INDICATOR SCALING FOR DAM SAFETY USING RISK ASSESSMENT THROUGH FUZZY LOGIC APPROACH

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ABSTRACT

The benefits of dams are unquestionable, with the water impoundment upstream and flood-control downstream usually being sufficient to increase investments and promote growth. However, their presence brings risks to the downstream population and the environment which must be properly managed in a continuous and updated process. The desire to better understand the risk posed by dams to the public requires shifting beyond a deterministic based assessment of its dams. Risk assessment and risk management were viewed as a logical method to prioritize the resources for the most benefit to the public. This paper proposes to apply fuzzy approximate reasoning for dam safety risk assessment, initially using a FAHP to weight the importance of the indicators suggested by dam experts and then adopt linguistic variables in a two stage risk assessment in the Indian context during the ICOLD 2020 conference. The risk of dam collapse, hereinafter called dam break shall be considered. The combined effect between the risk of a dam collapse and the socioeconomic and environmental impact on the surrounding area shall be evaluated, hereinafter called potential risk. The importance of extracting the knowledge of experts and incorporating it in the model specification through fuzzification of variables and the rule-based construction shall be highlighted from the study.

Keywords **:** *Risk assessment, Indicators, Fuzzy logic, Dam break, Potential risk.*

1. INTRODUCTION

Large dams as well as protective dikes and levees are critical infrastructures whose failure has high economic and social consequences. Although usually very low, these infrastructures have an associated risk that must be properly managed in a continuous and updated process. In the dam safety context, risk can be estimated by the combined impact of the scenario, probability of occurrence, and associated consequences (ICOLD, 2003). Risk analysis is a useful methodology that encompasses traditional and state-of-the-art approaches to manage dam safety in an accountable and comprehensive way (Bowles, 2000; Serrano-Lombillo et al., 2013). The development and application of risk assessment techniques worldwide in the dam industry (ANCOLD, 2003; ICOLD, 2005; SPANCOLD, 2012; USACE, 2011) has helped inform safety governance and support decision making in the adoption of structural and non-structural risk reduction measures. The concept of risk comprises both uncertainty and some kind of loss or damage that might happen. In other words, risk is the possibility of loss or injury and the degree of probability of such loss (Kaplan and Garrick 1981).

Risk assessment is primarily used for analyzing the probability of accidents under all kinds of conditions, and the consequences of these potential accidents, such as loss of life and economic loss, and negative impact on society and the environment. In addition to the risk criteria, determining whether the public can accept or tolerate the risk is also part of the assessment. As a result, a reasonable system for developing risk criteria is the key to obtaining an accurate and reliable risk assessment.

Risk assessment method for dam safety can fall into three categories: standard-based (International Commission on Large Dams 2005), and qualitative and semi-quantitative approaches (Cooper et al. 2005). The standard-based approach relies on the use of classification systems as a basis to identify the hazardous nature of dams, the relative severity of the consequences of failure, design loads for unlikely events, and safety coefficients (Aydemir and Güven 2007; Brown et al. 2009; Hariri-Ardebili and Saouma 2015; Kalinina et al. 2016). The qualitative techniques are based on nominal or descriptive scales, fully supported by an engineering judgment approach (Hughes et al. 2000; Morris et al. 2012; Shi et al. 2017). Semi-quantitative techniques extend the qualitative techniques by allocating numerical values to the descriptive scales. These numbers are used to derive quantitative risk factors for likelihoods and consequences (Bocchiola and Rosso 2014; Hartford and Baecher 2004; Hernández et al. 2012).

The engineering standard-based approach has been a consolidated procedure over the years for dam safety assessment and management. Dam engineers have historically included uncertainty as part of their best practice methods, such as the safety factors. Lately, these professionals have reached a consensus on the role and usefulness of risk assessment as an aid to dam safety management (International Commission on Large Dams 2005).

The estimation of dam break low probabilities is impaired due to scarcity of major accidents' relevant data, partly assessed by accident precursor data and Bayesian modeling technique (Khakzad et al. 2015; Yu et al. 2017). Many of the indicators that have to be quantified are subjective, not well defined, and imprecise. The non numerical definition of the likelihood and, in some cases the consequences, forces the adoption of linguistic variables, subjective thresholds, and rating scales (Cole and Withey 1981). Fuzzy inference can be used to deal with such imprecision and to quantify the likelihood and consequences (Tah and Carr 2000).

An additional issue arises when the risk assessment deals with vague concepts expressed in natural language. The link of crisp numbers with the corresponding linguistic terms of the subjective scales can result in a certain level of vagueness. Fuzzy conditional statements are an efficient tool to formulate rules in linguistic terms and create 'If–Then' sentences to compare the antecedent inputs for the parameters with their consequent results. Thus, all the rules that have any truth in the input–output relation will contribute to the fuzzy conclusion set. FAHP technique is one of the efficient tools to perform a hierarchical ranking and weight assessment (Taylan et al. 2014).

This paper employs the novel fuzzy-based methodology developed by (Ribas & Pérez-Díaz, 2019) for dam safety risk assessment simultaneously using an FAHP to weight the importance of the indicators suggested by a dam expert and adopting an FES in a two-stage risk evaluation. This paper attempts to utilize the knowledge of experts present during the ICOLD 2020 conference to be held in Delhi to fix the intervals of indicators for fuzzy based dam safety risk assessment in the Indian context. The uncertainties in the assessment of risk of the dam collapse through indicators can be reduced with more reliable inputs from dam experts. The indicators of combined effect between the risk of a dam collapse and the socioeconomic and environmental impact on the surrounding area can also be improved using such inputs.

2. METHODOLOGY

Sohler and Caldeira (2016) proposed a bottom-up method for dam failure risk assessment that performs criticality analysis and severity classification assigned to specific indicators subjectively evaluated, with scales ranging from one to a variable upper limit. Their ground rules are based on the upper limits laid down by the local dam safety regulations. Three risk categories are established: (1) the potential danger, involving the indicators related to the project specification; (2) the potential vulnerability, involving the indicators related to the procedure for regular monitoring; and (3) and the potential impact, containing the indicators related to the socioeconomic and environmental consequences' downstream.

In this study, the set of indicators of dam threat, dam vulnerability, and potential impact can serve as the framework for a method involving fuzzy weighting, scoring, and inference phases for the Indian region. In the weighting phase, the measurement of preferences among indicators can be performed through the Simos method and converted into the corresponding Saaty scores, arranged in a matrix of paired comparisons. TMFs and FAHP method can be used to determine the weights for each of the indicators and their related interval scales. Then, expert based input system shall be constructed for the dam break and potential risk using fuzzy rule bases. The defuzzification shall convert fuzzy sets into single crisp indexes. The danger scale of dam break and the hazard scale of potential risk can be constructed.

A flowchart representing the different stages of the risk management process carried out by the proposed methodology is shown in Fig. 1. As can be seen, there are interventions of expert R and expert D in all phases of the risk assessment process. This paper attempts reduce the uncertainties by taking reliable inputs for informed decision making. The model has two entities, as shown in Fig. 1: the contexts composed by the Dam Threat, representing the manner in which design and construction were performed; Dam Vulnerability, resulting from the operational and safety procedures; and Potential Impact, characterized by the socioeconomic and environmental consequences on the surrounding area; and the indicators inherent in each context which are the elements that indicate or contribute to a specific state or risk level.

3. INDICATORS AND INTERVALS

The indicators used for assessment of dam risks as proposed by Ribas & Pérez-Díaz (2019) have been given in Table 1, 2 and 3 for Dam Threat, Dam Vulnerability and Potential Impacts respectively.

Table 1 : Dam Threat indicators and intervals

Indicator	Intervals
Design outflow (DO)	(1) $1000 < T < 10{,}000$; (3.3) $500 < T < 1000$; (6.7) $100 < T < 500$; (10) $T < 100$, where T is design return period in years
Dam height (DH)	(1) $H \leq 15$; (3) $15 < H < 30$; (6) $30 < H < 60$; (9) $H > 60$, where H is the dam height in meters
Dam type (DT)	(1) Concrete dam; (3) Rockfill dam; (5) Earthen dam
Foundation material (FM)	(1) Bedrock; (3) treated rock; (5) treated alluvium; (7) sandy alluvium

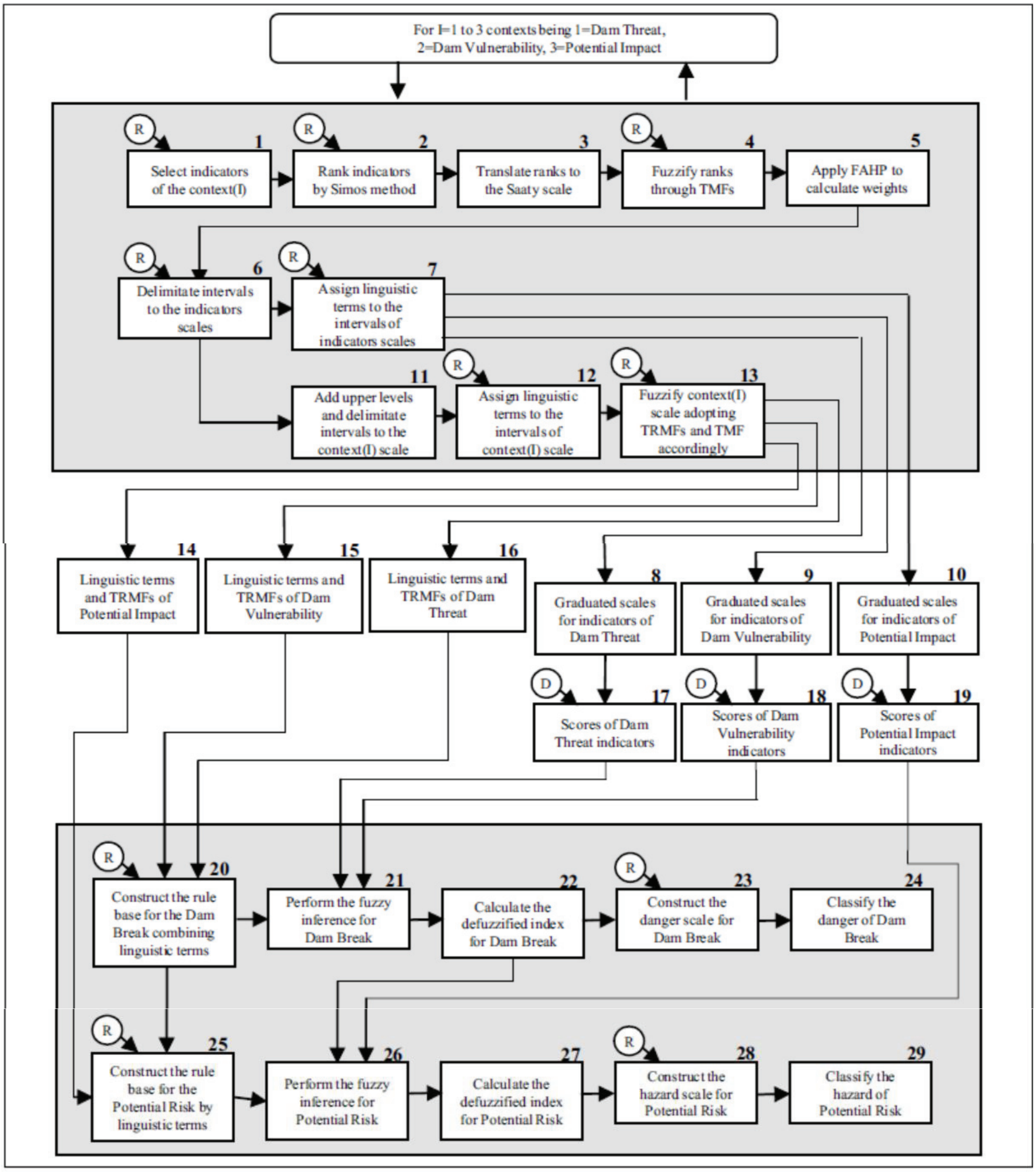

Figure 1 : Fuzzy development process of dam safety assessment (Adapted from Ribas & Pérez-Díaz, 2019)

Table 2 : Dam Vulnerability indicators and intervals

Indicator	**Intervals**
Technical expertise of the safety staff (TE)	(1) A certified professional belongs to the staff; (5) there is no certified professional on the staff
Dam safety report (DS)	(1) Regular dam safety report; (2.5) dam safety report at irregular intervals; (5) does not issue a dam safety report
Availability of basic and detailed design, As-Built (AD) (1)	Complete set of designs; (3.5) incomplete set of designs; (7) there are no designs
Instability of slopes (IL)	(1) Slopes are stabilized; (3) protection failure of slopes and walls; (6) surface cracks, exposed reinforcement, growth of vegetation; (9) large depressions on the slopes, landslides, and deep erosion furrows

Water percolation through the dam (WP)	(1) Percolation is controlled by the drainage system; (3.3) monitored humidity or flooding downstream; (6.7) humidity or untreated water flood downstream being diagnosed; (10) occurrence of an increasing flood carrying solid material downstream
Cracks and deformations at the dam (CD)	(1) Cracks and fractures are in conformity with design; (3.3) cracks and fractures of small extension; (6.7) cracks and fractures of medium exten-sion; (10) cracks and fractures of large extension
Spillway reliability (SR)	(1) System fully operational and spillway is unobstructed; (2.7) system is operational, without emergency power, and/or spillway has small obstructions; (5.3) system is out of service and being repaired and/or spillway is partially obstructed; (8) system is out of service without repair pending and/or spillway is almost totally obstructed
Frequency of assessment of dam performance (FA)	(1) Regular inspections with issuance of reports; (2) inspections are not regular; (3) there are no inspections
Condition of the equipment (CE)	(1) Good; (6) fair

Table 3 : Potential Impact indicators and intervals

Indicator	**Intervals**
Water volume of the reservoir (VR)	(1) VR ≤ 5 million; (2.7) 5 < VR ≤ 75; (5.3) 75 < VR ≤ 200; (8) VR > 200. VR in million m3
Economic impact downstream (ED)	(1) No residential damages or expenses < USD 200,000; (3.3) fewer than 5 damaged residences or expenses < USD 1 million; (6.7) fewer than 49 damaged residences or expenses < USD 10 million; (10) more than 49 damaged residences or expenses > USD 10 million
Social impact downstream (SD)	(1) Nobody was affected; (3.3) people affected < 100 or LPC < 10%; (6.7) people affected < 1000 or LPC < 30%; (10) people affected > 1000 or LPC > 30%. LPC: loss of productive capacity
Environmental impact downstream (EI)	(1) AA < 0.1 or ID < 1 or no ecological impact; (3.3) AA < 1 or ID < 24 or only flora affected; (6.7) AA < 10 or ID < 240 or fauna and flora affected; (10) AA > 10 or ID > 240 or severee ecological impact. AA: affected area in km2; ID impact duration in months
Dam Capex—relatively to others (DC)	(1) Small; (2) medium; (3) high (5)
Generation capacity (GC)	CG ≤ 30 MW; (3.4) CG ≤ 250 MW; (1.7) CG ≤ 500 MW; (1) CG > 500 MW.
Early warning and alert system (WA)	(1) Available and processed automatically; (6) available and not processed automatically; (9) unavailable

4. WAY FORWARD

Through this paper it is proposed to utilize the knowledge of domain experts to fix the intervals and the scale of the dam safety risk assessment indicators. This can then be used for fuzzy based risk assessment of dam safety. The importance of extracting the knowledge of experts and incorporating it in the model specification through fuzzification of variables and the rule-based construction is the need of the hour for reliable assessment of dam safety.

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