios are considered equally plausible, as suggested by IPCC (2013).

b) **Pure random weights.** In this case, probabilities are randomly generated while verifying that their sum is always equal to 1 (Equation (5.2)).

c) **Based on subjective criteria.** Weights can also be established based on subjective criteria, giving preference to those cases that better suit the objectives or conditions of the study. Such weighting can be done at the level of the Global/Regional climate models (GCMs/RCMs) and/or of the Representative Concentration Pathways (RCPs).

d) **Based on climate model performance.** There are different available techniques for model weighting based on multiple performance metrics. For example, Christensen et al. (2010) explored the applicability of combining a set of six performance metrics to produce one aggregated model weight. Giorgi and Mearns (2002) weighted the results from an ensemble of GCMs based on two criteria: 1) the skill with which an individual model reproduces historic climate change, and 2) the extent to which the projections of an individual model converge to the ensemble mean. However, as stated in Weigel et al. (2010), if the weights do not appropriately represent the true underlying uncertainties, weighted multi-models may perform worse than equally weighted approaches.

Such schemes can be applied to the entire ensemble of available climate projections or to a subset of them. This is true when one of the several projections are not reliable or when they are ill-suited for the study case. The subset of projections itself may even vary between each repetition (step (**e**) in the Section 5.3.4.2).

A particular case of ensemble subsetting is presented when a single climate projection is used, although this does not correspond *stricto sensu* with a robust decision-making approach. This may be true when only one climate projection is available, or when the objective is to plan risk adaptation based on the worst-case scenario, i.e., choosing the projection that presents the highest risk. However, this approach is not recommended because it may lead to an unrealistic scenario. In addition, it is not always simple or automatic to identify the worst-case climatic model, and the concept of highest risk varies because the risk can evolve with time (Fluixá-Sanmartín et al. 2019c).

5.3.5 Definition of prioritization strategy

When applying the expected utility theory to a specific probability configuration, the alternatives with the highest utility value (or lowest AACSLS, in this case) should be prioritized. However, the results from previous steps are given in the form of a table with multiple probability configurations and multiple classifications of alternatives or rankings (Table 5-2). A prioritization strategy that considers such diverse results is therefore needed. Four approaches are proposed in this paper: (i) average ranking, (ii) likelihood of rankings, (iii) index of ranking coincidence, and (iv) consensus ranking.

5.3.5.1 Average ranking

The simplest approach is to assess the preferences of each measure based on its average priority order from the corresponding row in Table 5-2. That is, the final priority order PO_j of each measure j among the M probabilities configurations is defined as:

$$PO_j = \sum_{i=1}^{M}(PO_{i,j}) \Big/ M \tag{5.4}$$

The measure with the lowest final PO value is then prioritized, which is equivalent to averaging the rankings and then ranking the averages. Although simple in application, this approach may underestimate the possible non-linearities due to the sequential application of risk reduction measures. To increase its robustness, this methodology should be complemented with the use of additional descriptive statistics (e.g., median, mode, and standard deviation of the $PO_{i,j}$) as well as with descriptive graphics (e.g., boxplots) to detect possible dispersion in the results.

5.3.5.2 Likelihood of rankings

This technique consists of assigning a probability to a certain ranking depending on how many times the ranking is repeated across the columns of Table 5-2. First, all plausible rankings of the measures are identified by removing duplicates from Table 5-2. Then, the frequency of coincidences for each ranking is calculated as the number of times it is repeated divided by the total number M of tested probability configurations. Finally, the scale proposed by Mastrandrea et al. (2010) is used to sort the rankings by their rate of recurrence and to classify them by their probability or likelihood of suitability (Table 5-3). The ranking with highest preference is selected.

By considering each ranking independently, this method cannot capture the similarity of ranking pairs. For example, among the following prioritization rankings, A and B (where alternatives 2 and 1 are the most suitable) are much more similar than ranking C. However, each ranking is treated as a separate entity without correlation with the others. This ineffectiveness is reduced when testing more probability configurations.

- **Ranking A**: 2, 1, 4, 5, 3
- **Ranking B**: 2, 1, 5, 4, 3
- **Ranking C**: 5, 4, 3, 1, 2

Table 5-3. *Classification of the ranking preference according to their frequency.*

Frequency of ranking	Preference of ranking
>99%	Exceptionally high
90% - 99%	Very high
60% - 90%	High
33% - 66%	About as preferable as not
10% - 33%	Low
1% - 10%	Very low
0% - 1%	Exceptionally low

5.3.5.3 Index of ranking coincidence

Morales-Torres et al. (2019) proposed a methodology to consider epistemic uncertainty for risk-informed management. They developed an index of coincidence to measure the effects of uncertainty when calculating the prioritization sequences. The index quantifies differences in the order of measures between each sequence issued from the results of a second-order probabilistic risk analysis and the reference sequence obtained from the averages of the first-order risk analysis.

Therefore, a new index is proposed in this work to obtain the likelihood of an ensemble of rankings for measures with respect to a series of reference rankings. The index of ranking coincidence (IRC) is expressed as:

$$IRC = \frac{\sum_{i=1}^{M}\left(\sum_{j=1}^{N}\left(1-\frac{\left|PO_j^{(r)}-PO_{i,j}\right|}{max\left(PO_j^{(r)}-1, N-PO_j^{(r)}\right)}\right)\right)}{M \cdot N} \tag{5.5}$$

where M is the number of probability configurations tested, N is the number of proposed measures, $PO_j^{(r)}$ is the priority order of measure j in the reference ranking, and $PO_{i,j}$ is the priority order of measure j in the ranking from probability configuration i. It is noted that the expression $max\left(PO_j^{(r)}-1, N-PO_j^{(r)}\right)$ represents the maximum possible distance between the priority orders of the reference and the compared rankings.

The proposed procedure based on this index is as follows:

- Extract the *N!* permutations without repetition of the *N* envisioned measures.

- Consider each permutation as a reference ranking to calculate the IRC compared with the rest of the *M* rankings.
- The ranking presenting the highest IRC is adopted.

5.3.5.4 Consensus ranking

A more complex approach consists of applying consensus ranking analyses. The resulting prioritization matrix given in Table 5-2 represents a set of *M* ordinal rankings of *N* risk reduction measures. The goal is to define a consensus ranking that presents the maximum degree of consensus within the *M* rankings. This technique has received growing consideration over the past few years and has been widely used in a variety of domains (Leyva López and Alvarez Carrillo 2015; Luo et al. 2018; Meila et al. 2012; Plaia et al. 2019).

The procedure consists primarily of two stages. First, the agreement between rankings needs to be quantified, which can be achieved through dissimilarity or distance measures between the rankings. The most common measures are those related to distances or correlations. The measures related to distances evaluate the distance between any two elements in the set of *N* ordered objects (Farnoud Hassanzadeh and Milenkovic 2014). Rank correlation coefficients measure the degree of similarity between two rankings by associating a value of +1 to those in full agreement and -1 to those in full disagreement (and all others in between). A large assortment of methods can be used to accomplish this (Kendall and Gibbons 1990). Typical examples of metrics in this framework are Spearman's ρ and Kendall's τ (Kendall 1938) rank correlation coefficients. Spearman's ρ is the sum of square differences in the ranks at which items appear, while Kendall's τ is based on the concept of measuring the minimum number of interchanges for adjacent ranked objects as required to transform one ranking into the other. However, other metrics, such as the Kemeny distance (Kemeny and Snell 1962) or the τ_x of Emond and Mason (Emond and Mason 2002), have been developed to solve different limitations of common methods.

Second, the agreements among rankings must then be combined to identify a compromise or a consensus. The objective is to select the ranking that maximizes the average correlation with (or, equivalently, minimizes the average distance to) the *M* rankings. Different strategies and algorithms can be used for complex problems (Amodio et al. 2016; Emond and Mason 2002).

In the context of the proposed prioritization strategy and similar to the previous strategy, the suggested approach includes:

- Extract the *N!* permutations without repetition of the *N* envisioned measures.
- For each permutation, measure the agreement with the remaining *M* rankings using one of the available metrics.

- Choose the combination that verifies the defined consensus criteria.

5.3.6 Identification of sequence of implementation

The proposed approach is an iterative process that must be repeated (steps 2 to 6 in Figure 5-2) until the sequence of implementation for all measures is obtained. In its first iteration, the entire set of risk reduction measures is ranked from best- to worst-suited based on their efficiency, and the best measure is selected as the first to be implemented. At each new iteration, the new base state is defined from the previous implemented measures and the effects of the remaining proposed measures are analyzed. The process is applied again, but to the set of measures not including the ones selected from the previous iterations. A sequence of measures is finally obtained after this process is consecutively followed. Hence, the procedure does not intend to choose between different alternatives but prioritizes them by assuming that sufficient time and resources would allow all of them to be implemented. Although the final sequence may not be systematically the optimal option, it is intended to be the most agreed not only among all the climate projections but across the different probability configurations.

For each iteration, the decision time horizon and the time of implementation of the measures must be re-assessed based on the efficiency of the previous measures and on other factors such as the remaining funding capacity or the program of scheduled maintenance works.

5.4 Case study

The proposed methodology was applied to the case study of a Spanish dam from the Duero River Basin Authority. The Santa Teresa dam is a concrete gravity dam built in 1960 with a height of 60 m and a length of 517 m. The reservoir has a capacity of 496 hm^3 at its normal operating level and is bound by the Santa Teresa dam and a smaller auxiliary dike. The dam is equipped with a spillway regulated by five gates capable of relieving a total of 2,017 m^3/s with two bottom outlets each having a release capacity of 88 m^3/s.

The effects of climate change on the failure risk of this dam through the end of the 21st century were assessed by Fluixá-Sanmartín et al. (2019c). It is worth mentioning that, although there may be other sources of uncertainty embodied in other risk components, in this assessment a first-order probabilistic analysis (Pate-Cornell 2002) for the structural response was carried out. This assumes a mean conditional failure probability for each loading state ($p(f|e)$ from Equation (5.1)), which allows us to focus on the influence of climate-related uncertainties.

An overall risk increase is expected based on most scenarios, which indicates significant risk uncertainty as given by the dispersion in the climate projection inputs. This highlights the difficulty of unequivocally defining recommendations for dam owners and managers on how to develop and implement risk reduction strategies. Such issues impose a need to address the associated uncertainty of climate modeling under a decision-making approach. Therefore, this approach was used to define a robust decision-making strategy for risk reduction under climate uncertainty based on the procedure displayed in Figure 5-2.

5.4.1 Risk estimation

The authors used in Fluixá-Sanmartín et al. (2019c) a risk model for the dam with the iPresas software (iPresas 2019) to compute the associated failure risks for current conditions and for future climate scenarios. This study integrated the various projected effects acting on each component of the risk and was based on existing data and models from different sources such as climate projections, historical hydro-meteorological data or the water resource management model. It is worth mentioning that the reservoir's exploitation rules were extracted from the current Hydrological Plan of the Duero River Basin (Confederación Hidrográfica del Duero 2015) and were adapted based on the expected population evolution in the study area. A complete description of the model and the methodology followed to obtain future risks can be found in Fluixá-Sanmartín et al. (2019c).

The analysis was applied using 21 climate projections (CPs) extracted from the World Climate Research Programme (WCRP) Coordinated Regional Downscaling Experiment (CORDEX) project (Giorgi et al. 2009) that encompassed three RCPs (RCP2.6, RCP4.5 and RCP8.5). This gave a total of 47 combinations of CPs and RCPs (Table 5-4).

The results were obtained over four periods (1970-2005; 2010-2039; 2040-2069; and 2070-2099), which were used as reference points (years 2005, 2039, 2069, and 2099, respectively) to interpolate the risk and failure probability for any given year. Accordingly, the evolution of risk for each CP–RCP combination through the end of the 21st century was calculated.

5.4.2 Risk evaluation

The USBR tolerability criteria (USBR 2011) was applied to determine the convenience of implementing mitigation measures. These tolerability guidelines were represented on an f-N graph where the vertical axis represents the failure probability and the horizontal axis represents the average life loss, which can be obtained by dividing the social risk by the failure probability.

Table 5-4. *List of climatic projections (CP) used in the case study showing the driving GCM, ensemble member, institute, and RCM for each where the RCP is available.*

ID	Driving GCM	Ensemble	Institute	RCM	RCP2.6	RCP4.5	RCP8.5
CP1	CNRM-CERFACS-CNRM-CM5	r1i1p1	CLMcom	CCLM4-8-17		x	x
CP2	CNRM-CERFACS-CNRM-CM5	r1i1p1	SMHI	RCA4		x	x
CP3	ICHEC-EC-EARTH	r12i1p1	CLMcom	CCLM4-8-17	x	x	x
CP4	ICHEC-EC-EARTH	r12i1p1	KNMI	RACMO22E	x	x	x
CP5	ICHEC-EC-EARTH	r12i1p1	SMHI	RCA4	x	x	x
CP6	ICHEC-EC-EARTH	r1i1p1	KNMI	RACMO22E		x	x
CP7	ICHEC-EC-EARTH	r3i1p1	DMI	HIRHAM5	x	x	x
CP8	IPSL-IPSL-CM5A-LR	r1i1p1	GERICS	REMO2015	x		
CP9	IPSL-IPSL-CM5A-MR	r1i1p1	IPSL-INERIS	WRF331F		x	x
CP10	IPSL-IPSL-CM5A-MR	r1i1p1	SMHI	RCA4		x	x
CP11	MOHC-HadGEM2-ES	r1i1p1	CLMcom	CCLM4-8-17		x	x
CP12	MOHC-HadGEM2-ES	r1i1p1	DMI	HIRHAM5			x
CP13	MOHC-HadGEM2-ES	r1i1p1	KNMI	RACMO22E	x	x	x
CP14	MOHC-HadGEM2-ES	r1i1p1	SMHI	RCA4	x	x	x
CP15	MPI-M-MPI-ESM-LR	r1i1p1	CLMcom	CCLM4-8-17		x	x
CP16	MPI-M-MPI-ESM-LR	r1i1p1	MPI-CSC	REMO2009	x	x	x
CP17	MPI-M-MPI-ESM-LR	r1i1p1	SMHI	RCA4	x	x	x
CP18	MPI-M-MPI-ESM-LR	r2i1p1	MPI-CSC	REMO2009	x	x	x
CP19	NCC-NorESM1-M	r1i1p1	DMI	HIRHAM5		x	x
CP20	NCC-NorESM1-M	r1i1p1	SMHI	RCA4			x
CP21	NOAA-GFDL-GFDL-ESM2G	r1i1p1	GERICS	REMO2015	x		

An initial limit was set at a failure probability of 10^{-4} years^{-1}, which is related to individual risk, public responsibility of the dam owner, and protecting the image of the organization. A second limit was set for social risk, suggesting a maximum of 10^{-3} lives/year. These limits define two areas. The upper (lower) area indicates that the risk reduction measures are more (less) justified when further from the limit lines. Moreover, a limit on consequences is placed on the value of 1,000 lives. If the risk is to the right of this line, risks should be evaluated carefully, ensuring the as-low-as-reasonably-practicable (ALARP) considerations are addressed. The ALARP suggest that tolerable risks should only be assumed if their reduction is impracticable or the cost of such reductions is disproportional to its safety gain.

Figure 5-4 presents the results corresponding to the year 2019 (present), which were calculated using linear interpolation of the risks for the four different periods described before. Each point represents the 2019 projected dam risk situation based on a certain CP-RCP combination. The USBR recommendations suggest that none of the cases indicate an urgent need for risk reduction measures.

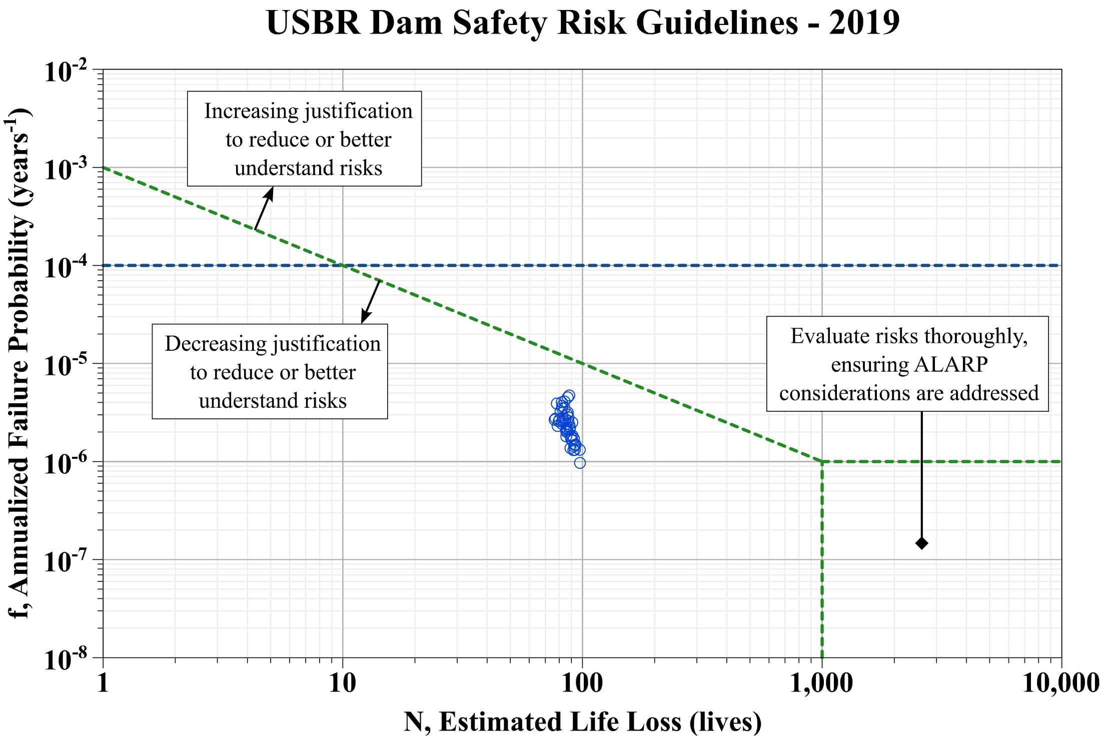

Figure 5-4. *USBR tolerability criteria and f-N points representing the estimated failure probability and loss of life based on the risk results for 2019 (present).*

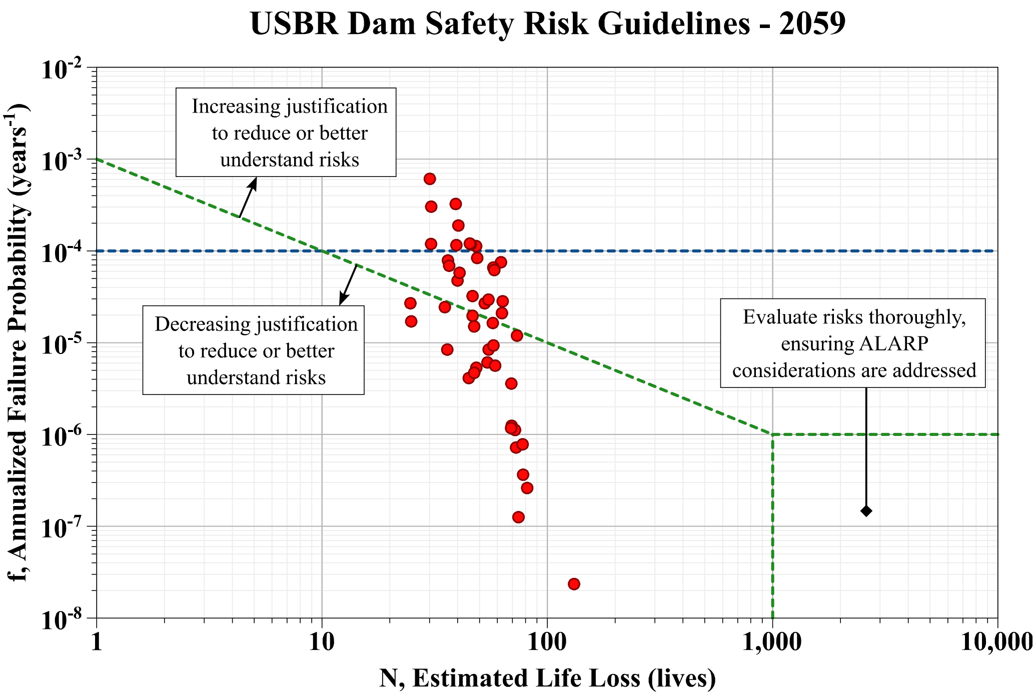

Figure 5-5. *USBR tolerability criteria and f-N points representing the estimated failure probability and loss of life based on the risk results for 2059.*

However, the results show a progressive deterioration of the dam risk conditions for most of the projections. For example, Figure 5-5 shows the risk in 2059 is confronted with the USBR tolerability criteria. As risk progresses with time, more cases are found to be above the tolerability limits. Therefore, the need for risk mitigation becomes progressively more important.

5.4.3 Definition of risk reduction measures

The results justify the implementation of risk reduction measures to address risk in the medium and long term. Four measures are proposed based on prior risk analyses performed on a set of dams from the Duero River Basin Authority (Ardiles et al. 2011; Morales-Torres et al. 2016) combining the recommendations of failure mode identification working sessions and the actions foreseen by the dam manager. Quantitative risk results were used to select the most efficient options for further analysis and prioritization. In addition, two measures (C and D) were designed selecting the most efficient configuration of wall height and spillway crest level by comparing its costs with the risk reduction achieved. A description of each measure is presented below, and the corresponding implementation and operation costs are provided in Table 5-5.

- **Measure A**: Implementation of an emergency action plan. This measure reduces the potential societal consequences of dam failure by applying adequate protocols and systems for warning and evacuating the downstream population. Measure A does not impact the failure probability or economic risk, but only affects social risk as it only addresses the exposure of at-risk populations.
- **Measure B**: Construction of a continuous concrete parapet wall with height of 1.5 m along the dam and the auxiliary saddle dam. The direct effect is an increased dam freeboard, which reduces the probability of overtopping.
- **Measure C**: Lowering the spillway crest level by 1.5 m and replacing the Tainter gates that regulate the outflows. This increases the discharge capacity through each gate from 403 m^3/s at its nominal operating level up to 588 m^3/s.
- **Measure D**: Implementation of an enhanced maintenance program for spillway gates. The gate reliability is assumed to progressively deteriorate with time. Under this measure, the individual reliabilities are conserved, which reduces future dam failure risks.

Table 5-5. *Implementation and maintenance costs for each risk reduction measure.*

Measure	Implementation cost	Operation cost (present value)
A	601,528.00 €	30,076.00 €/year
B	479,413.00 €	0 €/year
C	2,817,365.00 €	0 €/year
D	0 €	82,750.00 €/year

5.4.4 Estimation of the efficiency in risk reduction of each measure

The risk model was used to compute the evolution of social and economic risks through the end of the 21st century by considering the effects of each measure on the different dam safety components. This assesses the efficiency of each measure and for each future scenario by applying the AACSLS indicator (Fluixá-Sanmartín et al. 2020). One of the key factors in assessing the efficiency of each measure using the AACSLS is the definition of the decision time horizon, which is the upper limit of the time interval during which the investment is justifiably financed (Lind 2007). Given the age of the Santa Teresa dam and the functionality of the proposed risk reduction measures, the decision time horizon was set to 40 years. Thus, the study period is from 2019 (present) to 2059.

Once the indicator was computed, the four proposed risk reduction measures were ranked for each of the 47 CP-RCP combinations using only the AACSLS indicator (lower AACSLS values indicate more efficient options). Figure 5-6 shows the uncertainty behind the analysis as the number of combinations that lead to a specific priority order for each measure. As a result, it appears that Measure A is ranked primarily in the 2nd position and Measure D is in last position. However, it remains unclear what positions (1st and 3rd) occupy Measures B and C. This highlights the need for a more robust approach to define the sequence of measures to implement.

5.4.5 Multi-model combination

Next, the Multi-Prior Weighted Scenarios Ranking method was applied. The robustness of the four measures were first evaluated, and a total of 100 probability configurations were established. For each configuration, a set of 47 probabilities were generated and associated with each CP and RCP combination. The scenario weighting scheme was then used to produce purely random probabilities. Next, the expected utility of each measure *j* was calculated following Equation (5.3) to establish the measure ranking based on the increasing expected utility. For each probability configuration, the measures were prioritized and a table analogous to Table 5-2 was obtained from their prioritization orders.

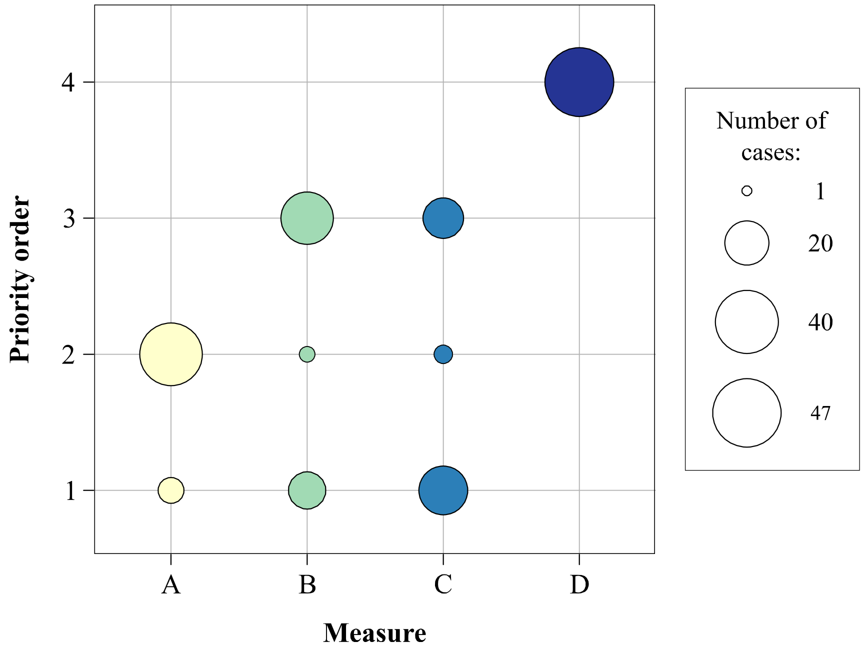

Figure 5-6. *Number of cases (CP-RCP combinations) leading to the priority order for each risk reduction measure.*

5.4.6 Prioritization strategy

Once the rankings were obtained for the 100 tested probability configurations, the four prioritization strategies were applied. These measures are the average ranking, likelihood of rankings, index of ranking coincidence, and consensus ranking (in this case, using the Spearman's ρ rank correlation coefficient to quantify the agreement between rankings).

5.4.7 Identification of the sequence of implementation

The procedure from steps 2 to 6 of Figure 5-2 has been sequentially applied to identify the optimal sequence of risk reduction measures. The procedure was repeated at each implementation step (i.e., considering each step as the case with the previous measures already implemented to analyze the effects of the remaining proposed measures) until the sequence of measures was finally obtained.

At each step of the implementation, the same prioritization ranking of measures was consistently obtained with all the tested methods, which highlights the robustness and high confidence of the choices made. It is noted that a waiting period of 2 years was fixed between each measure implementation to account for budget limitations and the completion of measures. Subsequent application of this procedure led to the following sequence of measure implementation (Table 5-6):

- 1st step: Measure B
- 2nd step: Measure A
- 3rd step: Measure C
- 4th step: Measure D

The homogeneity of the obtained results is in contrast with the uncertainty shown in Figure 5-6, which emphasizes the convenience of the proposed approach.

Moreover, the risks in 2059 (after the 40-years decision time horizon) resulting from the sequential implementation of the four measures were computed and are presented in Figure 5-7. Starting with the base case situation in 2059 (Figure 5-5), a progressive reduction in both the failure probability and life loss is observed as the measures are implemented. It is noted that some measures, such as B or C, reduce both the failure probability and the average consequences. However, as mentioned above, Measure A only reduces the societal consequences and does not impact the failure probability.

Furthermore, as the implementation of the measures progresses, progressively fewer cases are above the tolerability criteria. For example, after implementing Measure A, all cases are below the social risk limit of 10^{-3} lives/year. While this would imply that the implementation of further measures is no longer justified, risk is expected to continue to rise through the end of the 21st century. Therefore, the measures that may not be entirely justified for a specific period could be necessary when considering a wider time horizon.

It is noted that current USBR guidelines do not include the temporal dimension in their criteria, indicating they do not account for the influence of climate change. Therefore, a re-definition of such recommendations is worthwhile. After revising these criteria, the proposed methodology is re-defined or techniques to update its application are established.

Moreover, in order to assess the sensitivity of the results to the weighting scheme selected, the analysis has been repeated using the “Equal weights” scheme instead of purely random probabilities. In this case, the procedure consists of a unique configuration where all climate projections have equal probabilities. According to the results, the same sequence of measure implementation as in Table 5-6 has been obtained for the four proposed prioritization strategies.

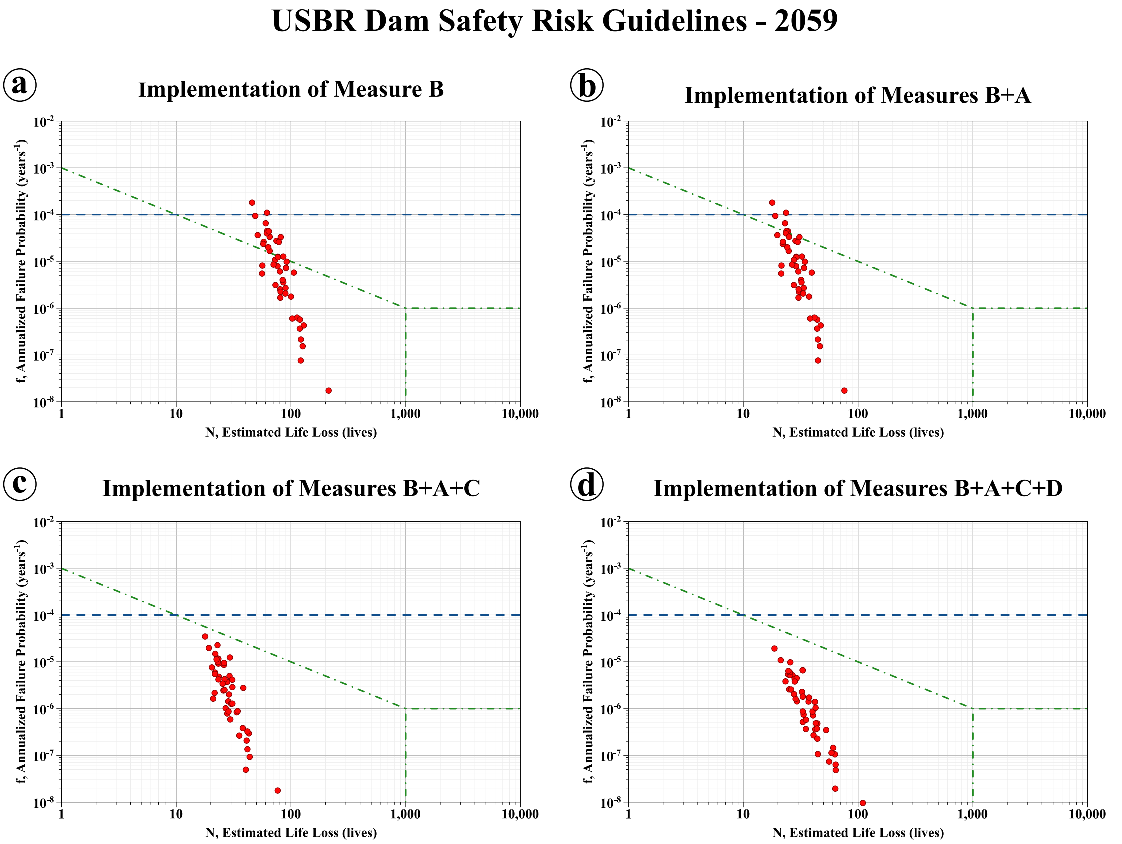

Figure 5-7. *Representation of the f-N points for the estimated failure probability and loss of life in 2059 after sequentially implementing (a) Measure B, (b) Measures B and A, (c) Measures B, A and C, and (d) Measures B, A, C and D.*

Table 5-6. *Order of implementation in the sequence of risk reduction measures based on each of the proposed prioritization strategies.*

Strategy	Measure			
	A	B	C	D
Average ranking	2	1	3	4
Likelihood of rankings	2	1	3	4
Index of ranking coincidence	2	1	3	4
Consensus ranking	2	1	3	4

5.5 Conclusions

Advances are being made towards adaptation approaches for dam risk management under the influence of climate change to help dam owners and safety practitioners in their decision-making processes. However, some factors remain a challenge and must be comprehensively integrated in such a process. In particular, further efforts that address the intrinsic uncertainties related to climate change are needed. This work presents an innovative approach on dealing with climate uncertainty applied to dam risk management based on robust decision-making strategies coupled with climate scenario probabilities assignation.

The proposed Multi-Prior Weighted Scenarios Ranking approach encompasses a complete procedure that allows defining and ranking risk reduction measures based on their efficiency on short- to long-term operations. The methodology helps to establish the consensus sequence of risk reduction measures to be implemented by integrating the uncertainty of future scenarios. It guides the dam practitioner in selecting the scenario weighting scheme as well as in defining the alternatives prioritization strategy, while introducing a new index (IRC) to obtain the likelihood of an ensemble of rankings for measures. The usefulness of the approach consists of aggregating multiple scenarios by applying and adapting the expected utility theory and the multiple priors approach, providing different results than simply considering a compilation of states. The final result will be expressed as the most agreed sequence of measures, not only among all the climate projections considered, but across the different probability configurations.

The developed methodology was applied to the case study of a Spanish dam for which the risks were quantified for present and future states using a quantitative risk model. The results revealed the need for mitigation measures to reduce risks in the medium and long term. Four risk reduction measures were proposed and their effects analyzed. Different prioritization strategies were tested and the resulting measure rankings were compared for each implementation step using the AACSLS indicator and a multi-model combination procedure. Finally, the most favorable sequence of measure implementations was obtained, which prioritizes those that reduce future accumulated risk at lower costs. The results indicate a homogeneous portrayal of the most convenient and agreed courses of action for risk adaptation. It was demonstrated that such a methodology helps to cope with uncertainty that arises from the existence of multiple climate scenarios while adopting a cost-benefit approach to help optimize economic resources in dam risk management.

Although climate change-related uncertainty was addressed in this work, other sources of uncertainty remain highly influential in dam risk assessment and should be integrated in a comprehensive approach for decision-making. Some of these include incomplete knowledge of the dam behavior (e.g., fragility curves) while others are affected by the intrinsic variability of climatic and environmental systems, or the effect of socioeconomic scenarios on the exploitation rules of the dam-reservoir system. Moreover, the assessment of climate change impacts on dam safety incorporates a series of limitations that remain a challenge, as raised in previous references of the authors (Fluixá-Sanmartín et al. 2018, 2019c, 2020). This type of strategies would therefore benefit from complete analyses combining all sources of uncertainty, thus helping support decisions based on all of them altogether. Under this perspective, the advantage of using the risk modelling approach is that the impact of all types of uncertainties on each component of the risk can be easily identified and analyzed, taking into account their potential interrelations.

Chapter 6

Results and discussion

This thesis arises from the need to define robust strategies for dam safety management in the face of the future climate effects. The state-of-the-art review on dam safety adaptation to climate change has revealed different challenges:

1. The complexity of structuring and quantitatively assessing the overall impact of climate change on dam safety, given the multidisciplinary nature of climatic and non-climatic effects and their interdependencies.
2. The mutable nature of dam risks subjected to the effect of climate change and the convenience of approaching decision-making from a time-dependent perspective.
3. The inherent uncertainty of climate projections and its impact on the process of decision-making.

A comprehensive approach based on the risk analysis framework is proposed to incorporate climate change to dam risk management, from the treatment of the risk estimation until the identification of sequence of implementation of adaptation measures. The thesis is structured according to three axes to tackle the above-mentioned challenges.

6.1 Quantification of multidisciplinary impacts

Identification and structuring of impacts

First, an approach to quantify the impacts of climate change on dam safety must be defined. Since climate change is likely to affect the different factors of dam failure risk, its impacts have to be assessed through the integration of the various effects acting on each component, considering their interdependencies. However, the information needed to assess climate change effects of each safety aspect is often vast and complex to integrate. In light of this situation, performing an analysis without a proper guidance can be unaffordable and induce to inefficiencies or conceptual errors. Therefore, the risk analysis framework is chosen for the identification and the quantitative assessment of such impacts and their evolution with time.

A multidisciplinary review of the potential impacts of climate change on dam safety has been performed attending to both climatic and non-climatic drivers and is presented in Chapter 2. This includes a catalogue of methodologies and techniques to help assess these impacts (Table 2-2). Since it is not always advisable to perform analyses with a high level of detail, these are based on the scope of the analysis and the availability of data. The review follows the structure of dam risk models, which allows incorporating and connecting the different components of the risk: *Loads of the system*, *System response* and *Consequences*.

Under this framework, the analysis can be performed in a comprehensive way, evaluating the total risk and the climate change impacts as well as their evolution over time. Since all the risk components are jointly evaluated, we avoid neglecting certain factors that affect the global safety. Moreover, it is also possible to determine the contribution of each dam safety component to the overall risk impact, therefore highlighting which is more susceptible to climate change or has more influence in the final risk level.

It is worth mentioning that the review focuses on the impacts of climate change under a hydrological scenario, which means that floods are the main load component to which the dam-reservoir system is subjected.

Calculation of climate change effects

Once the different climate change effects are identified, risk models can be used to quantify the resulting risk at present situation and for different time horizons in the future (Step 2* of Figure 1-2). Quantifying risks allows:

- Comparing the risk under the current climate scenario and under one or several future scenarios. This helps to evaluate the vulnerability of the dam to climate change, i.e. the additional risk imposed by climate change effects. It justifies whether specific adaptation approaches should be conducted or whether the risk level of a dam is not substantially different from the current situation and no update is required.

- Determining the contribution of each dam safety component to the overall risk impact, therefore highlighting which is more susceptible to climate change or has more influence in the final risk level.
- Comparing the future dam risk under different climate scenarios for adaptation and decision-making support on climate mitigation. Assessing the different ways in which risk may evolve in the future helps to define flexible measures that can be implemented adaptively, hence increasing the effectiveness and robustness of investments.

A methodology has been proposed to select, process and integrate the different sources of information into the dam risk models. This is based on the following main steps:

- Extraction and correction of climate projections (downscaling and bias-correction) to obtain high-resolution climate scenarios.
- Hydrological modelling to obtain the probability distribution of the previous pool levels and to calculate the flood hydrographs.
- Risk modelling to assess climate change impacts on dam failure risk.
- Adjustment of resulting risks to consistently assess and compare the modelled risks.

This methodology has been successfully applied to quantify the climate change impacts on the risk of the Santa Teresa dam (Spain) until the end of the 21st century under hydrological scenarios. This study case and its results are described in Chapter 3.

The analysis required integrating existing data from different sources in a multi-model framework. In particular, 47 combinations of climate projections (CPs) and Representative Concentration Pathways (RCP2.6, RCP4.5 and RCP8.5) were treated and adapted for the study case. Moreover, a hydrometeorological model was elaborated to simulate the hydrological response of the basin to present and future climatic conditions. Finally, the existing risk model of the Santa Teresa dam was adapted to incorporate the climate change impacts on the most relevant risk components: previous pool levels in the reservoir, outlet works reliability, floods entering the reservoir and social consequences used to compute the social risk.

The social and economic risks were calculated for the present situation and for all the CP-RCP combinations. For the present situation, the failure probability is 2.91×10^{-6}/year, while the social and economic risks are 2.56×10^{-4} lives/year and 7.53×10^{-4} M€/year respectively. In general, the results indicate that in most future scenarios a deterioration of both the social and economic risks occurs, in comparison to the present risk level (Figure 3-11 and Figure 3-12). The use of a risk model allowed decomposing the resulting risks in its associated probability of failure and average consequences: most cases indicate a reduction in the average consequences as well as an increase of the probability of failure of the dam.

Moreover, the contribution of each risk component (*Previous pool level*, *Gate performance*, *Floods* and *Social consequences*) in the final risk was studied (Figure 3-13). According to the results, the effects of climate change on the dam failure risk are mainly explained by the changes in the flood loads and the changes in the reservoir water levels regime. Higher hydrological loads are expected over time, thus increasing the failure risk of the dam. Regarding the previous pool level component, as the emission scenario worsens (from RCP2.6 to RCP8.5) the discharge contributions and especially the higher evapotranspiration related to the increase of temperatures are expected to reduce the water levels in the reservoir, which will ultimately lead to a lower risk for the RCP8.5 scenario compared to the RCP2.6 scenario.

The use of a dam risk model and the application of the proposed methodology allow integrating the expected effects of climate change to obtain the overall dam failure risk, representing a key tool for dam managers and technicians. Without the use of these models, the evaluation of the contribution of each dam risk component aspect could not be possible.

This study case analysis has provided valuable new information with respect to previous dam risk studies, mainly regarding the contribution of each risk component to the total risk, and the sensitivity of the model to certain aspects (e.g., the meteorological input data or the climate scenarios).

Results and uncertainty

From the study case carried out, the uncertainty of the results can be characterized. Although a general increase of the risk can be extracted from the analysis, results present a significant uncertainty given by the dispersion of climate projections. The span of dam failure probabilities issued from the climate projections encompasses 4 to 5 magnitude orders (from the current situation) until the end of the 21st century. Similar ranges are found for social and economic risks.

In addition to the influence of future climate scenarios, a sensitivity analysis was performed to assess the uncertainty related to the statistical distribution used to extrapolate the maximum daily precipitations. The analysis, applied to the present meteorological data series used, showed a significant sensitivity of risks to the meteorological modelling, and in particular to the statistical distribution fitting used to obtain maximum daily precipitations (Figure 3-15). The obtained failure probabilities ranged from 3×10^{-7}/year to 3×10^{-5}/year, that is two magnitude orders. Compared to the one associated with future climate (4-5 magnitude orders), the uncertainty from the treatment of meteorological records represents a substantial source of uncertainty.

This illustrates how data uncertainty can affect final risk results, and therefore make it difficult to directly define unequivocal recommendations. Incorporating other sources of uncertainty (e.g., hydrological modelling or population projections) could increase the dispersion of results on which decision must be made.

In particular, uncertainties related to the accuracy and post-processing (downscaling, bias-correction, etc.) of climate information need to be analyzed and compared to the rest of the uncertainty sources. Based on the results of such an analysis, one might wonder whether focusing on hydrological studies for future climate or on updating hydrological studies with recent field data. Indeed, investing in hydrological and hydraulic models when no adequate data is available to calibrate and validate them could lead to poor performance and model errors. Therefore, the continuous collection and treatment of meteorological and hydrometrical data should be considered among the mitigation measures in order to reduce the associated uncertainty. This would lead dam operators and authorities to invest in updated hydrological studies, based on continuously extended meteorological and hydrometric time series.

6.2 Managing time-dependent effects

Importance of changing risks

Different consequences for dam safety management have been identified due to the mutable nature of risks due to the effects of climate change.

Firstly, the classification of a dam according to its safety level may vary from the present situation to future scenarios. Indeed, once the risk has been quantified, its importance must be evaluated to determine whether mitigation measures are required. Risk tolerability recommendations from different organizations (ANCOLD 2003; USACE 2011a; USBR 2011) establish the criteria to classify them as unacceptable, tolerable or broadly acceptable. Based on this classification, risk reduction measures can be proposed. But since risks are likely to evolve over time, the classification of a dam today may change in the future. For instance, a dam not presenting an urgent need for risk reduction measures at present time, may be subjected to a progressive deterioration and therefore the need for risk mitigation becomes progressively more important.

Secondly, the efficiency of adaptation measures may also change over time. In order to assess whether a measure is efficient and whether its implementation is justified, risk reduction indicators can be applied. They quantify each measure's efficiency based on its costs and the risk reduction it provides by applying the principles of cost–benefit analyses. This helps to optimize the existing resources and point at the most efficient ways of using them. In general, the measure that reduces the risk at the lowest cost presents the highest efficiency and therefore will be prioritized. Therefore, it is necessary to assess the efficiency of a measure not only in the current situation, but also considering how risks will evolve once it has been applied. Risk indicators must be adapted to integrate the non-stationarity of risks.

In this thesis, risk is treated as a time-dependent concept and must be tackled under a new perspective. A new approach has been defined to incorporate the evolution of risk and evaluate the impact of each measure for a defined period, as presented in Chapter 4.

Definition of a new risk indicator

This approach includes the definition of a new risk reduction indicator to consider time variability. The criterion on which such indicator is based consists of prioritizing those measures that present a higher efficiency in the risk reduction throughout a predefined period between the present time (year *0*) and a general time horizon (year *n*). The use of this risk reduction principle would prevent prioritizing measures that would no longer be necessary in the future or missing some measures that could efficiently reduce the future risk.

The new indicator defined is the Aggregated Adjusted Cost per Statistical Life Saved (AACSLS), which combines social and economic efficiency principles. The AACSLS indicator calculates the total cost of a statistical life saved during a given period. It is considered that measures may take a certain time to be fully implemented due to the duration of construction or administration processes among others, and that until completed they have no effects on the risk. For its formulation,

The use of the AACSLS indicator is framed within a procedure proposed in this work to evaluate risk and to assess the efficiency of the measures in the long term. This framework completes and improves the approach proposed in SPANCOLD (2012).

An important aspect to reflect in the application of the proposed procedure is the temporal horizon of the analysis (e.g., whether to use projections for 2030, 2050 or 2100). Short-term analyses (time horizons of less than 20 years) are more suitable to be matched to conventional planning time scales (Moss et al. 2008). However, a longer-term policy is preferable when we seek strategies for adaptation, mitigation, and development that are robust over the long term and able to cope with uncertainties. The expected lifetime of the dam or the projected investments also contributes to the choice of a time horizon (European Commission, 2011). For instance, newly constructed or in progress dams may require considering longer scenarios than obsolete ones.

Application to the study case

The application of the proposed methodology to the study case of the Santa Teresa dam has revealed useful to estimate the efficiency of risk reduction measures on the long-term compared with a static approach.

Based on the USBR tolerability criteria, the resulting risk corresponding to the present situation (Chapter 3) does not suggest an urgent need for risk reduction measures. However, the results show a progressive deterioration of the dam risk conditions over time. Therefore, the need for risk mitigation becomes progressively more important: four measures have been proposed to address risks in the mid and long term. These are based on the one hand on a previous quantitative risk analysis performed on several Spanish dams, and on the other hand on a study carried out by the author considering the expected climate change impacts.

Once the different risk reduction measures have been defined and their impact on the present and future risks quantified, it has been possible to evaluate their efficiency taking into account their annual maintenance and operation costs. For this, the AACSLS indicator has been calculated for the four measures proposed. Moreover, in order to assess the usefulness of applying the proposed methodology, the ACSLS indicator has been calculated as well considering that risk and failure probabilities do not evolve. This analysis has helped to obtain a ranking of the measures based on both indicators (i.e., the measure with the lowest value of the indicator is prioritized).

The ranking based on AACSLS has revealed what are the higher efficiencies on the long term, while the ranking based on ACSLS gives a short-term perspective. Without the application of the proposed approach, short-term efficient measures would have been prioritized over long-term efficient measures, lessening economic efficiency at the long-term. Moreover, the AACSLS present lower values than the ACSLS. This means that risk reduction measures are more justifiable economically when the risk evolution is taken into account.

It is worth noting that in this application to the study case, only one climate projection was used to assess the convenience of applying the proposed methodology. However, proceeding this way is not recommended because it may lead to an unrealistic scenario and consequently to suboptimal decisions. Integrating the uncertainty introduced by climate change scenarios is therefore of paramount importance to assess the impact on adaptation decisions. A more complete analysis has been performed incorporating all the climate projections available and is shown in Chapter 5.

Moreover, no accurate analysis of the availability of economic resources has been undertaken and a simple waiting period of 2 years between the implementation of each measure has been used for this study case. The problem is substantially more complex since the applicability of such measures depends on the financial planning of the funding agencies in terms of budget limitations and the construction schedule. This introduces a new dimension to the problem of long-term risk management that should be further addressed: how can financial planning be intersected with risk reduction needs to optimize economic resources?

Also, a deeper analysis could be performed to determine the optimal time for the implementation of each measure, since not all measures may be required as soon as possible. This could help to establish a more robust investment plan where measures would be applied when reaching their maximum efficiency instead of trying to make all decisions now. This way, some measures could be held off and even discarded as better information about climate change impact arises.

6.3 Incorporating climate change uncertainty

Definition of robust adaptation strategies under climate uncertainty

As discussed in Chapter 3, results from the quantification of climate change impacts on the risk of the Santa Teresa dam present a significant uncertainty related to the large range of climate scenarios. Although procedures can be established to deal with each climate projection individually and obtain the optimal implementation sequence of adaptation measures, response strategies that explicitly recognize climate-related uncertainties must be incorporated into the decision-making process under a comprehensive approach. The study of this problem has resulted in the development of a robust decision approach to select and prioritize measures that perform well over a very wide range of alternative futures. A description of this methodology is presented in Chapter 5.

Once a set of risk reduction measures is defined to increase the dam safety level on the short and the long term, the next step is the assessment of their efficiency to optimally reduce risks, which helps to prioritize those options that reduce risk at the lowest cost. In this thesis, it is proposed to perform this by applying the principles of Cost-benefit analyses (CBA) where the total expected cost of each measure is compared with their total expected benefit. In particular, the AACSLS indicator allows expressing the long-term efficiency of each measure in monetary terms. In general, the measure that reduces the risk with the lowest cost consequently presents the highest efficiency will be prioritized, which is the measure with the lowest indicator value.

The proposed approach is based on the expected utility framework, which uses scenario probabilities to characterize each measure's utility (i.e., its efficiency). However, under deep uncertainty no probabilities can be attached to the future climate scenarios and the adoption of a specific configuration of probabilities for the set of available climate projections remains a controversial topic that requires further development.

To overcome these difficulties, the so-called *Multi-Prior Weighted Scenarios Ranking* methodology has been developed in this thesis. This methodology, based on the multiple priors approach, helps to establish the consensus sequence of risk reduction measures to be implemented by integrating a wide range of climate scenarios and model results. The procedure of this methodology consists on:

- Generating a scheme of weighted probabilities configurations, each one describing a state of the climate future.
- Calculating the expected utility of each measure as the weighted average of all possible outcomes of such a measure under the different envisioned scenarios, and ranking the measures according to their expected utility for each configuration.
- Applying a prioritization strategy among those proposed in the description of the methodology that integrates the different rankings of measures.

The procedure must be sequentially applied considering the effect of the previously applied measures, until the sequence of implementation for all measures is obtained. The final sequence is intended to be the most agreed not only among all the climate projections but across the different probability configurations, thus lessening the sensitive of the results to the probability configuration assumed.

Case study results

The methodology has been applied to the study case of the Santa Teresa dam, but this time considering the entire range of available climate scenarios. Although the USBR tolerability recommendations do not suggest an urgent need for risk reduction measures at present situation, the evaluation of future risks affected by climate change indicates a progressive deterioration of the dam safety conditions for most of the projections. As risk progresses over time, more cases are found to be above these tolerability limits and therefore the need for risk mitigation becomes progressively more important. These results have revealed the need for mitigation measures to reduce risks in the medium and long term.

The efficiency of the same adaptation measures proposed above in reducing risks have been evaluated using the AACSLS indicator. Based on this, measures are ranked for each of the climate projection envisaged, firstly without applying any uncertainty treatment. Results have shown an important uncertainty in the implementation sequence that highlighted the need for a robust approach.

Afterwards, the Multi-Prior Weighted Scenarios Ranking method has been applied. The robustness of the four measures are first evaluated and ranked for a total of 100 probability configurations, and then a prioritization strategy is applied to obtain the optimal sequence of implementation. At each step of the implementation, the same prioritization ranking of measures has been consistently obtained with all the proposed ranking methods, which highlights the robustness and high confidence of the choices made. This contrasts with the uncertainty obtained in the first stage of the study.

Furthermore, as the implementation of the measures progresses risks tend to decrease until all of the cases are under the tolerability criteria used after the decision time horizon.

These results indicate a homogeneous portrayal of the most convenient and agreed courses of action for risk adaptation. It has been demonstrated that such a methodology helps to cope with uncertainty that arises from the existence of multiple climate scenarios while adopting a cost-benefit approach.

The way ahead in dealing with other uncertainties

Besides climate-related uncertainty, other sources of uncertainty remain highly influential. Some of these uncertainties include incomplete knowledge of the dam behavior (e.g., fragility curves) while others are affected by the intrinsic variability of climatic and environmental systems, or the effect of socioeconomic scenarios on the exploitation rules of the dam-reservoir system.

These should be integrated in a comprehensive approach for decision-making where there is not enough certainty to unambiguously establish the best solution. This type of strategies would therefore benefit from complete analyses combining all sources of uncertainty, helping support decisions based on all of them altogether. Under this perspective, the advantage of using the risk modelling approach is that the impact of all types of uncertainties on each component of the risk can be easily identified and analyzed, taking into account their potential interrelations.

6.4 Towards an adaptation strategy of dam safety management to climate change

The three challenges identified to incorporate climate change to dam safety governance have been addressed in this thesis through different contributions aiming at assessing climate-related impacts on dam risks, and defining and prioritizing robust risk reduction measures on the long term and in the context of climate uncertainty. However, the process in which these contributions will be integrated must not result in rigid pathways established at some point in time but rather ongoing assessment, action, reassessment, and response that will continue for decades, where each iteration learns from previous iterations (National Research Council 2010). These iterative adaptation strategies are widely used in the risk management industry (ISO 2018) facilitating continual improvement and enhancement of the approaches. Adopting plans that can adapt to changing conditions is well suited to situations involving deep uncertainty such as that imposed by climate change.

Recent efforts have been undertaken (Haasnoot et al. 2013; National Research Council 2010; Ranger et al. 2013; Willows and Connell 2003; Wise et al. 2014) to develop and integrate these dynamic decision-oriented approaches to climate change adaptation. These initiatives are mainly framed within the "pathways" approach as they seek exploring and sequencing a set of possible actions based on alternative external, uncertain developments over time. They help to adopt sound policy related to climate change because of the opportunities it offers for considering uncertainty and adjusting decisions to experience and new information.

In dam risk management the update and review are already integrated in the adaptation process when the conditions of the dam evolve (e.g., after the implementation of certain mitigation measures) or when new information is available (SPANCOLD 2012). Therefore, it would be relatively straightforward to incorporate the specificities of climate change to this decision-making framework, by acknowledging the challenges and particularities of the dam safety context.

As presented in Chapter 1, the overall approach proposed in this thesis is conceived as an adaptive process leading to a dynamic robust plan (Walker et al. 2013) and structured as follows:

A) State-of-the-art dam safety and climate information are extracted and treated to compute the current and future risks of the dam following the methods and procedures proposed in Chapter 2 and Chapter 3 of this thesis.

B) Based on the resulting risks, the safety level of the dam is evaluated by using tolerability criteria. This step defines whether the risk is broadly acceptable or not, and eventually at which point in time it becomes unacceptable.

C) If needed, robust adaptation measures are defined, aiming to cover a broad spectrum of future climate scenarios. Usually, dam risk reduction measures are not mutually exclusive (we don't implement one measure or the other, but rather one and then another), and their sequential implementation will tend to increase the overall safety level of the dam.

D) After quantifying the effect of such measures on the future risk of the dam, their long-term efficiency is calculated using the approach and indicator described in Chapter 4. This must include the definition of the optimal moment for the implementation of each measure.

E) A prioritization of these measures as proposed in Chapter 5 will help define an implementation plan that takes into account deep uncertainty from climate scenarios. Such a plan will consist on long-term adaptation strategies for the following years and must consider the availability of economic resources.

F) Since climate (and in general dam safety) information is highly dynamic, this strategy must be constantly updated along with the forthcoming innovations and advances in science and techniques. As new information emerges, the adaptation plans established in previous iterations should be re-assessed, which may imply changing the implementation plan, reverting already implemented measures (if possible) or proposing new ones.

Chapter 7

Conclusions

7.1 General conclusions

Dam failure risk management approaches and decision-making strategies have traditionally assumed the stationarity of climatic conditions, including the persistence of historical patterns of natural variability and the likelihood of extreme events. However, evidence shows that climate change is likely to increase dam risks in the mid and long term. Owners and operators of dams must therefore adapt their management and adaptation strategies to new climate scenarios in order to define the most efficient implementation sequence of risk reduction measures. A process based on the risk analysis framework is proposed in this thesis that encompasses all the phases, from the calculation of the risk up to the definition and prioritization of measures.

An important part of this process is the quantification of the impacts of climate change on dam risks. The global effect must be assessed through the integration of the various projected effects acting on each aspect of the risk. For this, the use of risk models has proved useful to structure and incorporate the impacts on the different dam safety components, from the input hydrology to the calculation of the downstream consequences of an inundation on the population and assets at risk.

However, dealing with climate change effects presents several challenges that have been addressed in this thesis. On the one hand, the concepts of failure probability as well as social and economic risk must be re-evaluated to incorporate their time-dependency. Since they can be treated as an evolutive concept, this is likely to change the way risks are conceived and managed: Should we base our decisions on future or present risks? What criteria should we follow to prioritize adaptation measures? How should we treat measures that are justifiable in the present but may not be necessary in the future (or vice versa)? To deal with such questions, a new time-dependent risk indicator that allows us to assess the efficiency of adaptation measures in optimally reducing dam risks at any time horizon has been defined. Its use makes it possible to better design risk reduction measures and to plan the implementation sequence that maximize their effectiveness.

On the other hand, working with climate projections introduces important uncertainties in the information on which final decisions are based, and that come on top of other uncertainty sources. Among the different approaches developed to deal with uncertainty in planning and decision-making, a robust strategy has been chosen as the main method since it can incorporate all the different plausible scenarios identified. The goal is to define solutions that perform well over a wide range of alternative projections. This approach is part of an evolutive process addressed to obtain the implementation sequence of risk reduction measures. It is worth stressing the value of obtaining field data and of establishing, calibrating and continuously validating digital clones of the hydraulic systems used to assess flood risk and adapt risk management policies and measures.

The application of the proposed methodology has proved useful to assess risk in the present and future, and to design mitigation measures to counteract the effects of climate change. The methodology proposed in this thesis has been contrasted and validated and can serve as a reference benchmark in other cases to support decision-making processes.

7.2 Original contributions

This thesis provides a comprehensive dam risk management strategy to improve adaptation schemes under the influence of climate change effects. A summary of the main results is presented here:

- A comprehensive approach has been proposed to incorporate climate change to dam risk management. The method encompasses a complete procedure, from the risk estimation and the treatment of uncertainty until the identification of sequence of implementation. It allows defining and prioritizing risk reduction measures based on their efficiency on short- to long-term operations while establishing the most agreed implementation sequence in the context of climate uncertainty. Despite the difficulties to allocate probabilities to specific events, such framework allows a systematic and objective analysis, reducing considerably the subjectivity.

- A thorough review of the potential impacts of climate change on dam safety has been accomplished. The review is presented as a guideline including the description of such impacts and different techniques of variable complexity to assess them. The goal is to serve as a decision-making supporting tool that can be adapted to the needs of dam owners and encompassed in an evolutive dam safety management framework.
- This review has been performed following the structure of dam risk models, which allows us to incorporate and connect most variables concerning dam safety. The analysis can be carried out in a comprehensive way through the integration of the various projected effects acting on each aspect of the risk, from the input hydrology to the calculation of the consequences of dam failure on the population and assets at risk.
- Moreover, a catalogue of methodologies and techniques has been proposed to help assess these impacts based on the level of detail of the analysis, the purpose of the study and the availability of data.
- Although traditional decision-making approaches assume the stationarity of factors defining risk, dam failure risks are likely to evolve and can no longer be assumed as a static but rather as a time-dependent concept. In order to adapt the methodology for risk adaptation, a new risk indicator has been proposed: the *Aggregated Adjusted Cost per Statistical Life Saved* (AACSLS). It represents an innovative contribution since no other indicator that takes into account the changeable nature of risks has been proposed before. The AACSLS has proved to be useful to prioritize adaptation measures that present a higher efficiency in the reduction of risk throughout a predefined period. This would prevent the selection of measures that would no longer be necessary in the future or the possibility of missing some measures that could efficiently reduce the future risk.
- As an inherent part of climate change projections, uncertainties must be incorporated into the process of defining risk reduction strategies. For this, an approach is proposed, called *Multi-Prior Weighted Scenarios Ranking*, based on robust decision-making strategies coupled with climate scenario probabilities assignation. This approach seeks to establish the consensus sequence of risk reduction measures to be implemented by integrating the uncertainty of future scenarios. It guides the dam practitioner in selecting the climate scenario weighting scheme, while introducing a new index (IRC) to obtain the likelihood of an ensemble of rankings for measures. The key aspects are the evaluation of the robustness of the measures and the definition of the prioritization strategy.
- The overall approach in which these contributions are integrated is conceived as an evolutive process that must be updated as new information on climate change arises. This strategy seeks to make the most of the resources available, while proposing long-term measures. This way, robust

decision-making initiatives are embedded within more dynamic and integrative strategies in the face of uncertainty and temporal complexity.

- The methodology proposed in this thesis has been applied to a real study case of the Santa Teresa dam. This is the first documented application of a comprehensive analysis of climate change impacts on dam risks under a hydrological scenario and serves as a reference benchmark for the definition of long-term adaptation strategies and the evaluation of their efficiency.
- For the quantification of the risk impacts, a multi-model approach that entails different models and data sources (climate projections, hydrological or water resource management models) has been used to cover all the risk components affected by climate change. Results from such models are easily integrable into the dam risk modelling concept and make it possible to assess the importance of each aspect on risk.
- This study case analysis has provided valuable new information with respect to previous dam risk studies. If no risk evolution is considered, the situation in the current state does not present an urgent need for adaptation measures. However, in general, it has been found that the risks are expected to increase over time and, as a result, new adaptation measures that were not justifiable for the present situation have been recommended. Additionally, a robust risk adaptation strategy has been established for the Santa Teresa dam, consisting of the definition of the consensus sequence of implementation of risk reduction measures that considers the long-term effects of climate change as well as their associated uncertainties.

7.3 Future research lines

According to the results of the thesis, the following research lines are proposed to better adapt dam risk management under the influence of climate change:

- The new risk reduction indicator AACSLS proposed is useful for the purposes of the analysis. It relies on the efficiency principles by which economic resources are spent in the most efficient way to reduce both social and economic risks. New indicators could be proposed to include the equity principle that arises from the premise that all individuals have unconditional rights to certain levels of protection. Since these two principles can conflict in their application, its consideration must be treated carefully.
- Existing dam risk tolerability recommendations (e.g., USBR or ANCOLD) do not include the temporal dimension in their criteria. In the light of the influence of climate change and its expected evolution over time, a re-

definition of such recommendations seems worthwhile. After a revision of these criteria, the proposed methodology could be re-defined, or techniques for updating its application could be established.

- Some of the techniques, formulas or assumptions used in this thesis have been originally defined assuming stationary conditions. For instance, in the application of the IDF curve used to estimate the maximum rainfall depths, the formula employed is climate- and location-dependent since it has been extracted from an analysis based on historical records. This could benefit from new studies and analyses that incorporate future climatic conditions to establish new relations.
- Although this thesis focuses on climate uncertainties and their influence in decision-making, other uncertainty sources related with time-dependent processes exist and have an important impact on dam safety. This can be the case of the degradation of the concrete-foundation resistance parameters, affecting the risk of dam sliding failure. The approach proposed could be adapted to incorporate uncertainties on a larger spectrum, consolidating the robustness of the methodology.
- The implementation of risk reduction measures usually represents major cost for dam owners and managers. Although a simple waiting period of 2 years has been used for the study case, the problem is substantially complex since the applicability of such measures depends on the financial planning of the funding agencies in terms of budget limitations and the construction schedule. This introduces a new dimension to the problem of long-term risk management that should be addressed further: how can financial planning be intersected with risk reduction needs to optimize economic resources?
- The proposed methodology has been designed for dam risk management. A similar approach based on the findings and structure of this thesis could be applied to other critical infrastructure potentially affected by future climatic (and non-climatic) factors, e.g., coastal protection dikes, nuclear plants or water treatment plants.
- It is recommended to investigate the implementation of evolutive risk management in a broader process of adaptive governance that would extend this practical framework to policy institutions. Indeed, dam owners and regulating agencies should adopt similar strategies for evolutive risk management to manage climate-related decisions, thus benefiting from shared experiences and common efforts. For this, use-oriented science and knowledge transfer between science hubs and decision-makers is needed.

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