Reliability Engineering and System Safety 203 (2020) 107100

Contents lists available at ScienceDirect

Reliability Engineering and System Safety

journal homepage: www.elsevier.com/locate/ress

Comprehensive decision-making approach for managing time dependent dam risks

Javier Fluixá-Sanmartín[a,*], Ignacio Escuder-Bueno[b,c], Adrián Morales-Torres[c], Jesica Tamara Castillo-Rodríguez[b]

[a] Centre de Recherche sur l'Environnement Alpin (CREALP), Sion 1951, Switzerland
[b] Instituto Universitario de Investigación de Ingeniería del Agua y Medio Ambiente, Universitat Politècnica de València (UPV), Valencia 46022, Spain
[c] iPresas Risk Analysis, Valencia 46023, Spain

ARTICLE INFO

Keywords:
Dam safety management
Decision-making
Long term
Climate change
Risk reduction

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 risk is 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 in 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 makes it possible to better design risk reduction measures and to plan the implementation sequence that maximizes 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.

1. Introduction

Dams are critical infrastructures whose associated risk must be properly managed in a continuous and updated process [1]. Risk can be estimated by the combined impact of a given scenario, probability of occurrence, and associated consequences [2]. Risk Analysis techniques are being used worldwide to inform dam safety management and assess the efficiency of adaptation measures [3–5] 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 [6]. However, risk is 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 [1,7–10].
- The increasing exposure of people and economic assets in at-risk areas due to population and economic growth [11,12], 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 [13–16]. 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 [17].
- 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

* Corresponding author
E-mail address: javier.fluixa@crealp.vs.ch (J. Fluixá-Sanmartín).

https://doi.org/10.1016/j.ress.2020.107100
Received 27 June 2019; Received in revised form 7 March 2020; Accepted 23 June 2020
Available online 27 June 2020

the associated risks [18].

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 [19]. 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 [20]. 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 [20,21] to consider climate change information in the agency decision making. This Strategy proposes qualitative methods that help identifying 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 [22] 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, [10] 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 [23,24].

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 [25]. 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 in the long term considering both human-induced and natural variation of risks as well as considering their economic and social components [26]. 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.

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 [27] and in particular in the field of dam safety management. They allow the integration of all the relevant aspects of dam safety and help optimizing the existing resources and pointing at the most efficient ways of using them [18,28–30].

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) [31]. 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 [18]. The associated failure probability can be defined as:

$$p(f) = \sum_{e} p(e) \cdot p(f|e) \tag{1}$$

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 Eq. (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:

$$R = \sum_{e} p(e) \cdot p(f|e) \cdot C(f|e) \tag{2}$$

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 [18,32]. A common practice in dam safety is working with incremental consequences [28,29,33]. 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 [34]. 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.

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 [30] and risk is generally classified as unacceptable, tolerable or broadly acceptable [35]. Different organizations have proposed risk tolerability recommendations to evaluate whether a dam risk is tolerable or not [18,28,29,36,37]. 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 effect and its expected evolution with time, a redefinition 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.

2.3. Risk reduction indicators

As shown in [38,39], 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 [40,41], 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 [42,43]. 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 [44,45] arises from the comparison of the cost of measure with the economic risk reduction benefit resulting from its implementation:

$$CBR = \frac{C_{meas} - (C_{op(base)} - C_{op(meas)})}{R_{e(base)} - R_{e(meas)}} \tag{3}$$

  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 [46], health science [47,48], soil pollution [49], dam safety [28] and road traffic safety [50]. It shows how much it costs to avoid each potential loss of life as a result of a dam failure by implementing a measure:

$$CSLS = \frac{C_{meas} - (C_{op(base)} - C_{op(meas)})}{R_{s(base)} - R_{s(meas)}} \tag{4}$$

  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 [3,28] is calculated as the previous CSLS but adjusting the cost to consider the benefit due to the economic risk reduction:

$$ACSLS = \frac{C_{meas} - (C_{op(base)} - C_{op(meas)}) - (R_{e(base)} - R_{e(meas)})}{R_{s(base)} - R_{s(meas)}} \tag{5}$$

  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) [35,44] 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 [35,38]. 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.

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 [18]. 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.

3.1. Re-evaluation of risk concepts

First, the concepts of failure probability as well as social and economic risk presented in Section 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, Fig. 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

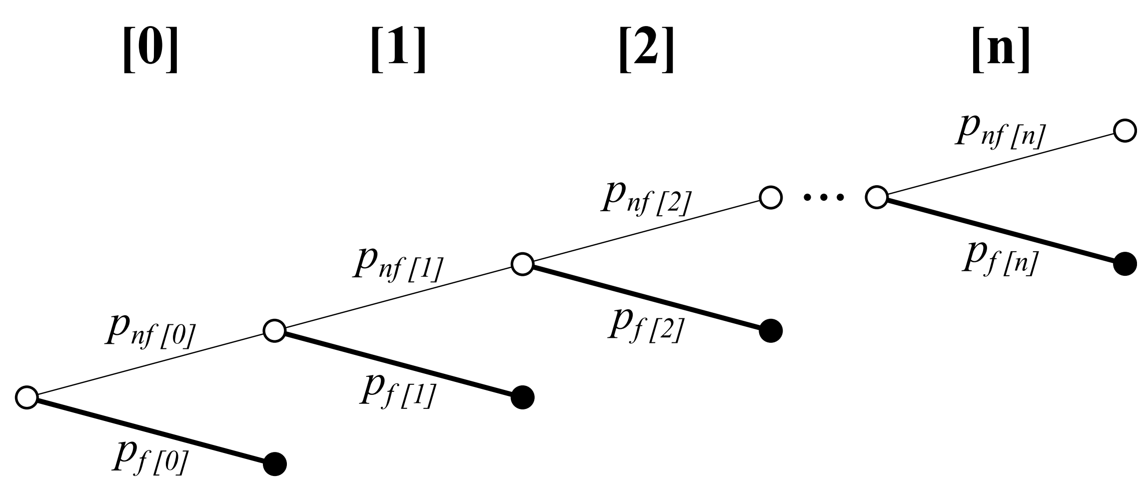

Fig. 1. Representation of an event tree modeling a risk system for the next n years.

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 Fig. 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 2.1).

Failure cases are represented as black circles in Fig. 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:

$$p_{f\,[\mathrm{i}]} + p_{nf\,[\mathrm{i}]} = 1 \tag{6}$$

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 new failure probabilities.

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 Fig. 1. Based on Eq. (6), this aggregated probability can be expressed depending of the failure probability of each branch as:

$$\begin{aligned} p_{f\,[0,n]} &= p_{f\,[0]} + p_{nf\,[0]}\cdot p_{f\,[1]} + \cdots + p_{nf\,[0]}\cdot p_{nf\,[1]}\cdot(\cdots)\cdot p_{nf\,[n-1]}\cdot p_{f\,[n]} \\ &= p_{f\,[0]} + (1-p_{f\,[0]})\cdot p_{f\,[1]} \\ &\quad + \cdots + (1-p_{f\,[0]})\cdot(1-p_{f\,[1]})\cdot(\cdots)\cdot(1-p_{f\,[n-1]})\cdot p_{f\,[n]} \end{aligned} \tag{7}$$

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 Fig. 1, this probability corresponds to the product of the probabilities of all the non-failure branches $p_{nf[i]}$ in the event tree:

$$p_{nf\,[0,n]} = p_{nf\,[0]}\cdot p_{nf\,[1]}\cdot(\cdots)\cdot p_{nf\,[n]} = (1-p_{f\,[0]})\cdot(1-p_{f\,[1]})\cdots(1-p_{f\,[n]}) \tag{8}$$

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:

$$\begin{aligned} R_{[0,n]} &= R_{[0]} + p_{nf\,[0]}\cdot R_{[1]} + \cdots + p_{nf\,[0]}\cdot p_{nf\,[1]}\cdot(\cdots)\cdot p_{nf\,[n-1]}\cdot R_{[n]} \\ &= R_{[0]} + R_{[1]}\cdot(1-p_{f\,[0]}) \\ &\quad + \cdots + R_{[n]}\cdot(1-p_{f\,[0]})\cdot(1-p_{f\,[1]})\cdot(\cdots)\cdot(1-p_{f\,[n-1]}) \end{aligned} \tag{9}$$

The formulas of Eqs. (7), (8) and (9) can be generalized as:

$$p_{f\,[0,n]} = p_{f\,[0]} + \sum_{j=1}^{n}\left[p_{f\,[j]}\cdot\prod_{k=0}^{j-1}(1-p_{f\,[k]})\right] \tag{10}$$

$$p_{nf\,[0,n]} = \prod_{j=0}^{n}(1-p_{f\,[j]}) \tag{11}$$

$$R_{[0,n]} = R_{[0]} + \sum_{j=1}^{n}\left[R_{[j]}\cdot\prod_{k=0}^{j-1}(1-p_{f\,[k]})\right] \tag{12}$$

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:

$$R^*_{e[0,n]} = R_{[0]} + \sum_{j=1}^{n}\left[\frac{R_{e[j]}}{\prod_{t=1}^{j}(1+i_t)}\cdot\prod_{k=0}^{j-1}(1-p_{f\,[k]})\right] \tag{13}$$

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

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 present 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 Eq. (5) (costs, economic and social risks) are evaluated cumulatively following the concepts presented in Section 3.1:

$$AACSLS_{[0,n]} = \frac{C^*_{meas\,[0,m]} - (C^*_{op(base)[0,n]} - C^*_{op(meas)[0,n]}) - (R^*_{e(base)[0,n]} - R^*_{e(meas)[0,n]})}{R_{s(base)[0,n]} - R_{s(meas)[0,n]}} \tag{14}$$

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 Eq. (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 Eq. (12). As in Eq. (13), the present value of the cost of the measure as well as of the operation costs must be used:

$$C^*_{meas\,[0,m]} = C_{meas\,[0]} + \sum_{j=1}^{m}\left[\frac{C_{meas\,[j]}}{\prod_{t=1}^{j}(1+i_t)}\cdot\prod_{k=0}^{j-1}(1-p_{f\,[k]})\right] \tag{15}$$

$$C^*_{op\,[0,n]} = C_{op\,[0]} + \sum_{j=1}^{n}\left[\frac{C_{op\,[j]}}{\prod_{t=1}^{j}(1+i_t)}\cdot\prod_{k=0}^{j-1}(1-p_{f\,[k]})\right] \tag{16}$$

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

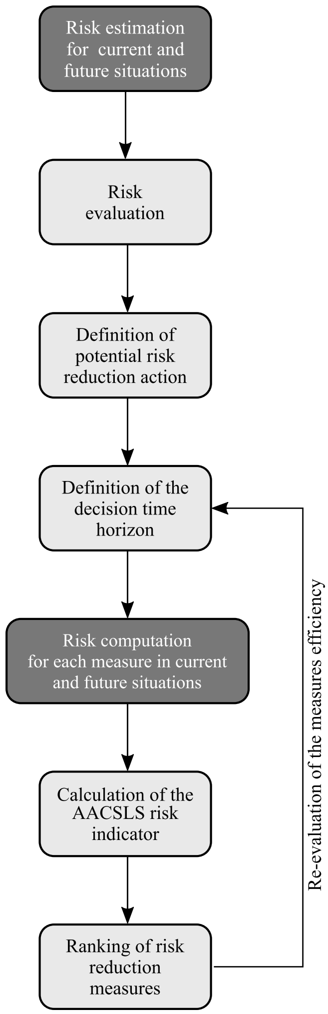

Fig. 2. Process to rank risk reduction measures based on long-term risk evaluation.

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 in the long term as follows (Fig. 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 [51–53]. Such models serve also as a supporting tool to assess the effects on risk imposed by climate change. Refer to [1,54] 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 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 step 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 [55]. 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) [56–59]; 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 [10].

(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 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).

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 (Fig. 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.

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,

Fig. 3. View of the Santa Teresa spillway from downstream.

including Salamanca city.

An analysis published in [54] 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.

4.1. Risk estimation

In [54], 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 [60], 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 [61] 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 [54] 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 as 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 [54] (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 [54]. Table 1 shows the failure probability and the social and economic risks for each period for the selected climate projection as obtained in [54]. Probability and risks for intermediate years can be extracted with a linear interpolation of these values.

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 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 [62,63]. 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 [64,65], Adaptation Pathways [66] or Real Options Analysis [67,68]. Such methods should be incorporated in a comprehensive approach to deal with climate-related uncertainties in long-term risk reduction strategies.

4.2. Risk evaluation

The previous results have been evaluated using the USBR tolerability criteria [36] to estimate whether the risks are tolerable or not.

Table 1
Results of failure probability, social risk and economic risk for the Base Case and future projections (from [54]).

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}

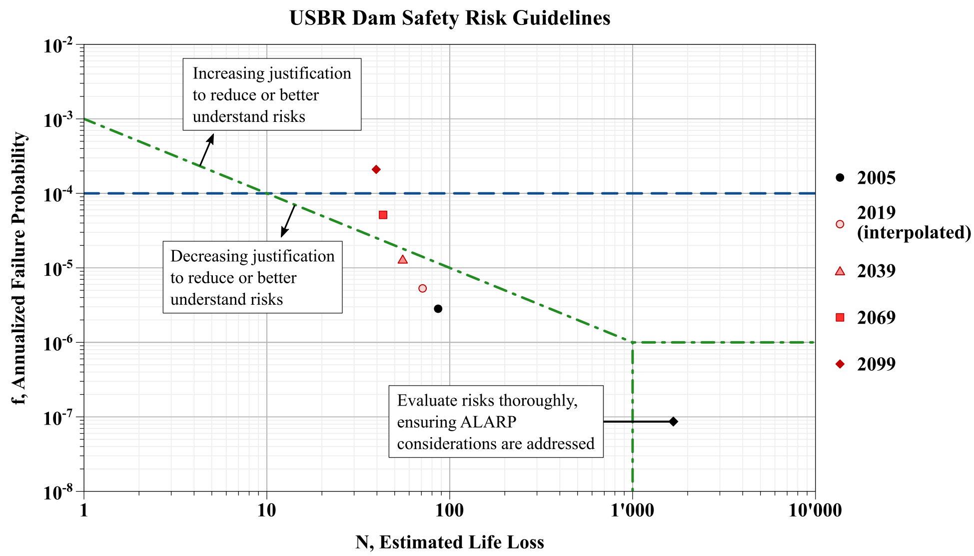

Fig. 4. USBR tolerability criteria, and f-N points representing the estimation of failure probability and loss of life based on the risk results from 2005 to 2099.

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

Measure	Implementation cost	Operation cost (present value)
A	601′528 €	30′076 €/year
B	479′413 €	0 €/year
C	2′817′365 €	0 €/year
D	0 €	82′750 €/year

This helps determining the convenience of implementing mitigation measures. As can be seen in Fig. 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, it 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.

Results obtained in the risk computation are plotted in Fig. 4. Each point represents the risk situation at a certain time horizon. Moreover, interpolated risk corresponding to the present scenario (year 2019) has been calculated using values from Table 1, as indicated above, and is also depicted in Fig. 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.

4.3. 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 [38,51] 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 [69]. The description of each measure is presented below, and the corresponding costs are shown in Table 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 [54], 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.

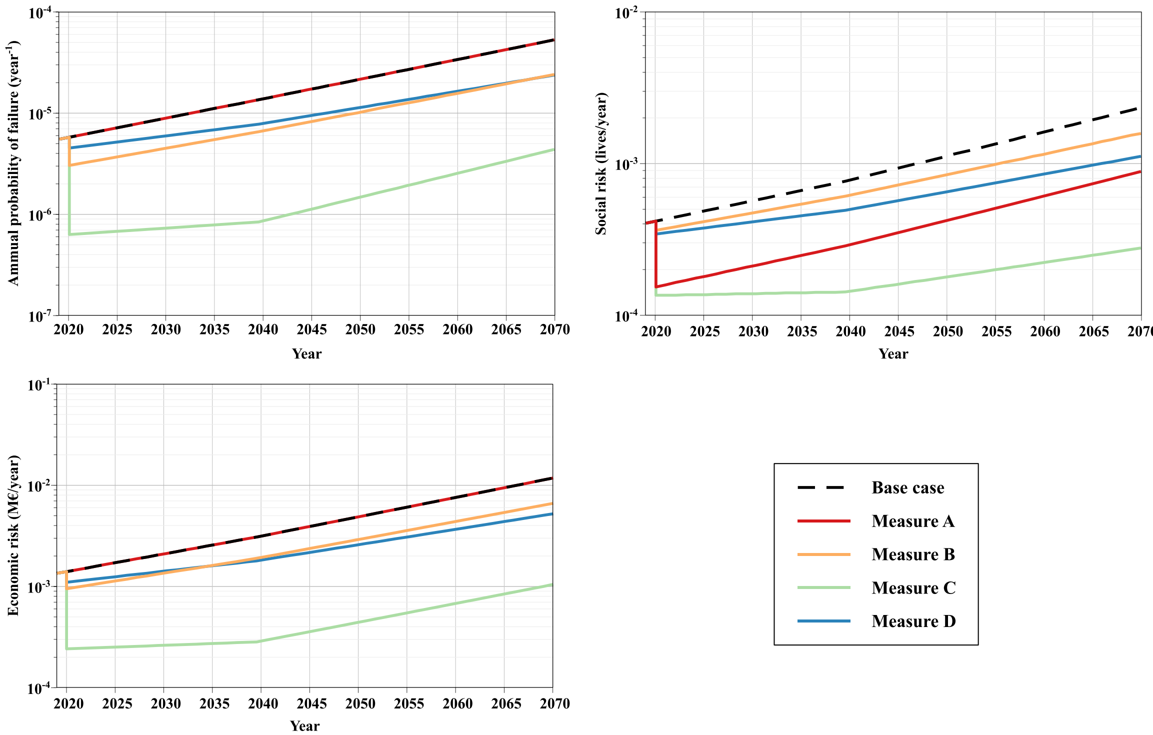

Fig. 5. Resulting evolution of failure probability (top-left), social risk (top-right), and economic risk (bottom-left) considering the implementation of each risk reduction measure.

4.4. Decision time horizon

Usually, the design lifespan of a concrete dam is usually comprised between 50 and 100 years, although it can be expanded as long as it is technically safe and operable. For this work, considering the age of the Santa Teresa dam and the functionality of the proposed risk reduction measures, it has been considered that the decision time horizon (T) is 50 years. Thus, the study period in which the proposed methodology is to be applied will be between 2019 (present) and 2069.

Moreover, a sensitivity analysis on the effect of the decision time horizon has been performed and is presented in Section 4.7.

4.5. 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 Fig. 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.

4.6. 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 Eq. (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 (Eq. (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 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 in 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 in the long term. Moreover, the AACSLS present lower values than the ACSLS. This means that risk reduction measures are more justifiable

Table 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

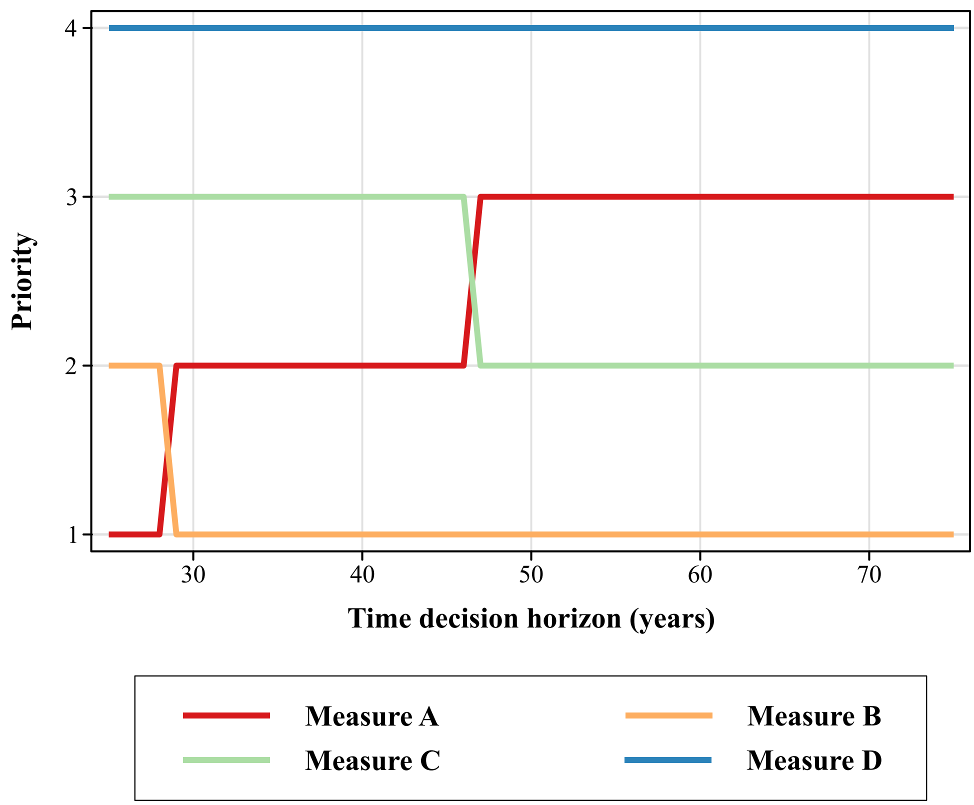

Fig. 6. Variation of the priority of each measure depending on the time decision horizon.

economically when the risk evolution is taken into account.

4.7. 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 Fig. 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.

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 risk is 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 consider 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 [70]. 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 in the long term where there is not enough certainty to unambiguously establish the best solution [71].

CRediT authorship contribution statement

Javier Fluixá-Sanmartín: Conceptualization, Methodology, Software, Writing - original draft. **Ignacio Escuder-Bueno:** Supervision, Validation. **Adrián Morales-Torres:** Validation, Methodology. **Jesica Tamara Castillo-Rodríguez:** Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

References

[1] Fluixá-Sanmartín J, Altarejos-García L, Morales-Torres A, Escuder-Bueno I. Review article: Climate change impacts on dam safety. Nat Hazard Earth Syst Sci 2018;18:2471–88. https://doi.org/10.5194/nhess-18-2471-2018.

[2] ICOLD. Bulletin on risk assessment in dam safety management. International Commission on Large Dams; 2003.

[3] Bowles DS. Advances in the practice and use of portfolio risk assessment. Proceedings of the ANCOLD Conference on dams. 2000.

[4] Escuder-Bueno I, Serrano-Lombillo A, Fluixá-Sanmartín J, Morales-Torres A. Evaluación de la seguridad hidrológica de presas mediante modelos de riesgo simplificados. Risk Analysis, Dam Safety, Dam Security and Critical Infrastructure Management, by Ignacio Escuder-Bueno, Enrique Matheu, Luis Altarejos-García, and Jesica T. Castillo-Rodríguez. Leiden: CRC Press; 2012. p. 335–42.

[5] Benjamin JR. Risk and decision analyses applied to dams and levees. Struct Saf 1982;1:257–68. https://doi.org/10.1016/0167-4730(82)90002-9.

[6] Milly PCD, Betancourt J, Falkenmark M, Hirsch RM, Kundzewicz ZW, Lettenmaier DP, et al. Stationarity is dead: whither water management? Science 2008;319:573–4. https://doi.org/10.1126/science.1151915.

[7] CH2014-Impacts. Toward Quantitative Scenarios of Climate Change Impacts in Switzerland, published by OCCR, FOEN, MeteoSwiss, C2SM, Agroscope, and ProClim, Bern, Switzerland, 2014 136 pp.

[8] IPCC. Managing the risks of extreme events and disasters to advance climate change adaptation: special report of the intergovernmental panel on climate change. Cambridge, UK. New York, NY, USA: Cambridge Univ. Press; 2012.

[9] Walsh J, Wuebbles D, Hayhoe K, Kossin J, Kunkel K, Stephens G, et al. Melillo JM, Richmond Terese (TC), Yohe GW, editors. U.S. Global Change Research Program; 2014. p. 19–67.

[10] Lee B-S, You GJ-Y. An assessment of long-term overtopping risk and optimal termination time of dam under climate change. J Environ Manag 2013;121:57–71. https://doi.org/10.1016/j.jenvman.2013.02.025.

[11] Bouwer LM. Have disaster losses increased due to anthropogenic climate change? Bull Am Meteorol Soc 2011;92:39–46. https://doi.org/10.1175/2010BAMS3092.1.

[12] Changnon SA, Pielke RA, Changnon D, Sylves RT, Pulwarty R. Human factors explain the increased losses from weather and climate extremes. Bull Am Meteorol Soc 2000;81:437–42. doi:10.1175/1520-0477(2000)081 < 0437:HFETIL > 2.3.C;2.

[13] Fischer G, Tubiello FN, van Velthuizen H, Wiberg DA. Climate change impacts on irrigation water requirements: Effects of mitigation, 1990–2080. Technol Forecast Soc Change 2007;74:1083–107. https://doi.org/10.1016/j.techfore.2006.05.021.

[14] Solaun K, Cerdá E. The impact of climate change on the generation of hydroelectric power—A case study in Southern Spain. Energies 2017;10:1343. https://doi.org/10.3390/en10091343.

[15] Rodríguez Díaz JA, Weatherhead EK, Knox JW, Camacho E. Climate change impacts on irrigation water requirements in the Guadalquivir river basin in Spain. Regional Environ. Change 2007;7:149–59. https://doi.org/10.1007/s10113-007-0035-3.

[16] U.S. Department of Energy. Effects of climate change on federal hydropower. DC: Washington; 2013.

[17] White S. Sediment yield prediction and modelling. Hydrol Processes 2005;19:3053–7. https://doi.org/10.1002/hyp.6003.

[18] SPANCOLD. Risk analysis as applied to dam safety. Technical guide on operation of dams and reservoirs. Spanish National Committe on Large Dams; 2012. http://www.spancold.es/Archivos/Monograph_Risk_Analysis.pdf.

[19] Lind N. Time effects in criteria for acceptable risk. Reliab Eng Syst Saf 2002;78:27–31. https://doi.org/10.1016/S0951-8320(02)00052-2.

[20] USBR. Climate Change Adaptation Strategy.. U.S. Department of the Interior. Bureau of Reclamation 2014.

[21] USBR. Climate Change Adaptation Strategy. 2016 Progress report. U.S. Department of the Interior. Bureau of Reclamation; 2016.

[22] USACE. Climate Change Adaptation Plan. U.S. Army Corps of Engineers Committee on Climate Preparedness and Resilience; 2014.

[23] Chen H-P, Mehrabani MB. Reliability analysis and optimum maintenance of coastal flood defences using probabilistic deterioration modelling. Reliab Eng Syst Saf 2019;185:163–74. https://doi.org/10.1016/j.ress.2018.12.021.

[24] Buijs FA, Hall JW, Sayers PB, Van Gelder PHAJM. Time-dependent reliability analysis of flood defences. Reliab Eng Syst Saf 2009;94:1942–53. https://doi.org/10.1016/j.ress.2009.06.012.

[25] Lind N. Social and economic criteria of acceptable risk. Reliab Eng Syst Saf 2002;78:21–5. https://doi.org/10.1016/S0951-8320(02)00051-0.

[26] Hall JW, Brown S, Nicholls RJ, Pidgeon NF, Watson RT. Proportionate adaptation. Nat Clim Change 2012;2:833–4. https://doi.org/10.1038/nclimate1749.

[27] Faber MH, Stewart MG. Risk assessment for civil engineering facilities: critical overview and discussion. Reliab Eng Syst Saf 2003;80:173–84. https://doi.org/10.1016/S0951-8320(03)00027-9.

[28] ANCOLD. Guidelines on risk assessment. Australian National Committee on Large Dams; 2003.

[29] USACE. Safety of dams - policy and procedures. Washington, DC: U.S. Army Corps of Engineers; 2011.

[30] ICOLD. Risk assessment in dam safety management. a reconnaissance of benefits, methods and current applications. International Commission on Large Dams; 2005.

[31] Kaplan S. The words of risk analysis. Risk Anal 1997;17:407–17. https://doi.org/10.1111/j.1539-6924.1997.tb00881.x.

[32] USBR, USACE. Dam safety risk analysis best practices training manual. Denver, Colorado: U.S. Bureau of Reclamation, U.S. Army Corps of Engineers; 2011.

[33] Serrano-Lombillo A, Escuder-Bueno I, de Membrillera-Ortuño MG, Altarejos-García L. Methodology for the calculation of annualized incremental risks in systems of dams: risk calculation for systems of dams. Risk Anal 2011;31:1000–15. https://doi.org/10.1111/j.1539-6924.2010.01547.x.

[34] Canadian Dam Association. Dam safety guidelines 2007. 2013.

[35] HSE. Reducing risks, protecting people: HSE's decision-making process. Sudbury: HSE Books; 2001.

[36] USBR. Dam safety public protection guidelines. a risk framework to support dam safety decision-making. U.S. Department of the Interior. Bureau of Reclamation; 2011.

[37] Li S, Zhou X, Wang Y, Zhou J, Du X, Chen Z. Study of risk acceptance criteria for dams. Sci China Technol Sci 2015;58:1263–71. https://doi.org/10.1007/s11431-015-5864-6.

[38] Morales-Torres A., Serrano-Lombillo A., Escuder-Bueno I., Altarejos-García L. The suitability of risk reduction indicators to inform dam safety management. Struct Infrastruct Eng2016:1–12. doi:10.1007/s11431-015-5864-6.

[39] Serrano-Lombillo A, Morales-Torres A, Escuder-Bueno I, Altarejos-García L. A new risk reduction indicator for dam safety management combining efficiency and equity principles. Struct Infrastruct Eng 2017;13:1157–66. https://doi.org/10.1080/15732479.2016.1245762.

[40] Baecher GB, Paté ME, De Neufville R. Risk of dam failure in benefit-cost analysis. Water Resour Res 1980;16:449–56. https://doi.org/10.1029/WR016i003p00449.

[41] Palmieri A, Shah F, Dinar A. Economics of reservoir sedimentation and sustainable management of dams. J Environ Manag 2001;61:149–63. https://doi.org/10.1006/jema.2000.0392.

[42] Paté-Cornell ME, Tagaras G. Risk Costs for New Dams: Economic Analysis and Effects of Monitoring. Water Resour Res 1986;22:5–14. https://doi.org/10.1029/WR022i001p00005.

[43] Hugenbusch D, Neumann T. Cost-Benefit analysis of disaster risk reduction: A synthesis for informed decision making. Aktion Deutschland Hilft e.V. – Bündnis deutscher Hilfsorganisationen 2016.

[44] Bowles D. ALARP evaluation using cost effectiveness and disproportionality to justify risk reduction. Bulletin 127. Australian National Committee on Large Dams (ANCOLD); 2004.

[45] Parker DJ, Green CH, Thompson PM. Urban flood protection benefits: a project appraisal guide. Aldershot, Hants, England ; Brookfield, Vt: U.S.A: Gower Technical Press; 1987.

[46] Stewart MG, Mueller J. A risk and cost-benefit assessment of United States aviation security measures. J Transp Secur 2008;1:143–59. https://doi.org/10.1007/s12198-008-0013-0.

[47] Lutter R, Morrall JF, Viscusi WK. The cost-per-life-saved cutoff for safety-enhancing regulations. Econ Inq 1999;37:599–608. https://doi.org/10.1111/j.1465-7295.1999.tb01450.x.

[48] Ramsberg JAL, Sjoberg L. The cost-effectiveness of lifesaving interventions in Sweden. Risk Anal 1997;17:467–78. https://doi.org/10.1111/j.1539-6924.1997.tb00887.x.

[49] Khadam IM, Kaluarachchi JJ. Multi-criteria decision analysis with probabilistic risk assessment for the management of contaminated ground water. Environ Impact Assess Rev 2003;23:683–721. https://doi.org/10.1016/S0195-9255(03)00117-3.

[50] de Blaeij A, Florax RJGM, Rietveld P, Verhoef E. The value of statistical life in road safety: a meta-analysis. Accid Anal Prev 2003;35:973–86. https://doi.org/10.1016/S0001-4575(02)00105-7.

[51] Ardiles L, Sanz D, Moreno P, Jenaro E, Fleitz J, Escuder-Bueno I. Risk assessment and management for 26 dams operated by the Duero River Authority (Spain). Proceedings of the sixth international conference on dam engineering. 2011.

[52] Bowles D, Brown A, Hughes A, Morris M, Sayers P, Topple A, et al. Guide to risk assessment for reservoir safety management, volume 1: guide. Horison House, Deanery Road, Bristol, BS1 9AH: Environment Agency; 2013.

[53] Serrano-Lombillo A, Escuder-Bueno I, Altarejos-García L. Use of risk models for evaluation of risk reduction measures for dams. Kyoto: Commission Internationale

des Grands Barrages 2012.
[54] Fluixá-Sanmartín J., Morales-Torres A., Escuder-Bueno I., Paredes-Arquiola J. Quantification of climate change impact on dam failure risk under hydrological scenarios: a case study from a Spanish dam. Nat Hazard Earth Syst Sci Discuss2019:1–31. doi:10.5194/nhess-2019-141.
[55] Lind N. Discounting risks in the far future. Reliab Eng Syst Saf 2007;92:1328–32. https://doi.org/10.1016/j.ress.2006.09.001.
[56] Diewert WE. Cost-benefit analysis and project evaluation. J Public Econ 1983;22:265–302. https://doi.org/10.1016/0047-2727(83)90037-3.
[57] Annema JA, Mouter N, Razaei J. Cost-benefit Analysis (CBA), or Multi-criteria Decision-making (MCDM) or Both: Politicians' Perspective in Transport Policy Appraisal. Transp Res Proc 2015;10:788–97. https://doi.org/10.1016/j.trpro.2015.09.032.
[58] Beria P, Maltese I, Mariotti I. Multicriteria versus cost benefit analysis: a comparative perspective in the assessment of sustainable mobility. Eur Transp Res Rev 2012;4:137–52. https://doi.org/10.1007/s12544-012-0074-9.
[59] Rackwitz R, Lentz A, Faber M. Socio-economically sustainable civil engineering infrastructures by optimization. Struct Saf 2005;27:187–229. https://doi.org/10.1016/j.strusafe.2004.10.002.
[60] iPresas. iPresas calc. user guide. Valencia: iPresas risk analysis; 2019.
[61] Jacob D, Petersen J, Eggert B, Alias A, Christensen OB, Bouwer LM, et al. EURO-CORDEX: new high-resolution climate change projections for European impact research. Reg. Environ. Change 2014;14:563–78. https://doi.org/10.1007/s10113-013-0499-2.
[62] Morales-Torres A, Escuder-Bueno I, Serrano-Lombillo A, Castillo Rodríguez JT. Dealing with epistemic uncertainty in risk-informed decision making for dam safety management. Reliab Eng Syst Saf 2019;191:106562https://doi.org/10.1016/j.ress.2019.106562.
[63] Delenne C, Cappelaere B, Guinot V. Uncertainty analysis of river flooding and dam failure risks using local sensitivity computations. Reliab Eng Syst Saf 2012;107:171–83. https://doi.org/10.1016/j.ress.2012.04.007.
[64] Walker W, Haasnoot M, Kwakkel J. Adapt or perish: a review of planning approaches for adaptation under deep uncertainty. Sustainability 2013;5:955–79. https://doi.org/10.3390/su5030955.
[65] Walker WE, Rahman SA, Cave J. Adaptive policies, policy analysis, and policy-making. Eur J Oper Res 2001;128:282–9. https://doi.org/10.1016/S0377-2217(00)00071-0.
[66] Haasnoot M, Middelkoop H, Offermans A, Beek Evan, Deursen WPAvan. Exploring pathways for sustainable water management in river deltas in a changing environment. Clim Change 2012;115:795–819. https://doi.org/10.1007/s10584-012-0444-2.
[67] Gersonius B, Morselt T, van Nieuwenhuijzen L, Ashley R, Zevenbergen C. How the failure to account for flexibility in the economic analysis of flood risk and coastal management strategies can result in maladaptive decisions. J Waterway Port Coastal Ocean Eng 2012;138:386–93. https://doi.org/10.1061/(ASCE)WW.1943-5460.0000142.
[68] Park T, Kim C, Kim H. Valuation of drainage infrastructure improvement under climate change using real options. Water Resour Manag 2014;28:445–57. https://doi.org/10.1007/s11269-013-0492-z.
[69] Dirección General de Carreteras. Base de precios de referencia. 2016. URL: http://normativa.itafec.com/proyecto/ES.03.02.001.OC.pdf.
[70] Willows RI, Connell RK. Climate adaptation: risk, uncertainty and decision-making editors Oxford: UKCIP; 2003.
[71] European Commission. Adapting infrastructure to climate change, 2020.