A new risk reduction indicator for dam safety management combining efficiency and equity principles

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Abstract

Large dams are critical infrastructures whose failure could produce high economic and social consequences. Risk analysis has been shown to be a suitable methodology to assess these risks and to inform dam safety management. In this sense, risk reduction indicators are a useful tool to manage risk results, yielding potential prioritization sequences of investments in dams portfolios. Risk management is usually informed by two basic principles: efficiency and equity. These two principles many times conflict, requiring a tradeoff between optimizing the expenditures and providing a high level of protection to all individuals. In this paper, the risk reduction indicator EWACSLS (Equity Weighted Adjusted Cost per Statistical Life Saved) is presented. This indicator allows obtaining prioritization sequences of investments while maintaining an equilibrium between equity and efficiency principles. In order to demonstrate its usefulness, it has been applied in a real world case study, a portfolio of 27 dams where 93 structural and non-structural investments are prioritized. The EWACSLS indicator is analyzed in detail and its results are compared with other existing risk reduction indicators, showing its flexibility and how it can be a very well balanced indicator for the purpose of prioritization of risk reduction measures.

Keywords

Dam safety, risk, risk management, infrastructure planning, decision making

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1. INTRODUCTION

Large dams are critical infrastructures whose failure could have high economic and social consequences. Worldwide state-of-the-practice recognizes the benefits of Quantitative Risk Analysis as a tool for informing dam safety management (ICOLD, 2005). This methodology allows supporting decision making in structural enhancements and other improvements in operation and maintenance, surveillance or emergency preparedness.

Risk analysis to inform dam safety management is generally contextualized within the HSE Tolerability of Risk (TOR) framework (HSE, 2001) for risk evaluation and management. This framework has been widely used worldwide to define risk management and dam safety programs (ANCOLD, 2003; SPANCOLD, 2012; USACE, 2014; USBR, 2011). According to this framework, two basic principles are generally used to guide decision making based on quantitative risk results (HSE, 2001; ICOLD, 2005):

- **Equity:** It is based on the premise that all individuals have unconditional rights to certain levels of protection.
- **Efficiency or utility:** It rises from the need society has to distribute and use its available resources in such a way as to gain maximum benefit.

These two principles can conflict, 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. This dilemma between efficiency and equity is not only restricted to risk analysis and safety management, but it also occurs in many other fields related with decision making in the public sector. For instance, in general public investments (Albalate, Bel, & Fageda, 2012; Blackorby & Donaldson, 1977; Yamano & Ohkawara, 2000), the health sector (Bleichrodt, 1997; Dolan, 1998), the transport sector (Joshi & Lambert, 2007) the education sector (De Fraja, 2001; Dundar & Lewis, 1999) and the environmental sector (Linnerooth-Bayer & Amendola, 2000; Swisher & Masters, 1992). Though in these cases the definitions of equity and efficiency are slightly different, the philosophy and the dilemma between both concepts remain the same. Most of these authors highlight the importance of combining efficiency and equity in an integrated management of public resources and it is precisely this conflict what underpins the ideas developed in this article.

When quantitative risk analysis is applied to inform safety management of portfolios of dams, a high number of results are obtained. In this context, risk reduction indicators have proved to be a useful tool to prioritize risk reduction measures (Bowles, Parsons, Anderson, & Glover, 1999; Morales-Torres, Serrano-Lombillo, Escuder-Bueno, & Altarejos-García, 2016). Risk reduction indicators are numeric values obtained for each potential measure based on its costs and the risk reduction it provides and they are widely used to inform safety management in different fields (Lutter, Morrall, & Viscusi, 1999; Ramsberg & Sjöberg, 1997; Stewart & Mueller, 2008).

The present paper is based on the results of (Morales-Torres et al., 2016), published by the same authors. In the previous work, existing risk reduction indicators were reviewed and their utility was demonstrated, applying them to obtain prioritization sequences of measures in a real portfolio of dams. It was concluded that existing risk reduction indicators for critical infrastructures safety management are based on either equity or efficiency principles, but none of them combine both principles in a balanced way. For this reason, the work presented in the current study introduces a new risk reduction indicator called Equity Weighted Adjusted Cost per Statistical Life Saved (EWACSLS), which combines efficiency and equity principles.

In order to provide a proper background on the use of risk reduction indicators to obtain prioritization sequences of measures, section 2 summarizes the main findings of (Morales-Torres et al., 2016). Section 3 presents the structure and the advantages of the proposed indicator and section 4 explains the results obtained when applied to prioritize risk reduction measures in a real portfolio of dams.

2. EQUITY AND EFFICIENCY PRINCIPLES FOR RISK MANAGEMENT IN DAM SAFETY

As defined by (Kaplan, 1997), risk can be understood as the combination of three concepts: what can happen, how likely it is to happen, and what its consequences are. In the dam safety field, what can happen is the failure of the dam and the analyzed consequences are usually economic and social in nature. Different metrics and definitions have been developed to quantify risk. In general, three types of risk are usually defined in the literature (Jonkman, van Gelder, & Vrijling, 2003; Morales-Torres et al., 2016):

- **Individual risk:** Refers to the probability of harming the individual which is most at risk. Different definitions can be used to quantify this concept, in this paper it is defined as the probability that at least one person dies as a result of the dam's failure (SPANCOLD, 2012). Therefore, this risk is computed by multiplying the probability of failure of the dam by the probability that at least one person dies due to this failure. Individual risk is directly related with the equity principle, since the lower the individual risk, the higher the minimum level of protection provided to all the individuals. For this reason, according to (HSE, 2001), the application of this principle should prevail when individual risk is above the recommended value of tolerability.
- **Societal risk:** It is obtained by combining failure probabilities and the harmful consequences suffered by the population as a result of that failure, generally expressed in terms of loss of life. In the dam safety field, this risk is commonly represented by a single value obtained combining dam failure probability and the loss of life produced by this failure (Bowles, 2004; SPANCOLD, 2012; USACE, 2014). The societal efficiency principle is followed when the objective is lowering societal risk at low costs.
- **Economic risk:** Similarly to societal risk, economic risk is obtained by combining failure probability and the economic consequences of that failure (Bowles, 2004). The economic efficiency principle prioritizes alternatives with lower economic risk at lower costs. According to some authors (Bowles, 2001; HSE, 2001), this type of efficiency should only prevail when the infrastructure complies with tolerability recommendations.

Reducing individual risk is aligned with the equity principle whereas reducing economic and societal risks at the lowest costs is aligned with the efficiency principle. Therefore, when different risk reduction measures are prioritized, following different principles can lead to conflicts between "individual rights" and "societal benefits".

When a portfolio of dams is analyzed through quantitative risk analysis, many risk reduction measures must be evaluated and prioritized. As demonstrated in (Morales-Torres et al., 2016), risk reduction indicators can be a useful tool to obtain prioritization sequences of risk reduction measures, which can then be used as an input to inform portfolio safety management. The article laid out a procedure to obtain prioritization sequences based on risk reduction indicators. In each step of the sequence, the measure with the lowest value of the indicator was chosen. Of course, the obtained prioritization sequence depends on the risk reduction indicator used to define it. Hence, this procedure does not intend to choose between different alternatives but to prioritize them, assuming that with enough time and resources, all of them will be implemented.

In (Morales-Torres et al., 2016) existing risk reduction indicators to compare different investment alternatives are reviewed. This review comprises the dam safety field and other hazardous industries and the relation between risk reduction measures and equity and efficiency principles. In the dam safety field, two indicators are prevalent in the evaluation of risk reduction measures:

- **CSLS (Cost per Statistical Life Saved):** (ANCOLD, 2003; HSE, 2001) This indicator shows how much it costs to avoid each potential loss of life as a result of a dam failure. It is widely used to manage quantitative risk results in different fields (de Blaeij, Florax, Rietveld, & Verhoef, 2003; Khadam & Kaluarachchi, 2003; Lutter et al., 1999; Stewart & Mueller, 2008). Its value is obtained through the following formula:

$$CSLS = \frac{C_a}{r_s(base) - r_s(mea)} \tag{1}$$

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 including its annualized implementation costs, annual maintenance costs and potential changes in operation costs produced by the adoption of the 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.

- **ACSLS (Adjusted Cost per Statistical Life Saved):** (ANCOLD, 2003; Bowles, 2001) This indicator 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:

$$ACSLS = \frac{C_a - (r_e(base) - r_e(mea))}{r_s(base) - r_s(mea)} \tag{2}$$

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. As in the previous case, it is based on the efficiency principle, though for adjusted costs, so it considers both societal and economic efficiency.

Other reviewed risk reduction indicators to prioritize risk reduction measures are:

- **CBR (Cost-Benefit Ratio):** Arises from the comparison of the costs of a measure with the economic risk reduction benefits resulting from its implementation. It follows the economic efficiency principle.

- **CSFP (Cost per Statistical Failure Prevented):** Expresses how much it costs to avoid infrastructure failure for each measure. Its formulation is based on failure probability, so it follows the equity principle.

- **ACSFP (Adjusted Cost per Statistical Failure Prevented):** Has 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.

- **Individual Risk Decrease Index (IRDI):** Used to select whichever measure produces the highest decrease in individual risk in each step in the sequence regardless of other factors. This criterion is related to equity.

- **Societal Risk Decrease Index (SRDI):** As before but minimizing societal risk. This criterion is related to societal efficiency.

- **Economic Risk Decrease Index (ERDI):** As before but minimizing economic risk. This criterion is related to economic efficiency.

Each indicator is therefore either based on the efficiency or the equity principle, but none of them takes both principles into account. For this reason, it seems suitable to develop a new indicator that allows obtaining prioritization sequences of risk reduction measures combining both principles.

As explained in the previous paper, prioritization sequences can be represented in variation curves (Figure 1), which represent the variation of the aggregated risk in the portfolio as measures are implemented. In the X axis, annualized costs or implementation steps can be displayed while in the Y axis aggregated individual risk, societal risk or economic risk can be shown.

Depending on what is represented in each axis, the risk reduction indicator which will lead to the optimum sequence is different. The optimum sequence of the variation curve which represents aggregated societal risk versus costs will be the optimum from the societal efficiency point of view, since it represents the sequence which reduces societal risk at the lowest costs. For this reason this variation curve is called in this paper societal efficiency variation curve. Following the same logic, the graph showing individual risk versus costs is called equity variation graph and the graph showing economic risk versus costs is called economic efficiency variation graph.

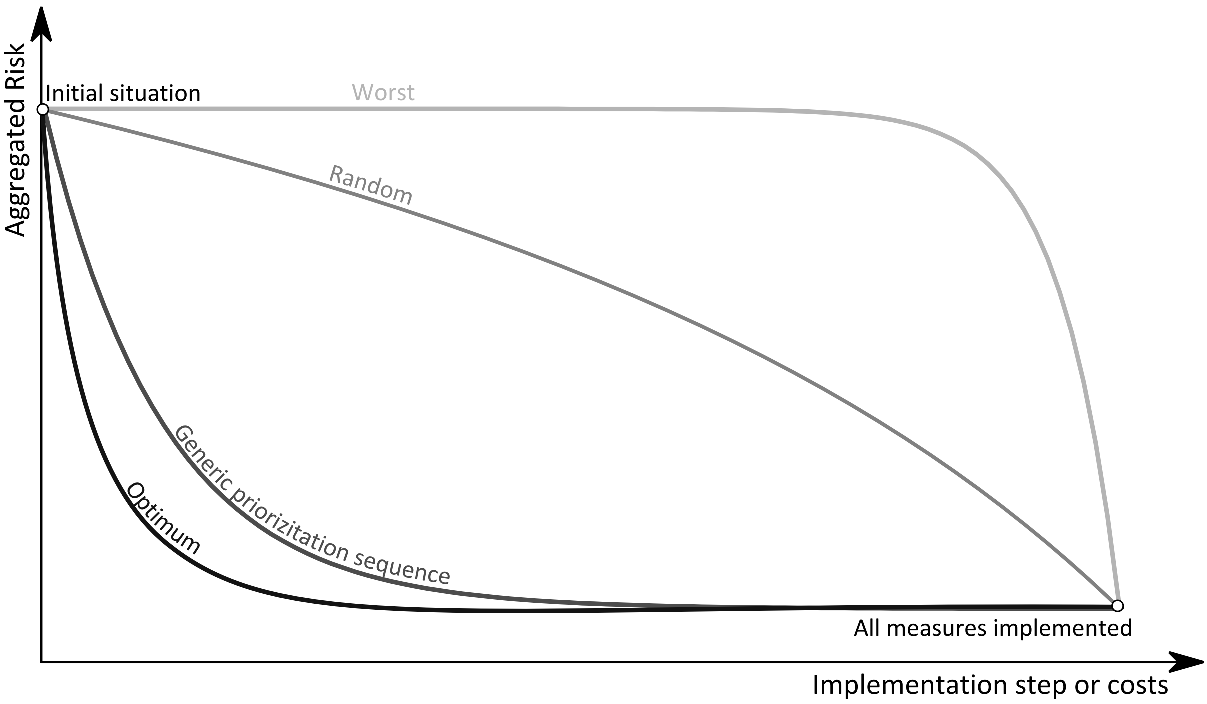

Figure 1. Generic representation of variation curves to define prioritization sequences.

In order to analyze how close prioritization sequences are to a risk reduction principle, three indexes based on variation curves were developed. These indexes are called CTB (closeness to the best) indexes and they are directly related to equity, societal efficiency and economic efficiency. For instance, in the equity variation graph, the prioritization sequences closer to the optimum will result in higher values of the CTB societal efficiency index. The same logic can be applied to equity and economic efficiency. These indexes allow evaluating any prioritization sequence of risk reduction measures against the general risk reduction principles.

3. EWACSLS: A RISK REDUCTION INDICATOR TO COMBINE EQUITY AND EFFICIENCY PRINCIPLES

As set out in the previous section, there is a need to find an indicator which can combine the principles of efficiency and effectiveness. We, therefore present here the Equity Weighted Adjusted Cost per Statistical Life Saved (EWACSLS), which is an indicator derived from ACSLS by introducing a correction to include the equity principle. EWACSLS is calculated with the following formula:

$$EWACSLS = \frac{ACSLS}{\left(\frac{\max(r_i(base), IRL)}{\max(r_i(mea), IRL)}\right)^n} \tag{3}$$

Where $r_i(base)$ is the individual risk for the base case expressed in years^{-1}, $r_i(mea)$ is the individual risk in years^{-1} after the implementation of the measure, *IRL* stands for Individual Risk Limit and *n* is a parameter that allows assigning a higher weight to either efficiency or equity in the prioritization process. The EWACSLS indicator has economic units, as ACSLS does. As can be derived from the previous formula, if the individual risk is lower than IRL, the only prevailing principle is efficiency (through ACSLS), since the denominator of the formula is then 1. Therefore, the equity principle only modifies the value of the indicator in the cases where individual risk is above tolerability thresholds. In this sense, it follows the HSE recommendations for risk management, combining equity and efficiency for non-tolerable risks and taking only efficiency into account in the tolerable area.

Consequently, the Individual Risk Limit indicates the level of protection to be provided to all the individuals in order to satisfy the equity principle. This limit cannot be prescribed in this article in a general way which could be blindly applied to all infrastructures. Its level is linked to implications on values which are subjective and which can vary from one organization or country to another and it is therefore part of the wider risk tolerability framework which should underlie any risk management effort. The formula itself, however, is flexible enough to accommodate these differences. In dam safety, an IRL of 10^{-4} years^{-1} can be a sensible choice in many cases, following recommendations on risk tolerability which are widely used in the field (USACE, 2014).

The *n* parameter can be used to provide flexibility to the EWACSLS. If the value of *n* is very high, the prevailing prioritization principle is equity whereas if it is very low, efficiency prevails. Hence, once a value of *n* is set, it can be used to consistently compare an array of measures. A value of *n* equal to 1 seems to be a reasonable compromise between both principles, as shown in Table 1. This table has been elaborated based on the authors' practical experience, after having used this risk reduction indicator to inform dam safety management in more than 35 dams worldwide. The effect of this parameter in the prioritization sequences of a real case is analyzed in the following section.

n parameter	Predominant risk reduction principle when r_i > IRL
1/10	Societal and economic efficiency clearly prevailing
1/2	Efficiency slightly more significant than equity
1	Equilibrium between equity and efficiency
2	Equity slightly more significant than efficiency
10	Equity clearly prevailing

Table 1. Recommended values for the n parameter of the EWACSLS indicator.

Summarizing, the EWACSLS indicator incorporates equity, societal efficiency and economic efficiency principles. Figure 1 uses a Venn diagram to visualize the relationship between all the reviewed indicators and principles. As can be observed in this figure, EWACSLS is the only indicator that is related with the three risk reduction principles.

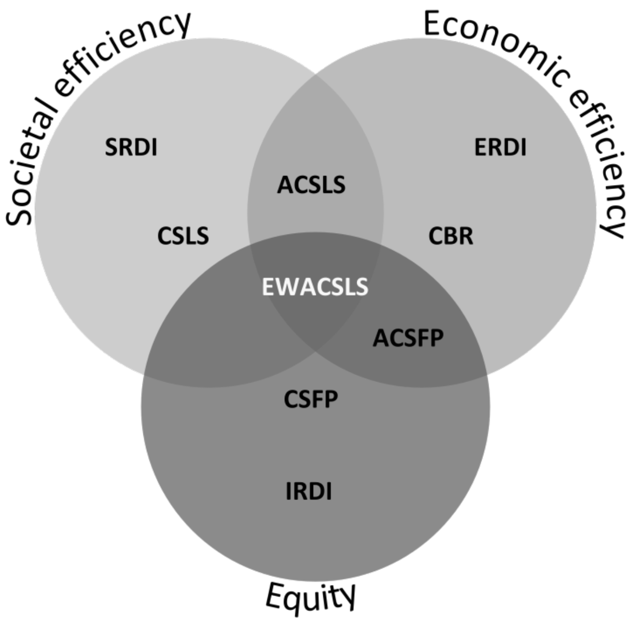

Figure 2. EWACSLS in a Venn diagram that shows the relationship between risk reduction indicators and efficiency and equity principles.

The EWACSLS indicator allows a smooth transition between equity and efficiency principles, since the closer the individual risk is to its limit, the less weight the equity principle has. This indicator is better aligned with risk analysis principles than simply establishing a binary threshold determining whether equity should prevail or not. If this kind of binary threshold is used, only equity is taken into consideration in the non-tolerable area and only efficiency in the tolerable area, so principles are used in separated domains. The results of this approach would be more sensible to existing uncertainties in risk estimation, since small changes in individual risk could produce changes in the prevailing principles. Risk evaluation and governance should not be about being above or under a threshold, but about informing decision making combining both principles in order to reduce risk as much as possible.

4. CASE STUDY: A PORTFOLIO OF 27 DAMS IN SPAIN

In order to compare the results of EWACSLS with the other risk reduction indicators, the same case study as in (Morales-Torres et al., 2016) has been used. EWACSLS has been applied to prioritize safety investments in a real portfolio of 27 dams in Spain. These dams belong to the same owner, which has defined a list of 93 safety measures to be implemented in the dams in the following years. It is a very heterogeneous portfolio of dams including structures of different typology as can be observed in Table 2. .

Tipologies	
Concrete gravity dams	15
Small diversion dams	4
Embankments	3
Double-curve arch dams	3
Single-curve arch dams	2
TOTAL	27
Maximum height (m)	11.6 - 100.6
Reservoir volume (m^3)	0.2 - 641
Construction year	1923 - Under construction

Table 2. General data of the dams in the Portfolio.

During four years, a risk analysis process was completed in this set of dams to develop quantitative risk models in order to inform dam safety management. In this process, numerous professionals related with the dams operation and management participated in the working sessions to define the potential failure modes and the architecture and inputs of the risk models. The quantitative risk results obtained from this process are the starting point of this case study, which is focused on how to manage these results using the EWACSLS indicator.

In this risk analysis process, a quantitative risk model was set up for each dam using iPresas software (iPresas, 2014). An example of these models is shown in Figure 3. These risk models are based on event trees (SPANCOLD, 2012) and they analyze the different ways in which a dam can fail (failure modes) resulting from a loading event, calculating their probabilities, consequences and risks. Input data in the risk models were elaborated during the risk analysis process and are the result of existing technical documents (safety reviews, emergency action plans, operating rules, construction projects…), numerical models and working group sessions. Risk models were elaborated for normal and hydrological loading scenarios and include probability of flood events, water pool levels and outlets availability, flood routing results, fragility curves for each failure mode and expected consequences of failure (loss of life and economic damages). Detailed procedures followed to develop these risk models can be found in (Altarejos-García, Escuder-Bueno, Serrano-Lombillo, & Morales-Torres, 2012; Ardiles et al., 2011; Serrano-Lombillo, Escuder-Bueno, de Membrillera-Ortuño, & Altarejos-García, 2011; Serrano-Lombillo, Fluixá-Sanmartín, & Espert-Canet, 2012; Serrano-Lombillo, Morales-Torres, & García-Kabbabe, 2012).

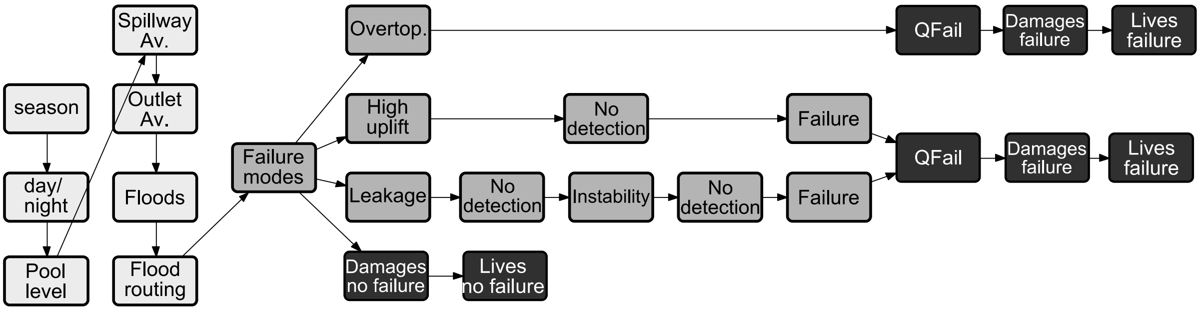

Figure 3. Quantitative risk model of one of the case study dams.

The 93 measures planned to improve dams safety include 38 structural measures and 55 non-structural measures. Proposed measures are not general measures for all the dams: each of them is planned and tailored to be applied only in one dam. Some examples of the planned structural measures are increment of spillway capacity or improvements in the gates reliability, the foundation conditions or the dam body imperviousness. The non- structural measures are mainly focused on developing Emergency Action Plans and risk awareness campaigns, improving the monitoring systems and introducing more restrictive freeboards in the reservoirs.

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.

In this case study, individual risk was assumed to be equal to the failure probability of the dams. This is a common hypothesis in large dams (USBR, 2011) as the ones studied in this case, since dam failure would almost certainly result in at least one fatality. Risk models were used to quantify the risk reduction provided by each measure planned. Therefore, these results were combined with the annualized cost to compute EWACSLS. The limit of individual risk (IRL) used to calculate EWACSLS was 10^{-4}, following USACE recommendations (USACE, 2014).

Incremental risk results have been used to compute risk reduction indicators. Incremental risk is the part of risk usually used to inform dam safety management (ANCOLD, 2003; SPANCOLD, 2012; USACE, 2014), since it is exclusively due to the dam failure. It is obtained by subtracting from the consequences of the dam failure the ones that would have happened even if the dam had not failed.

Before presenting the results for the full case and with the aim of clarifying the prioritization process with the EWACSLS indicator, a first sequence is shown below using only 3 dams of the Portfolio and 9 of their potential risk reduction measures. This sequence is obtained with a value of the *n* parameter equal to 1. The procedure to obtain the prioritization sequence can be observed in Table 3. In each step, EWACSLS is computed for each measure based on its cost and the risk results for the initial situation and the situation with the measure implemented. Then, the measure with the lowest value of the EWACSLS indicators is chosen. In the next step of the sequence, the initial situation will assume that the measures of the previous steps have already been implemented, so risk reduction provided by each measure and EWACSLS are recomputed to choose a new measure. Finally, when the whole sequence has been defined, aggregated risks can be represented versus annualized costs in each step to obtain the variation graphs.

Dam	Measure	Annualized cost (M€/year)	Initial situation: Individual risk ($years^{-1}$)	Initial situation: Economic risk (M€/year)	Initial situation: Societal risk (lives/year)	Situation with measure: Individual risk ($years^{-1}$)	Situation with measure: Economic risk (M€/year)	Situation with measure: Societal risk (lives/year)	EWACSLS (M€/live)
				CURRENT SITUATION					
A	Emergency action plan	4.768E-02				1.958E-05	1.457E-03	1.463E-03	31.54
A	Parapet wall reinforcement	4.728E-03	1.958E-05	1.457E-03	2.975E-03	6.452E-08	4.893E-06	1.014E-05	1.10
A	New bottom outlet	1.122E-02				1.614E-05	1.201E-03	2.450E-03	20.88
A	New gates in spillway	2.738E-02				1.375E-05	1.023E-03	2.082E-03	30.17
B	Emergency action plan	7.984E-02				7.645E-07	6.873E-04	3.484E-04	151.01
B	Monitoring improvement	3.910E-03	7.645E-07	6.873E-04	8.771E-04	4.196E-07	3.905E-04	5.190E-04	10.09
B	New power generator	2.597E-03				5.891E-07	5.218E-04	6.547E-04	10.93
C	Emergency action plan	9.847E-02	5.582E-04	3.231E-03	6.815E-04	5.582E-04	3.231E-03	4.407E-04	409.05
C	Saddle dam reinforcement	1.507E-01				3.613E-07	1.193E-04	5.327E-04	177.78
				STEP 1: DAM A - PARAPET WALL REINFORCEMENT					
A	Emergency action plan	4.768E-02				6.452E-08	4.893E-06	4.970E-06	9224.08
A	New bottom outlet	1.122E-02	6.452E-08	4.893E-06	1.014E-05	3.882E-08	2.944E-06	6.105E-06	2780.15
A	New gates in spillway	2.738E-02				6.056E-09	4.592E-07	9.506E-07	2978.95
B	Emergency action plan	7.984E-02				7.645E-07	6.873E-04	3.484E-04	151.01
B	Monitoring improvement	3.910E-03	7.645E-07	6.873E-04	8.771E-04	4.196E-07	3.905E-04	5.190E-04	10.09
B	New power generator	2.597E-03				5.891E-07	5.218E-04	6.547E-04	10.93
C	Emergency action plan	9.847E-02	5.582E-04	3.231E-03	6.815E-04	5.582E-04	3.231E-03	4.407E-04	409.05
C	Saddle dam reinforcement	1.507E-01				3.613E-07	1.193E-04	5.327E-04	177.78
				STEP 2: DAM B - MONITORING IMPROVEMENT					
A	Emergency action plan	4.768E-02				6.452E-08	4.893E-06	4.970E-06	9224.08
A	New bottom outlet	1.122E-02	6.452E-08	4.893E-06	1.014E-05	3.882E-08	2.944E-06	6.105E-06	2780.15
A	New gates in spillway	2.738E-02				6.056E-09	4.592E-07	9.506E-07	2978.95
B	Emergency action plan	7.984E-02	4.196E-07	3.905E-04	5.190E-04	4.196E-07	3.905E-04	2.097E-04	258.13
B	New power generator	2.597E-03				2.444E-07	2.253E-04	2.969E-04	10.95
C	Emergency action plan	9.847E-02	5.582E-04	3.231E-03	6.815E-04	5.582E-04	3.231E-03	4.407E-04	409.05
C	Saddle dam reinforcement	1.507E-01				3.613E-07	1.193E-04	5.327E-04	177.78
				STEP 3: DAM B - NEW POWER GENERATOR					
A	Emergency action plan	4.768E-02				6.452E-08	4.893E-06	4.970E-06	9224.08
A	New bottom outlet	1.122E-02	6.452E-08	4.893E-06	1.014E-05	3.882E-08	2.944E-06	6.105E-06	2780.15
A	New gates in spillway	2.738E-02				6.056E-09	4.592E-07	9.506E-07	2978.95
B	Emergency action plan	7.984E-02	2.444E-07	2.253E-04	2.969E-04	2.444E-07	2.253E-04	1.196E-04	450.44
C	Emergency action plan	9.847E-02	5.582E-04	3.231E-03	6.815E-04	5.582E-04	3.231E-03	4.407E-04	409.05
C	Saddle dam reinforcement	1.507E-01				3.613E-07	1.193E-04	5.327E-04	177.78
				STEP 4: DAM C - SADDLE DAM REINFORCEMENT					
A	Emergency action plan	4.768E-02				6.452E-08	4.893E-06	4.970E-06	9224.08
A	New bottom outlet	1.122E-02	6.452E-08	4.893E-06	1.014E-05	3.882E-08	2.944E-06	6.105E-06	2780.15
A	New gates in spillway	2.738E-02				6.056E-09	4.592E-07	9.506E-07	2978.95
B	Emergency action plan	7.984E-02	2.444E-07	2.253E-04	2.969E-04	2.444E-07	2.253E-04	1.196E-04	450.44
C	Emergency action plan	9.847E-02	3.613E-07	1.193E-04	5.327E-04	3.613E-07	1.193E-04	3.147E-04	451.60
				STEP 5: DAM B - EMERGENCY ACTION PLAN					
A	Emergency action plan	4.768E-02				6.452E-08	4.893E-06	4.970E-06	9224.08
A	New bottom outlet	1.122E-02	6.452E-08	4.893E-06	1.014E-05	3.882E-08	2.944E-06	6.105E-06	2780.15
A	New gates in spillway	2.738E-02				6.056E-09	4.592E-07	9.506E-07	2978.95
C	Emergency action plan	9.847E-02	3.613E-07	1.193E-04	5.327E-04	3.613E-07	1.193E-04	3.147E-04	451.60
				STEP 6: DAM C - EMERGENCY ACTION PLAN					
A	Emergency action plan	4.768E-02				6.452E-08	4.893E-06	4.970E-06	9224.08
A	New bottom outlet	1.122E-02	6.452E-08	4.893E-06	1.014E-05	3.882E-08	2.944E-06	6.105E-06	2780.15
A	New gates in spillway	2.738E-02				6.056E-09	4.592E-07	9.506E-07	2978.95
				STEP 7: DAM A - NEW BOTTOM OUTLET					
A	Emergency action plan	4.768E-02	3.882E-08	2.944E-06	6.105E-06	3.882E-08	2.944E-06	2.992E-06	15317.54
A	New gates in spillway	2.738E-02				2.465E-09	1.869E-07	3.868E-07	4787.06
				STEP 8: DAM A - NEW GATES IN SPILLWAY					
A	Emergency action plan	4.768E-02	2.465E-09	1.869E-07	3.868E-07	2.465E-09	1.869E-07	1.897E-07	241848.36
				STEP 9: DAM A - EMERGENCY ACTION PLAN					

Table 3. Detailed process to obtain a prioritization sequence for 3 dams and 9 measures.

The same process described above as an example for 3 dams was applied to the full case with 27 dams and 93 risk reduction measures, resulting in a more numerically complex calculation, where each step of the sequence requires a large amount of computations. The process, however, remains the same. Below, we discuss the results obtained.

The high number of risk reduction measures to be prioritized justifies the use of risk reduction indicators to define these sequences more efficiently, since there are $93! \approx 10^{144}$ possible sequences of measures to be considered. In order to illustrate it, a sequence corresponding to a random average case has been calculated to compare with the implementation sequences obtained from the application of the risk reduction indicators. In order to obtain this average, 1,000 random sequences have been obtained, choosing the measure randomly in each step. The random average case has been then determined by obtaining the average risk variation of all of them for each implementation step. Figure 4 compares these sequences with the sequence obtained choosing in each step the measure with a lower value of the EWACSLS indicator. As can be observed, the sequence obtained with EWACSLS performs much better than any of the random sequences, since it reduces risks with lower costs. It should be remarked that the Optimum sequence shown in Figure 4 is only the best for this type of variation graph (with the societal risk represented in the Y axis and annualized cost in the X axis) since no sequence of measures that is optimum for all the types of variation graphs and principles exists. In this variation graph, this sequence is obtained using the CSLS indicator.

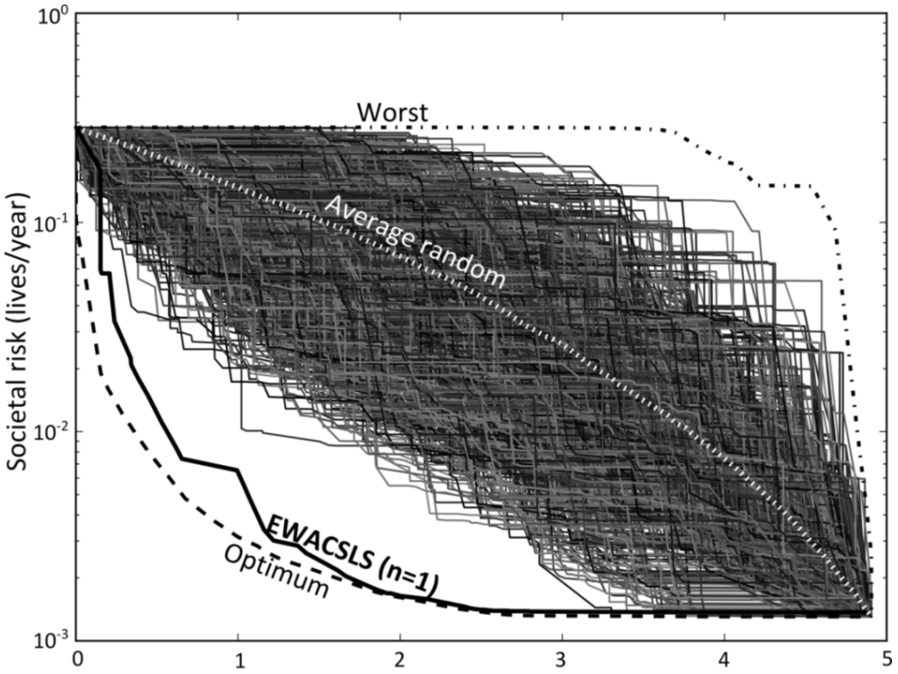

Figure 4. Comparison of the results of the 1000 randomly calculated cases with the sequence obtained with EWACSLS indicator in the societal efficiency variation curve.

In order to analyze in detail the results obtained through the use of the indicator proposed in this article, EWACSLS, several implementation sequences were obtained for different values of the *n* parameter: 20, 5, 2, 1, 0.5, 0.2 and 0.05. Figure 5 shows implementation sequences for different *n* values in the equity, societal efficiency and economic efficiency variation curves. It should be remarked that in each variation curve, optimum sequences have been obtained with a different indicator (CSFP, CSLS and ECBR respectively), since no sequence that is optimum for the three of them exists.

Table 4 shows how CTB indexes vary for different values of the n parameter. In this table, EWACSLS CTB values are compared with the results of the sequences produced by the other risk reduction indicators. The result labelled as "ACSFP/ACSLS" represents a sequence obtained combining these two indicators: ACSFP (with failure probabilities higher than 10^{-4}) and ACSLS (with failure probabilities lower than 10^{-4}). As can be observed in these results, EWACSLS, is not the optimum in any of the ratios, but has a very good score in all of them, being the most balanced of all of the indicators under study. Differences between the sequences obtained with ACSLS and EWACSLS are due to measures which are not so valuable from a pure efficiency point of view but are more justified from an equity point of view.

As can be observed in Table 4 and in Figure 6, higher *n* values produce better results of equity index, whereas lower values prioritize societal efficiency. Economic efficiency increases slightly with n, due to two opposed effects: if the value of *n* is lower, ACSLS is more important in the prioritization and has to take into account economic efficiency since it uses adjusted costs. If the value of *n* is higher, equity prevails, which also produces good economic efficiency in this specific case study, since none of the introduced measures directly diminishes economic consequences and that failure probability reductions produce a similar change of economic risk. In every case, the values of economic efficiency CTB are very good independently of the value of *n*.

In order to compare graphically how efficiency and equity principles are combined according to the value of parameter n, the CTB indexes obtained for both principles have been represented in Figures 7 and 8. These figures strengthen the notion that EWACSLS is a good criterion of measure prioritization since it combines evenly the principles of societal and economic efficiency with equity, obtaining values of their three CTB close to one.

Furthermore, with EWACSLS it is possible to vary a measure implementation sequence giving more or less relative weight to the principles of efficiency or equity thanks to parameter *n*, while still obtaining values of CTB indexes that are close to the optimal ones. As can be seen in Figures 7 and 8, the dotted line of EWACSLS varies between ACSLS ($n = 0$) and the ACSFP/ACSLS combination ($n \to \infty$), which is a logical consequence of its mathematical formulation. Finally, this indicator allows the introduction of a two-step-like process in an implicit way, since it only considers the equity principle when dam failure probability is over the IRL (10^{-4} in this case).

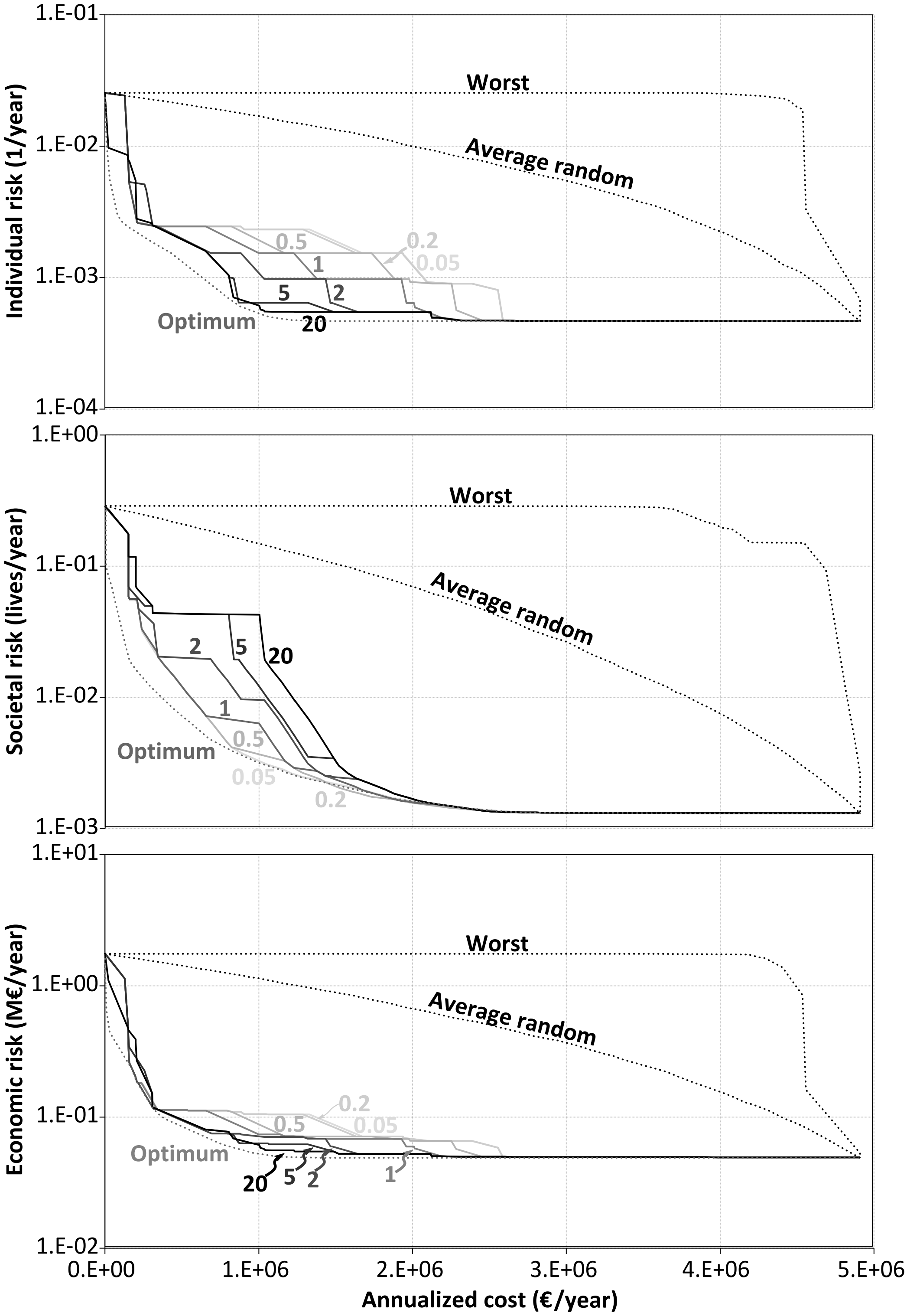

Figure 5. Implementation sequences for different n values in the variation curves of equity, societal efficiency and economic efficiency.

Indicator		Economic efficiency CTB	Societal efficiency CTB	Equity CTB
	n=0.05	87.9%	87.5%	79.8%
	n=0.1	87.9%	87.5%	79.9%
	n=0.2	88.0%	87.5%	79.9%
	n=0.33	89.1%	87.5%	81.8%
	n=0.5	89.3%	87.4%	82.2%
	n=0.75	89.7%	87.2%	84.0%
EWACSLS	**n=1**	90.2%	86.6%	84.7%
	n=1.5	91.4%	85.1%	86.3%
	n=2	91.8%	84.3%	87.7%
	n=3	91.7%	82.8%	88.1%
	n=5	92.0%	81.9%	89.2%
	n=10	92.6%	80.8%	90.3%
	n=20	92.5%	80.1%	90.5%
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 4. CTB indexes for EWACSLS (with different values of the n parameter) and the others risk indicators. Results in boldface show the highest and lowest values for each CTB index.

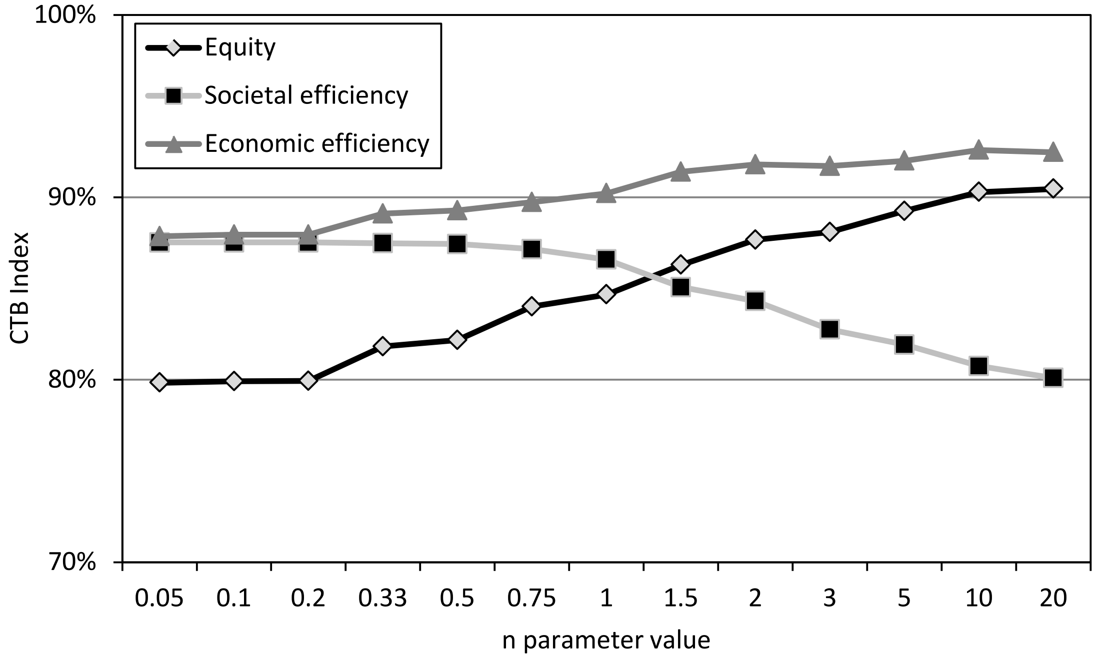

Figure 6. CTB variation for EWACSLS with different values of the parameter n.

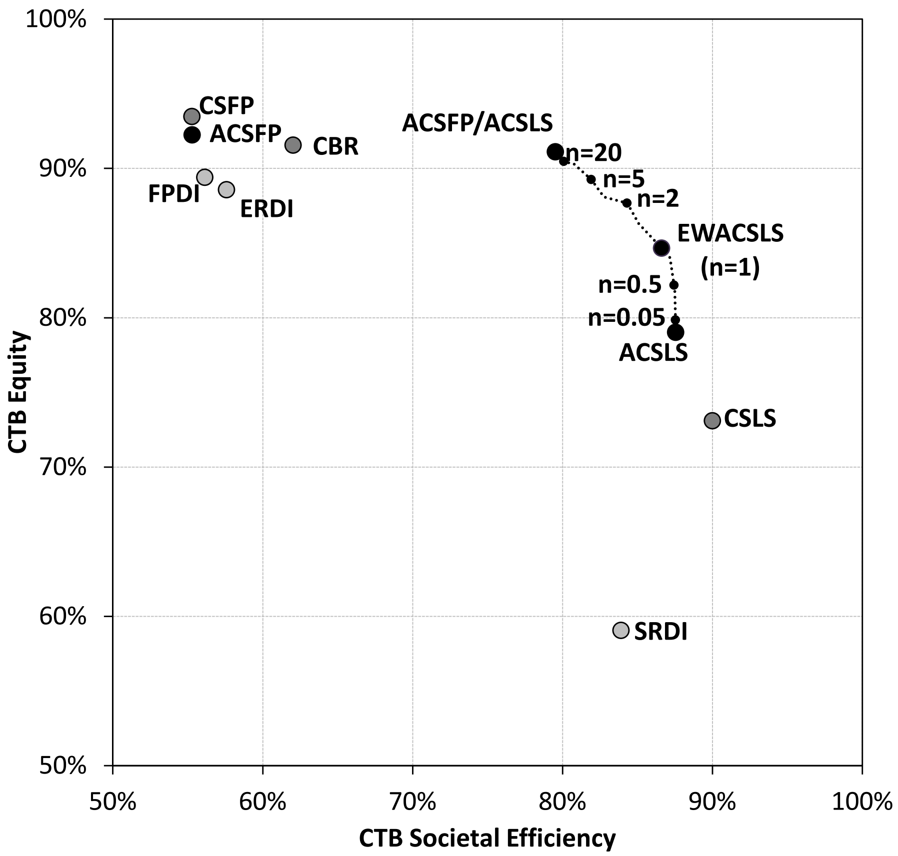

Figure 7. Comparison between societal efficiency CTB and equity CTB for EWACSLS and the other risk indicators.

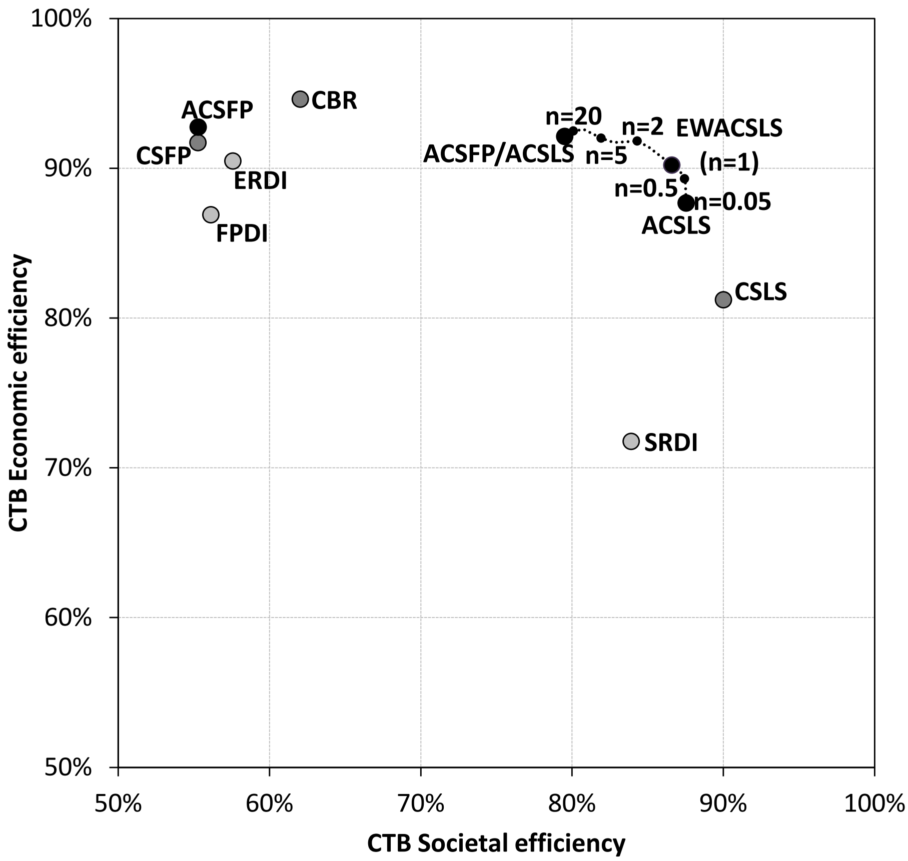

Figure 8. Comparison between societal efficiency CTB and economic efficiency CTB for EWACSLS and the other risk indicators.

5. DISCUSSION AND CONCLUSIONS

Governance of critical infrastructures safety is a complex process, where techniques, people, policies, resources, social norms, and information interact. For this reason, not only technical but also economic, social and political issues play a significant role. Quantitative risk analysis has proved to be a suitable methodology to inform dam safety management, since it provides a clear identification of the risks and of the effects of risk reduction measures.

In this context, risk reduction indicators are a useful tool to manage quantitative risk results since they allow risk managers to obtain prioritization sequences of very different structural and non-structural measures in a clear and justifiable way. These sequences should not be taken as a prescription but as a valuable input to decision-making and can be an input to a more global multi criteria analysis in order to combine them with other economic, social, psychological and political considerations.

Sound risk management is based on the efficiency and equity principles. Whereas equity is related to providing a certain level of protection to everybody, efficiency is related to reducing risks at the lowest costs. In many cases, these principles can conflict, producing different prioritizations of risk reduction measures. This conflict between equity and efficiency principles is the underlying motive of this article, as existing risk indicators are either based on the equity or efficiency principles but cannot accommodate both at the same time.

The Equity Weighted Adjusted Cost per Statistical Life Saved (EWACSLS) indicator presented in the article enables to obtain a prioritized sequence that balances efficiency and equity while offering good results for both principles. Moreover, the indicator has been formulated in a flexible way, such that by changing one parameter (n), more or less relative weight can be granted to efficiency or equity. These advantages make EWACSLS an excellent indicator for real-world use in risk management decision making which smoothly blends efficiency and equity considerations.

The utility of this indicator has been proved in a real case study of 27 dams with 93 potential risk reduction measures to be prioritized. The sequence obtained with EWACSLS has been compared with sequences obtained with other existing risk reduction indicators. Results show that EWACSLS is not the best from any single perspective, but has very good results from all of them, being the most balanced of all of the compared indicators.

This paper is mainly focused on risk analysis to inform dam safety management, but the EWACSLS indicator can also be used in other fields in order to analyze quantitative risk results for safety management. The concepts and the dilemma behind this indicator are equally appropriate for other critical infrastructures, since combining equity and efficiency principles is of vital importance for a balanced and integrated risk management.

In real cases, the prevailing principle will depend on the preferences, values and legal restrictions of each country and owner. In any case, comparing and combining both principles in a flexible way will be very interesting for managers, especially in the public sector, where equity and efficiency principles have traditionally produced more conflicts.

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