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PAPER

The suitability of risk reduction indicators to inform dam safety management

Adrián Morales-Torres[a]*, Armando Serrano-Lombillo[b], Ignacio Escuder-Bueno[b] and Luis Altarejos-García[c]

[a]*iPresas Risk Analysis, Avenida del Puerto 180, 1º-B. 46023 Valencia, Spain* [b]*Universitat Politècnica de València. Research Institute of Water and Environmental Engineering. Camino de Vera, s/n 46022 Valencia, Spain* [c]*Universidad Politécnica de Cartagena. Ud. Predepartamental de Ingeniería Civil. Paseo de Alfonso XIII, 52 30203 Cartagena, Spain*

Risk analysis can provide very suitable and useful information to manage the safety of critical civil infrastructures. Indeed, results of quantitative risk models can be used to inform prioritization of safety investments on infrastructures' assets and portfolios. In order to inform this prioritization, a series of risk reduction indicators can be used. This paper reviews existing indicators for dam safety, tracks how equity and efficiency principles are captured, propose additional indicators and provides insights on how tolerability guidelines and benefit-cost analysis can also play a role in decision-making. All reviewed, analyzed and/or combined indicators are later applied in a case study, a portfolio of 27 dams where 93 structural and non-structural investments are prioritized. The case study shows that prioritization sequences based on risk model results provide suitable and useful information, acknowledging that other concerns may be conditioning decision-making processes. With the results of the case study, a full comparison between all studied risk reduction indicators is made, and three indexes are calculated for all of them to measure how close they are to a theoretical best.

Keywords: Dam Safety; Decision making; Risk management; Risk & probability analysis; Quantitative analysis; Risk reduction indicators; Risk reduction principles; Equity & efficiency

1. Introduction

Critical infrastructures are those whose failure or destruction would entail serious consequences for community safety, from economic damage to even loss of life. Some examples include electrical power systems, gas and oil storage and transportation, water supply systems, transportation, finance and banking, emergency and government entities (Clinton (1996)). In the hydraulic infrastructures field, one of the most critical infrastructures are large dams and protective dikes and levees.

There is always a probability associated with critical infrastructure failure, even if it might be very low. Thus, since there are always possibilities for adverse consequences to happen there is always an associated risk. Risk Analysis is a useful methodology to characterize this risk and establish priorities in critical infrastructure safety management since it allows the integration of all existing information on threats, vulnerability and consequences (Moteff (2005)). It enables robust and defendable safety decisions (Bowles (2001)) and the comparison of risk in all kinds of critical infrastructures (Ayyub et al. (2007);Ellingwood (2005)).

A full Quantitative Risk Analysis (QRA) provides a lot of information and many insights into the safety of a critical infrastructure. This detailed information can be used to better understand safety issues, propose risk reduction measures and estimate their impacts. On the other hand, when

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*Corresponding author. Email: adrian.morales@ipresas.com. Other authors emails: arserlom@alumni.upv.es, iescuder@hma.upv.es, luis.altarejos@upct.es.

dealing with a large portfolio of infrastructures and risk reduction measures, some kind of summary indicator or indicators can be used in order to make manageable comparisons possible.

This paper reviews several risk reduction indicators and shows their utility to manage quantitative risk results in complex systems with many alternatives of investment. These indicators can be used to create prioritization sequences of risk reduction measures according to two risk reduction principles: equity and efficiency. This prioritization procedure is contextualized within the Tolerability of Risk (TOR) framework, which was set out by UK's HSE (2001) for risk evaluation and management and has been widely used in dam safety (ANCOLD (2003); SPANCOLD (2012); USACE (2014); USBR (2011a)). In order to show the utility of this procedure, it was applied to the safety management of a group of 27 dams and different mitigation measures sequences were obtained according to efficiency and equity principles.

This paper does not discuss the way in which QRA are carried out but rather takes their results as its starting point to obtain these risk indicators. However, it is important to note that a single indicator can never convey all the information that a full QRA provides, therefore, one must refer back to the full QRA when looking for specific information. Moreover, recommendations based on this type of indicators should not be taken as prescriptions, since there is always the possibility that an important issue may not be adequately reflected in a summary indicator.

It should be mentioned that risk informed decision-making is very complex, and not only technical aspects are important, but political, psychological and societal considerations also play a significant role (Jonkman (2003)) and it may not be possible to include them in a quantitative risk analysis. In such a broad and interconnected context, multi criteria analysis (Figueira et al. (2005); Keeney & Raiffa (1993); Saaty (1988); Kabir et al. (2014)) is universally seen and used as a conceptual and analytical tool to make all kind of decisions related, among many others, to investments.

2. Risk informed safety management based on equity and efficiency principles

2.1. *Risk estimation*

In risk analysis applied to critical infrastructures, risk can be defined as the combination of three concepts: what can happen (critical infrastructure 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)). Based on this definition, risk can be quantified in several ways, and sometimes several conflicting definitions are used for similar concepts. Those used in the present paper are defined below:

- **Individual risk (R_I):** Several subtly different definitions of individual risk are in use. One of them is the probability that an average unprotected person, permanently present at a certain location is killed due to an accident resulting from a hazardous activity (Bottelberghs (2000); Jonkman (2011)). This definition yields an individual risk *distribution* which varies spatially. Another definition is the probability that at least one person dies as a result of the critical infrastructure's failure (SPANCOLD (2012)). This definition has the advantage of yielding a single number. Its units are 1/year and it can be formulated as:

  $$R_I = \int_e p(e) \cdot p(f|e) \cdot p(d \geq 1|f,e) \cdot de \tag{1}$$

  Where the integral is defined over 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 $p(d \geq 1|f,e)$ is the probability that at least one person dies due to this failure. If in an specific application it can be assumed that all failures would produce at least one fatality, that is, if $p(d \geq 1|f,e) = 1$, then individual risk is equivalent to failure probability.
- **Societal risk (R_S):** It is obtained by combining failure probabilities and the harmful con-

sequences suffered by the population as a result of that failure (Jones (1985)). These consequences are generally expressed in terms of loss of life. Societal risk is commonly represented through FN curves that show the relation between loss of life and exceedance probability. The area under these curves is equivalent to the expected number of deaths per year (Vrijling & van Gelder (1997)). This number can be used to represent societal risk with a single value, and it is also known as estimated annualized loss of life (Bowles (2004)). Mathematically, it is obtained through the following formula:

$$R_S = \int_e p(e) \cdot p(f|e) \cdot c_S(f,e) \cdot de \tag{2}$$

Where $c_S(f,e)$ is the loss of life due to each failure f and event e.

- **Economic risk (R_E):** Economic risk is obtained by combining failure probability and the economic consequences of that failure (Jonkman (2003)). These consequences are expressed in monetary units. Similarly to societal risk, economic risk can be represented with FD curves or with the expected annualized economic damage (Bowles (2004)), obtained through the following formula:

$$R_E = \int_e p(e) \cdot p(f|e) \cdot c_E(f,e) \cdot de \tag{3}$$

Where $c_E(f,e)$ are the economic consequences produced as a result of each failure f and event e.

For risk calculation, the use of risk models (USBR (2011b)) that define the variables affecting infrastructure safety and the relations between them is common. Once a risk model is set up, it is then possible to estimate failure probability, consequences and risks.

2.2. *Risk evaluation and management*

Once the risk is calculated it must be evaluated in order to determine the need of implementing mitigation measures. Risk evaluation is the stage where judgments and values are introduced into the decision-making (whether explicitly or implicitly) by including the consideration of the importance of the estimated risks (ICOLD (2005)). The procedure described in this paper is based on the concepts of the Tolerability of Risk (TOR) framework HSE (2001) for risk evaluation and management. Therefore, these core concepts and principles regarding risk, tolerability of risk and risk management are not discussed in this paper, where such principles are taken in the same way as the above mentioned references do. This framework is widely used worldwide for risk informed dam safety management (ANCOLD (2003); SPANCOLD (2012); USACE (2014); USBR (2011a)).

Within this framework, risk evaluation is based on the concepts of unacceptable risk, tolerable risk and broadly tolerable risk (HSE (2001)). From these concepts, several international organizations have developed risk tolerability recommendations to evaluate whether a risk is tolerable or not. Several examples for hydraulic infrastructures can be found (Bottelberghs (2000); NSWDSC (2006); USACE (2014); USBR (2011a); Vrijling & van Gelder (1995)) for individual and societal risk.

Finally, the key part of the risk analysis process is decision-making for risk management. Decisions are made after considering possible alternatives and analyzing their effect on infrastructure risk. Generally, two principles are recommended to guide this decision-making process (HSE (2001); ICOLD (2005); USACE (2014)):

- **Equity:** In the context of critical infrastructure safety management, this principle arises from the premise that all individuals have unconditional rights to certain levels of protection (Le Guen (2010)). Among the different risk components which have been presented (see definitions in section 2.1), individual risk (the probability that at least one person dies as a result of the critical infrastructure's failure) is the most related to this concept.

Hence, individual risk tolerability recommendations seeking a certain level of protection for every individual of the population are related to the principle of equity. According to HSE (2001), the application of this principle should prevail when individual risk is above the recommended value of tolerability. There are numerous recommendations to establish this value, varying according to the activity or industry under study. Some examples can be seen in the Dutch regulations (Vrijling & van Gelder (1995)) and in the guidelines by USACE (2014).

- **Efficiency:** This principle arises from the fact that society possesses limited resources which must be spent in the most efficient way. When considering several risk reduction measures, the one producing a higher risk reduction at a lower cost (the one that optimizes expenditure) should generally be chosen first. This is usually the prevailing principle when risk is tolerable (HSE (2001)). In this paper we suggest a distinction between two types of efficiency, depending on the targeted risk:
    - **Societal efficiency:** When the target risk to be reduced is societal risk.
    - **Economic efficiency:** When what is analyzed is economic risk reduction, that is, the searched strategy is the most advantageous from an economic point of view. According to some authors (Bowles (2001)), this type of efficiency should only prevail when the infrastructure complies with tolerability recommendations.

  The efficiency principle is followed when a Benefit-Cost Analysis is made for risk informed decision-making. This approach addresses societal and economic efficiency by aggregating societal and economic risk (Baecher et al. (1980); HSE (2001); NRC (2014)). For this purpose, loss of life is given an economic value (known as Value Per Fatality or VPF), estimated from the population's willingness to pay to acquire a certain level of protection.

In summary, two different principles are generally used to guide decision-making within the tolerability framework: equity and efficiency. This can result in contradictions since what can be an optimal measure from the equity point of view may not be so from the efficiency point of view and vice versa. Decisions based on tolerability criteria and equity could lead to economically inefficient investments but a pure efficiency approach does not include the societal views on unacceptable risks (NRC (2014)).

The dilemma between efficiency and equity is also found in fields others than risk management, such as decision-making about infrastructure construction (Albalate et al. (2012); Joshi & Lambert (2007); Yamano & Ohkawara (2000)). Though in these cases the definitions of equity and efficiency are slightly different, the philosophy and the dilemma between both concepts remain the same.

3. Review of risk reduction indicators

As explained in the previous section, different risk reduction principles can be followed to guide safety management. Risk reduction indicators can be a useful tool to prioritize risk reduction alternatives according to these principles. These indicators are obtained from the effect a measure has on infrastructure risk and from its implementation and maintenance costs. In this section, different risk reduction indicators are presented and their relation to the risk reduction principles is explained. The main risk reduction indicators found in literature are:

- **Cost per Statistical Life Saved (CSLS):** This indicator is used to analyze risk management measures (HSE (2001)) in numerous fields such as aerospace (Stewart & Mueller (2008)), health science (Lutter et al. (1999); Ramsberg & Sjöberg (1997)), soil pollution (Khadam & Kaluarachchi (2003)), dam safety (ANCOLD (2003)) and road traffic safety (de Blaeij et al. (2003)). This indicator shows how much it costs to avoid each potential loss of life as a result of infrastructure failure when applying a measure. Its value is obtained through the following formula:

$$\text{CSLS} = \frac{C_a}{R_S^{base} - R_S^{mea}} \tag{4}$$

Where R_S^{base} is the risk expressed in loss of lives for the base case, R_S^{mea} is the risk in lives after the implementation of the measure and C_a is the annualized cost of the measure that includes its annualized implementation costs, annual maintenance costs and the potential changes in operation costs generated by the adoption of that measure.

CSLS compares costs with societal risk reduction, so when considering several measures, the measure with a minimal value of this indicator will be the one that employs the resources in a most efficient way. Therefore, this indicator is based on the principle of societal efficiency.

- **Economic Cost-Benefit Ratio (ECBR):** This indicator (Bowles (2004); Parker (1987)) arises from the comparison of the costs of a measure with the benefits on the economic risk reduction resulting from its implementation. According to the formula used in this paper, the lower this indicator is, the better the measure is.

$$\text{ECBR} = \frac{C_a}{R_E^{base} - R_E^{mea}} \tag{5}$$

- **Adjusted Cost per Statistical Life Saved (ACSLS):** This indicator (ANCOLD (2003); Bowles (2001)) has the same structure as CSLS but introduces an adjustment of the annualized cost to consider the economic risk reduction generated by the implementation of the measure. It is obtained with the following equation:

$$\text{ACSLS} = \frac{C_a - (R_E^{base} - R_E^{mea})}{R_S^{base} - R_S^{mea}} \tag{6}$$

Where R_E^{base} is the economic risk of the infrastructure for the base case and R_E^{mea} is the economic risk after the implementation of the measure.

ACSLS is usually used to apply the ALARP (As Low as Reasonably Practicable) (Bowles (2004); HSE (2001)) criterion, by indicating that as long as tolerability recommendations are respected, a measure can be rejected if it is not cost-efficient enough. ANCOLD's Bulletin 112 (Bowles et al. (1999)) contains a simple example of measure prioritization for a portfolio of dams by using ACSLS to apply the ALARP criterion.

ACSLS is focused on societal and economic efficiency, which are also the principles followed in a Benefit-Cost Analysis. In this analysis, the chosen alternative would be the one with the highest net benefits (Baecher et al. (1980); NRC (2014)). In annualized terms, net benefits are defined with the following equation:

$$\text{NB} = (R_E^{base} - R_E^{mea}) + VPF \cdot (R_S^{base} - R_S^{mea}) - C_a \tag{7}$$

Where VPF is the Value per Fatality applied. If the two previous equations are combined, the following relation is obtained:

$$\frac{NB}{R_S^{base} - R_S^{mea}} = VPF - ACSLS \tag{8}$$

As can be observed in the previous equation, net benefits are zero when ACSLS is equal to the value per fatality. Furthermore, the lower the ACSLS is, the higher the net benefits are, although these two approaches can produce different prioritization sequences due to the $R_S^{base} - R_S^{mea}$ term. The main advantage of using ACSLS to evaluate risk reduction measures instead of Benefit-Cost Analysis is that the controversial issue of defining a Value Per Fatality (citeViscusi2003) is avoided .

In addition to the former risk reduction indicators, it is also possible to directly use the risk reduction of individual, societal or economic risk produced by the mitigation measures (Bohnenblust (1998); Bowles (2004); Khadam & Kaluarachchi (2003)). In order to compare these possibilities with other risk reduction indicators in a homogenous way, the authors have put them in indicator form: **Individual Risk Decrease Index (IRDI), Societal Risk Decrease Index (SRDI) and Economic Risk Decrease Index (ERDI)**. For instance, the proposed form for the IRDI indicator is:

$$\text{IRDI} = \frac{1}{R_I^{base} - R_I^{mea}} \tag{9}$$

Where R_I^{base} is the individual risk for the base case and R_I^{mea} is the individual risk after implementing the measure. The same structure is followed for SRDI (with societal risk) and ERDI (with economic risk). According to this structure, the lower these indicators are, the better the measure is.

Finally, the authors propose two risk reduction indicators that allow the combination of economic costs with failure probability (which is strongly related to individual risk) and therefore the establishment of a relation between efficiency and equity:

- **Cost per Statistical Failure Prevented (CSFP):** This indicator expresses how much it costs to avoid infrastructure failure. The lower this value, the better the measure is. It is calculated as follows:

$$\text{CSFP} = \frac{C_a}{p_f^{base} - p_f^{mea}} \tag{10}$$

  Where p_f^{base} is the annual failure probability for the base case and p_f^{mea} is the failure probability after the measure implementation.

  In many critical infrastructures (nuclear plants, large dams...), certain types of failures (catastrophic failures) almost always produce fatalities. In these cases, failure probability may be used as a proxy of individual risk and CSFP may be used as a proxy indicator of equity. When applying this indicator to decision-making the authors recommend considering a two-step process. When individual risk is not tolerable, the CSFP is used. Once individual risk is below the tolerability level, then efficiency based indicators such as CSLS or ACSLS may be more convenient.

- **Adjusted Cost per Statistical Failure Prevented (ACSFP):** This indicator presents the same form as CSFP but introduces an adjustment on the annualized cost to consider the reduction of economic risk produced by the implementation of the measure. It is calculated with the following formula:

$$\text{ACSFP} = \frac{C_a - (R_E^{base} - R_E^{mea})}{p_f^{base} - p_f^{mea}} \tag{11}$$

This indicator is strongly related to the principle of economic efficiency and, as with CSFP, in some cases it can also be used to measure equity. A two-step approach like the one described for the CSFP is also recommended for the ACSFP.

Figure 1 uses a Venn diagram to visualize the relationship between indicators and principles described in this section.

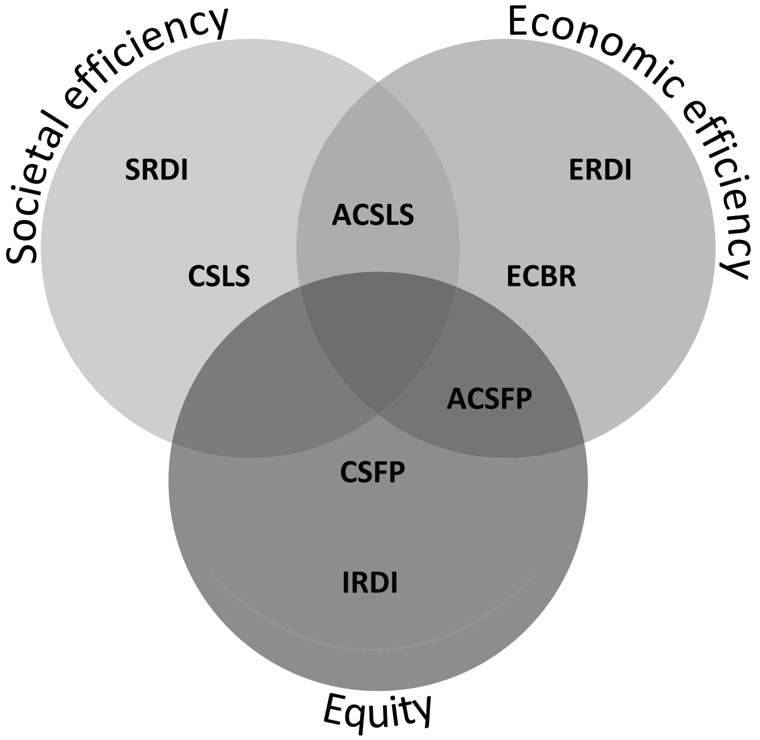

Figure 1. Venn diagram showing the relationship between risk reduction indicators and efficiency and equity principles.

4. Obtaining and assessing implementation sequences of risk reduction measures from risk reduction indicators

4.1. *Obtaining implementation sequences*

The relations explained in the previous section between risk indicators and risk reduction principles are used to obtain implementation sequences of risk reduction measures that follow these principles. These sequences are combined with the tolerability criteria to support a risk informed decision making process.

Once a risk model for the base case and for each risk reduction measure is set up, it is possible to calculate all risk reduction indicators for all measures. With this information, whichever measure has the best value of the preferred indicator can be picked up to be implemented in the first place. Then, the analysis is repeated assuming the first measure has already been implemented (in order to capture in an adequate way possible nonlinearities in the superposition of measures). By following this process iteratively a measure implementation sequence emerges, which is optimal[1] with regard to the employed criterion.

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[1] Under certain circumstances, due to nonlinearities in the application of risk reduction measures, it is possible that this strategy will not yield the absolute optimum sequence. In these cases, the optimum sequence can still be obtained, but it is computationally more costly. However, the sequence obtained with the simple iterative strategy is typically either optimal or very close to optimal and will therefore be used throughout the paper.

4.2. *Variation curves*

Variation curves are graphical representations of the results obtained when defining a sequence of measures implementation. These curves show how risk or failure probability varies according to the number of measures implemented or their cost. On the y axis, aggregated risk of the analyzed infrastructures is plotted. On the x axis, either implementation step or accumulated costs are plotted. Also, when costs are plotted, two types of costs can be used: annualized costs (annualized implementation costs + annual maintenance costs + changes in annual operation costs) or annualized and adjusted costs (total annualized costs - decrease in annual economic risk). Figure 2 shows a conceptual representation of this kind of curves.

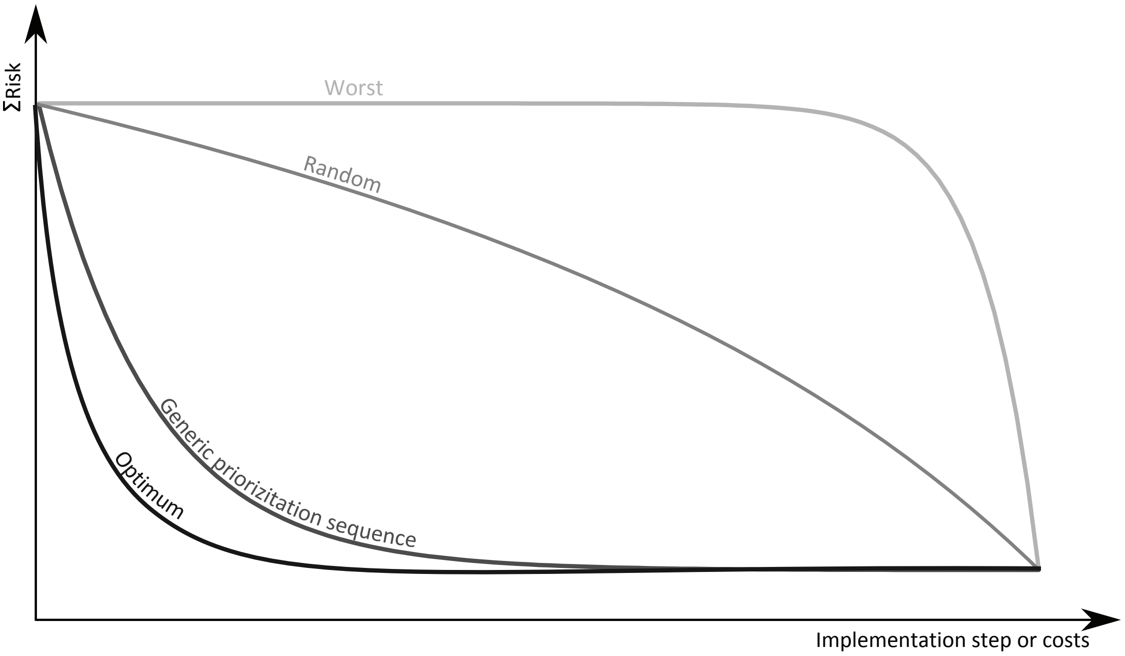

Figure 2. Generic representation of a variation curve showing four different prioritization sequences.

In this figure, each line represents the risk variation for a different prioritization sequence. In this type of curves, the best prioritization is given by the curve that approaches the X axis first, that is, the one that reduces risk or failure probability at a lower cost or with a lower number of implemented measures. Figure 2 shows four different types of variation curves:

- **Generic prioritization curve:** represents the usual shape presented by measure implementation sequences when obtained by applying a risk indicator.
- **Optimal curve:** Depending on the axes defined in the variation curve, there is an optimal measure implementation sequence. This sequence is the one that produces a more significant risk reduction or failure probability reduction at a lower cost or with a lower number of steps. Table 1 defines which variation curve produces the optimal sequence for each indicator (under certain linearity assumptions). As this table shows, each indicator produces an optimal curve in a different variation curve.
- **Worst curve:** This is the usual shape these curves have when representing for each sequence the measure with the worst value of risk indicator, that is, the least appropriate measure according to that factor. This curve and the optimal one delimit the space where all variation curves of all possible measure implementation sequences lie.
- **Average random curve:** This curve represents an average shape of variation curves when no particular risk indicator is followed to define the implementation sequence and instead, measures are chosen randomly.

Optimal Risk indicator	Variation graph X axis	Y axis
CSLS	Annualized measures cost	Societal risk
ACSLS	Annualized and adjusted measures cost	Societal risk
ECBR	Annualized measures cost	Economic risk
IRDI	Implementation step	Individual risk
SRDI	Implementation step	Societal risk
ERDI	Implementation step	Economic risk
CSFP	Annualized measures cost	Failure probability
ACSFP	Annualized and adjusted measures cost	Failure probability

Table 1. Variation curves where each risk indicator produces the optimal result.

It is worth noting that all curves share the same origin point (current situation of the set of infrastructures) and the same final point (situation of all infrastructures when all risk reduction measures are implemented). This responds to the fact that what is being decided is not which measures to adopt but in which order.

4.3. *Assessing the closeness to theoretical best of a measure implementation sequence*

In order to assess how "good" a measure implementation sequence is, some kind of metric must be used. Next, an index is proposed to accomplish this, the Closeness to Theoretical Best (CTB). It measures how close a prioritization sequence is from the theoretical best, which would consist in reducing all the risk in the first step, and is usually unachievable. In general, a sequence is better than another one if it reduces risk faster.

Moreover, the concept of how "good" a measure implementation sequence is varies according to the prioritization principle against which it is compared. A very appropriate sequence with regard to efficiency may not be so with regard to equity. Hence, not 1 but 3 CTB indexes have been devised in order to allow the assessment of efficiency and equity principles of a measure implementation sequence.

The optimal sequence according to the equity principle is the one that causes higher individual risk reduction at a lower measure implementation cost. Thus, the following CTB index is suggested for equity:

$$\mathrm{CTB}_{Eq} = 1 - \frac{\sum_{i=1}^{N} \Delta C^i \cdot (\log(R_I^i) - \log(R_I^{end})}{C_T \cdot (\log(R_I^{ini}) - \log(R_I^{end})} \tag{12}$$

Where N is the number of steps of the sequence, R_I^i is the individual risk for step i of the implementation sequence, R_I^{ini} is the initial individual risk, R_I^{end} is the individual risk of the last point of the sequence, ΔC^i is the increase in annualized cost produced after implementing measure i and C_T is the total annualized implementation cost of all measures.

If it were possible to achieve the final individual risk with a null cost (best possible case), the numerator would be 0, so CTB would equal 1. On the contrary, if individual risk was equal to the original value for all measure implementation costs (worst possible case), the denominator and numerator would be the same, so CTB would be 0.

The differences of each point of the sequence relative to the final individual risk are obtained using logarithms. In this way, a decrease of an order of magnitude in risk is valued equally, irrespective of whether it is in a low or high risk range. This is in accordance with the common practice of showing FN and fN graphs in logarithmic scales.

The same structure has been followed to define a CTB index for the societal efficiency (replacing individual risk with societal risk) and for the economic efficiency (replacing individual risk by economic risk).

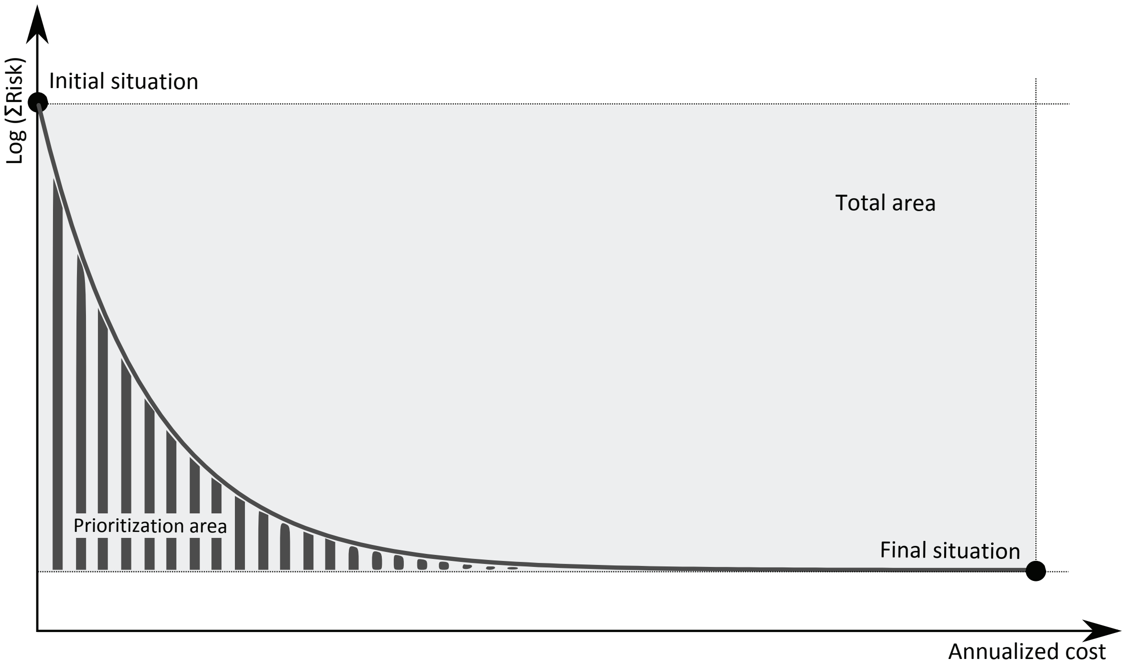

Figure 3. Definition of areas in variation curves in order to interpret CTB.

CTB indexes can have a graphical interpretation using the previously defined variation curves. The numerator of the suggested indexes is equal to the area under the curve in figure 3 (*Prioritization area*) whereas the denominator is equal to the total area of the rectangle defined by the initial and final points of the sequence (*Total area*). Thus, CTB can also be calculated with the following equation:

$$\mathrm{CTB} = 1 - \frac{\textit{Prioritization area}}{\textit{Total area}} \tag{13}$$

The value of this index is 0 when the area under the variation curve is equal to the total area of the rectangle and its value is 1 when the area under the curve is null. For each analyzed principle, different variables are used in the axis of the variation curve to allow this graphic interpretation of CTB indexes:

- **Equity variation curve:** It represents annualized cost on the X axis and failure probability on the Y axis.
- **Societal efficiency variation curve:** It represents annualized cost on the X axis and societal risk on the Y axis.
- **Economic efficiency variation curve:** It represents annualized cost on the X axis and economic risk on the Y axis.

5. Case study: Management of a portfolio of 27 large dams

Next, a case study is shown where all presented prioritization strategies can be compared. This case study concerns an existing group of 27 dams located in Spain belonging to the same owner and the implementation of the presented measures is currently being studied in order to improve safety. It is a very heterogeneous set of dams including structures of different typology (15 concrete gravity dams, 4 small diversion dams, 3 double-curve arch dams, 3 earthfill dams and 2 single-curve arch dams), size (from 100.6 m to 11.6 m), construction year (from 1923 to even one currently under construction) and reservoir volume (from 641 hm^3 to 0.2 hm^3).

The starting point for this case study are the results obtained in a Quantitative Risk Analysis performed on each dam. As part of the analysis process, risk models were set up with iPresas software (iPresas (2014)) for each dam. These risk models are based on event trees(SPANCOLD (2012)) and they analyze the different ways in which a dam can fail (failure modes) calculating their associated probabilities and consequences. Input data in the risk models were elaborated during three years and they are the result of dams technical documents, working group sessions and numerical models. Risk models were elaborated for normal and hydrological loading scenarios and they include:

- Flood events probability.
- Probability of outlets availability for flood routing.
- Pool water levels probability.
- Flood routing results.
- Fragility analysis results for each failure mode. Fragility curves of different failure modes are combined using Common Cause Adjustment techniques(SPANCOLD (2012)).
- Loss of life and economic consequences estimation results based on hydraulic models. Economic consequences for failure cases also include the cost of losing the dam.

Detailed procedures followed to develop these risk models can be found in Altarejos-García et al. (2012); Ardiles et al. (2011); Serrano-Lombillo et al. (2012a,b). Figure 4 shows an example of one of the risk models.

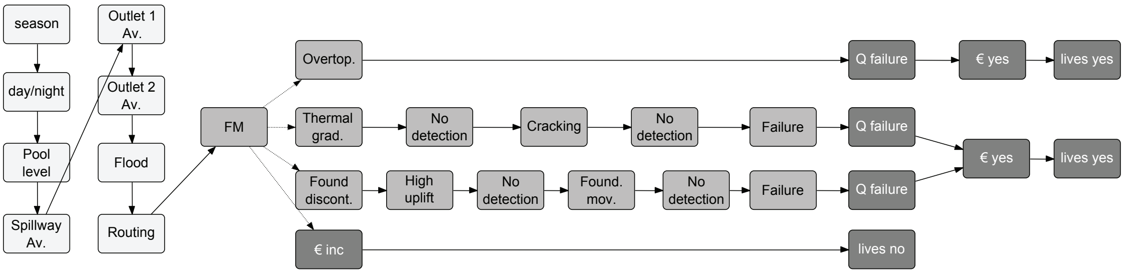

Figure 4. Risk model of one of the studied dams.

A total number of 93 measures were studied for the 27 analyzed dams. These measures came from a list of actions already planned to a higher or lower degree by the operator to improve dam safety along with the new needs revealed by the results of the Risk Analysis. Proposed measures are not general measures for all the dams but each one is planned to be applied only in one dam. Table 2 summarizes the risk reduction measures. As can be noticed, there is a great variety, with measures being of both structural and non-structural nature.

Structural measures		Non-structural measures	
Improve gates realiability	8	Emergency Action Plan (EAP)	23
Improve foundation condition	8	EAP + com., edu. and coord.	23
Improve dam body	8	Improve monitoring system	5
Renew gates and valves	5	Additional freeboards	4
Reinforce parapet wall	3		
Increase spillway capacity	3		
Additional outlet works	2		
Improve stilling basin	1		

Table 2. Summary of analyzed risk mitigation measures for the group of 27 dams.

Each proposed measured was budgeted by estimating implementation costs and maintenance and operations costs resulting from this implementation. Following Spanish recommendations on hydraulic infrastructures management (MMARM (2001)), the implementation cost of each measure was annualized by distributing it along its lifespan with a discount rate of 5%. Then, the annual maintenance and operation costs were added to the annualized implementation cost. In this way, the total cost of every measure was expressed in monetary units (in this case, euros) per year.

Different measure implementation sequences were obtained by using all of the risk reduction indicators defined in Section 3 as prioritization criteria. When doing these calculations, individual risk was assumed to be equal to failure probability. This is a usual hypothesis in large dams (USBR (2011a)) as the ones studied in this case, since dam failure would almost certainly result in at least one fatality.

Incremental consequences were used to calculate societal and economic risks. Incremental consequences are incremental losses or damage, which dam failure might inflict on upstream areas, downstream areas, or at the dam, over and above any losses which might have occurred for the same natural event or conditions, had the dam not failed (ANCOLD (2003)). Risk is then known as incremental risk and is usually employed in dam safety (ANCOLD (2003); USACE (2014)).

According to USACE (2014), the proposed tolerability limit for individual risk is 10^{-4}. Therefore, a sequence combining ACSFP (with failure probabilities higher than 10^{-4}) and ACSLS (with failure probabilities lower than 10^{-4}) was also calculated, following the recommendations in section 3. This sequence is labelled ACSLS/ACSFP in the following figures and tables. Furthermore, an additional sequence was obtained choosing in each step the measure with the highest Net Benefits according to a Benefits-Cost analysis. For this purpose, a Value per Fatality of 1.26 M€ was used according to HSE (2001) recommendations. This sequence is labelled BCA.

Before obtaining indicator based prioritizations, a sequence corresponding to a random average case was calculated to compare with the implementation sequences obtained from the application of the different prioritization criteria. This case represents the results of the average risk variation when no risk indicator is followed to define the sequence, but instead measures are chosen randomly at every step. In order to determine this random average case 1,000 different random prioritization sequences were generated. The average case was then determined by obtaining the average risk variation of all of them for each implementation step. Figure 5 shows the results in the efficiency variation curve. In this figure, they have been compared with the sequence obtained using the optimum indicator (CSLS as indicated in Table 1) and with the sequence obtained with the worst indicator (inverse of CSLS). As can be observed, the sequence obtained with the optimum indicator performs much better than any of the random sequences, since it reduces risks with lower costs. This fact justifies the use of risk reduction indicators to obtain sequences of risk reduction measures more efficiently. It would be necessary to compute many random sequences to find the optimum without these indicators since there are $93! \approx 10^{144}$ possible sequences of measures.

Next, using all indicators presented in this paper different measure implementation sequences were obtained for the set of dams under analysis. Figure 6 shows equity, societal efficiency and economic efficiency variation curves for the different calculated indicators.

In each variation curve the indicator that produces a better sequence (more significant risk reduction at a lower cost) is different. In the case of the societal efficiency curve, the optimal sequence is given by the indicator CSLS, for the economic curve, it is ECBR and in the case of equity, CSFP. Additionally, the worst implementation sequence was defined for each case, choosing at each step the measure with the highest value of the indicator that produces the optimal sequence. These sequences are also shown in figure 6.

The CTB indexes defined in section 4.3 were then used to numerically analyze the goodness of the implementation sequences according to each prioritization principle. As table 3 shows, the indicators that produce better values of societal efficiency are CSLS and ACSLS. The indicators producing higher economic efficiency are ECBR and ACSFP. Finally, the indicators producing better equity values are CSFP and ACSFP.

As can be seen, indicators produce good results for the CTB index of the principle on which

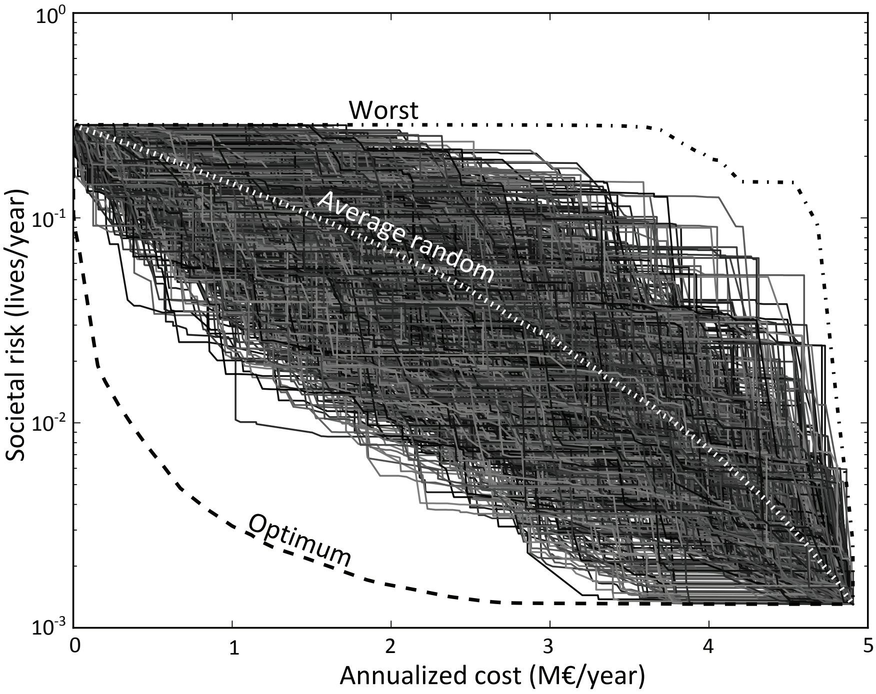

Figure 5. Results of the 1000 randomly calculated cases and average random case represented in a societal efficiency variation curve.

Indicator	Economic efficiency CTB	Societal efficiency CTB	Equity CTB
CSLS	81.2%	**90.0%**	73.1%
ACSLS	87.7%	87.5%	79.0%
ECBR	**94.6%**	62.0%	91.6%
IRDI	86.9%	56.1%	89.4%
SRDI	71.8%	83.9%	59.1%
ERDI	90.5%	57.6%	88.6%
CSFP	91.7%	55.3%	**93.5%**
ACSFP	92.7%	55.3%	92.2%
ACSFP/ACSLS	92.1%	79.5%	91.1%
BCA	82.7%	72.5%	71.3%
Random average	38.2%	38.3%	34.4%
Worst societal ef.	5.6%	**3.6%**	9.8%
Worst economic ef.	**5.2%**	37.2%	4.2%
Worst equity	5.5%	36.3%	**4.0%**

Table 3. CTB indexes for each risk indicator.

they are based. Besides, according to the obtained results, indicators based on equity produce good economic efficiency and vice-versa. This is a specificity of the chosen case study and it is due to the fact that none of the introduced measures directly diminishes economic consequences and that failure probability reductions produce a similar change of economic risk. Therefore, the sequences defined by indicators IRDI and ERDI present very similar CTBs. Additionally, both ACSFP and ACSLS have higher economic efficiency than CSFP and CSLS respectively, since they include economic risk on their formulation. In order to compare graphically how societal efficiency and equity principles are addressed for each indicator, the CTB indexes obtained for both principles have been represented in figure 7.

Finally, on the one hand, the results of the BCA sequence show that only the first ten measures produce positive net benefits so are justified from the Benefit-Cost point of view. The global an-

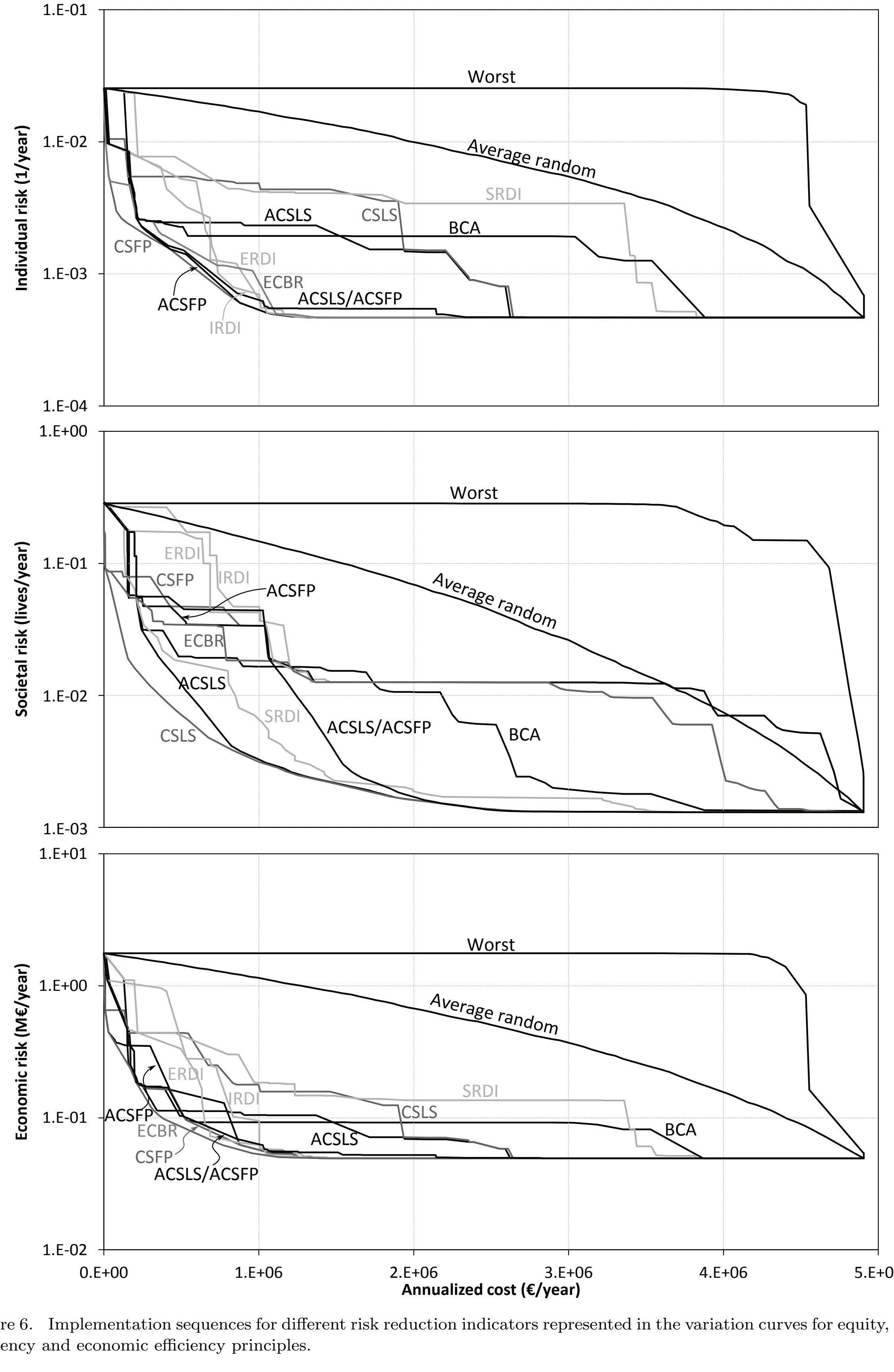

Figure 6. Implementation sequences for different risk reduction indicators represented in the variation curves for equity, societal efficiency and economic efficiency principles.

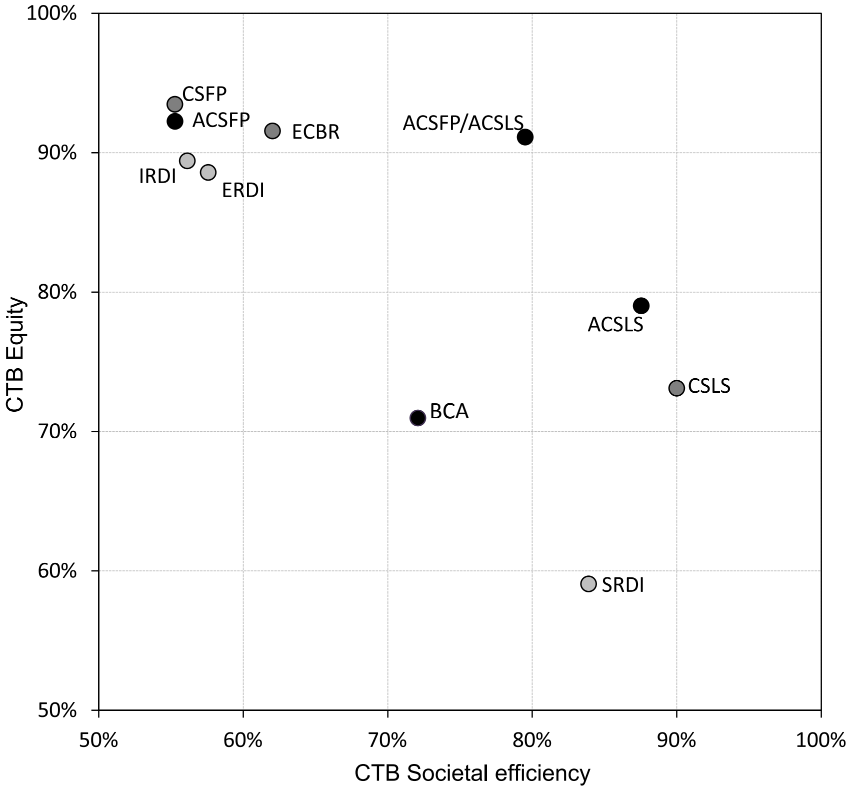

Figure 7. Comparison between efficiency CTB and equity CTB for each risk indicator.

nualized cost of these measures is 215,688€. On the other hand, the results of the ACSFP/ACSLS sequence (the only sequence that combines equity and efficiency) show that USBR (2011a) and USACE (2014) tolerability guidelines, are met in all the dams when 31 measures are implemented, being the global annualized cost of these measures 1,511,697€. This comparison shows that decisions considering equity and tolerability criteria can include measures that are not justified from a pure efficiency point of view.

6. Discussion and conclusions

The paper presents a rationale for prioritizing risk reduction measures when investing in the safety of a portfolio of hydraulic critical infrastructures. The principles framing such rationale go from how effective the investments in remedial actions are, their costs and benefits or the possible constraints on how they may comply with some well-established general statements on the hierarchy of risk controls, such as the more individually focused equity or the more socially and economically concerned efficiency.

The basis of the methodology relies on the fact that the relative merits of the options a decision maker may have can be quantified by examining such principles through a number of indicators, some of them originally developed, tested and used by the authors with a portfolio of 27 large dams. From the issues of applying the methodology and indicators to inform the safety management of such portfolio of dams, particular and general conclusions have been identified and are herein summarized.

Starting with the more specific ones, the main discussions and conclusions arising from the study presented in the paper are:

- The procedure outlined in this paper, based on risk reduction principles and its indicators, allows obtaining and assessing measure implementation sequences in a clear and simple way from quantitative risk results. This procedure reduces significantly the required computations to obtain an optimum prioritization sequence in complex portfolios with many proposed measures. It also allows to track the impact of different principles, to combine them and to compare them.

- It does not matter how quantitative risk results are built: as long as the former are reliable, it does not make any difference in the procedure presented in this paper.
- Furthermore, the use of the Closeness to Theoretical Best (CTB) index proposed in this paper can be a useful way to make quantitative comparisons between different sequences.
- As demonstrated in the case study, prioritization of different structural and non-structural measures in a consistent and justifiable way can be accomplished by using the results offered by risk models, even in heterogeneous groups of dams.
- The existing conflict between equity and tolerability criteria versus pure efficiency is highlighted with the results of the case study. On the one hand, tolerability criteria and equity can promote alternatives which do not maximize benefits. On the other hand, a pure efficiency approach does not include societal views on unacceptable risks and individuals' rights to certain levels of protection. A compromise between these approaches can be reached combining different risk indicators or different prioritization sequences.
- In practice, each critical infrastructure operator will choose the principles and tolerability limits that reflect its values and objectives more adequately. Besides, management of critical infrastructure safety actions can incorporate many factors of administrative, societal and economic order, difficult to quantify and that might condition decision-making. Within this context, measure implementation sequences based on risk results provide a valuable information to decision-making and in some cases can be an input to a more global multicriteria analysis.

From a broader perspective on how this type of approach will impact the safety management of any hydraulic critical infrastructure, some insights arising from this paper are:

- Having a more rational and structured quantitative information, able to capture different values depending on the context (country, regulatory framework, liability, business culture, etc.) will be in the benefit of any owner or decision maker regardless the specific type of infrastructures managed.
- It will also enable a clear and transparent way to communicate options in decision making both internally (to the upper management of a particular entity) and externally (to politicians and the general public), which is a premise for good governance.
- Though the methodology utility has been proved for a portfolio of critical hydraulic infrastructures such as large dams, it can be easily envisioned how it would be possible to tailor it for different types of civil infrastructures where best practices already include risk identification, calculation, evaluation, assessment and management (i.e. transportation, energy production, etc.)

Finally, major challenges to be addressed when using the suggested approach to inform decision making are, among others, to better understand and tackle the role of different sources of uncertainty (natural, epistemic etc.) as well as to find a consistent manner to evaluate time issues such as the expected time to complete a corrective action and the balance between short term and long term actions.

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