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Dam risk management framework on the lifecycle of dam: A comparative analysis in a legislation perspective

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Abstract

Dams play essential roles in water management and produce renewable energy but pose high potential risks, not only for communities downstream of the dam but also for economic and environmental damage. Risk management is an effort to reduce dam risks by knowing the measurable risk factors in a dam. Several countries have adopted risk management as one of the cycles in ensuring dam safety and include it in applicable regulations and guidelines. Using the comparative analysis method, this paper will compare risk management regarding regulations and guidelines in the context of dam safety in various countries such as New Zealand, India, Spain, and Indonesia. These results show that dam hazard classification is the primary basis for determining design, construction, operation, and maintenance criteria, such as design flood design and earthquake analysis. All of the countries stated that risk management is mandatory in the lifecycle of the dam, but only Indonesia still makes it voluntary. Guidelines on risk analysis have been prepared in each country to explain the legislation and regulations that have been established. Considering the current conditions where society demands transparency in decision-making, dam risk assessment as a method to assess risk-based information is essential, and regulations related to risk management should be made mandatory in the lifecycle of dams.

Keywords: Dam risk management, Dam safety, Legislation, Hazard, Risk-based decision.

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1. Introduction

Since ancient times, dams have been built to store water to fulfill people's needs [1]. As the population grows, dams play an essential role with benefits such as irrigation, hydropower, navigation, water supply, recreation, and floating

photovoltaic [2, 3]. Before 1900, it was estimated that there were 700 dams worldwide. Currently, the number of dams built worldwide is more than 45,000, with various benefits [4]. However, these water infrastructures always pose potential risks to people and property in the downstream area [5]. Understanding these hazard potentials will lead the stakeholders to prioritize management planning in the future to get a sufficient level of dam safety [6].

Dam development will increase the economy and population in the downstream area [7]. Conversely, dam failure can also impact the economy and finances [8]. Adopting legal standards of hazard potential classification across a portfolio of dams is expected to guarantee optimal prioritization in emergency preparedness measures [9]. Dams have multihazard risks, where one failure can trigger damage in other sectors [10]. Flood risks in ageing dam management in China have been adopted to rank dam rehabilitation, decommissioning and surveillance [11]. Other risks related to dam safety are constructive breaches in the filter and drain systems, concrete galleries, concrete bypass channels, and critical operational issues over the years of operation, which happened because of a lack of dam risk management [12]. Failure of dams caused catastrophic damage, such as Fundao's dam failure in Brazil, which released 44 million m^3 of tailings that recently established a value of US$ 43.8 billion to repair losses and damages [13].

Apart from that, society currently demands transparency in decision-making, so in determining the final decision related to dam safety, a risk assessment is needed so that all the risks in the dam are known [14]. A risk management framework could integrate the dam's design, construction, operation, and maintenance related to risk to ensure effective mitigation of natural and anthropic threats [15]. In order to build a dam hazard classification database, identification of each dam is required [16].

To preserve the sustainability of existing dams, various maintenance, repair, and rehabilitation efforts on old dams need to be carried out to improve their safety and operational performance [17]. Hazard identification, risk assessment, risk analysis, and how to reduce the risks are the core of risk management [18]. For agencies or business entities with many dams, the risk assessment framework provides a means to calculate the most effective costs for repair or rehabilitation actions to choose a priority scale with the most effective available time and funds [19].

In recent years, several works have been done to discuss the risk on dam, including: natural based system could measures to mitigate flood hazards as part of reducing risk [20]. Estimation on potential flood damage to roads is entirely based on the safety of people can be employed within the decision-making process in food risk management [21]. Risk management can mitigate flood risk management in transboundary area towards understanding the future impact (under climate change) of dam development and flood frequency reduction [22] analyzing the differences in dam risk assessment between probabilistic and non-probabilistic [23] scientific grouping on people at risk at the downstream in the risk evaluation, improving the effectiveness of risk control and help stakeholder allocate the funds for risk elimination and dam reinforcement more reasonably [24] evaluating the basis of indexes of environmental impact of dam break to reduce environmental risk [25] quantitative risk assessment using a data-driven method based on multivariate copulas to consider the correlation of displacement between each monitoring point at gravity dam [26] analysing human risk assessment after the initial filling of the reservoir which focused on residents affected by reservoir flooding [27] assess risk level in embankment dam focusing in dam safety which provide a complete and detail view of the risks that the owners must focus in their future inspections [28] dam hazard classification using a risk matrix approach with 4 dam hazard risk categories [29] determination of dam hazard risk using spatial quantification criteria in several scenarios for current, rehabilitated and demolished dams [11].

The existing dams have been a vital water resource infrastructure; due to the ageing of dams and reservoirs, at least a dam safety program should consist of dam inspection and rehabilitation programs (proactive), emergency action plans (reactive), and recovery plans (post-active) [30]. Based on dam failure in Brazil, improving the legislation and developing the safety management field is crucial to lessen the risk of negative consequences such as economic and financial impact [31]. The European Directive Floods of 2007 (2007/60/CE) or the European Directive of Protection of Critical Infrastructure of 2008 (208/114/CE) reflects risk-based informed decision-making to cope with the risk in dams. In the United States, the US Army Corps of Engineers (USACE), together with the Federal Energy Regulatory Commission (FERC), started to use risk information in 2005 as the basis of dam safety decisions. In comparison, the Bureau of Reclamation (USBR) started this method in the 1990s—other countries, such as France, already nationally used risk management on specific laws in 2008. Risk management, as stated in legislation that minimizes dam failure by reducing operational risks, is still insufficient in developing countries.

The objective of this paper is to comparatively analyse how dam risk management is being addressed by the water resources or dam safety legislation, the guidelines that support the integration of risk management, and the dam safety regulations in four countries where the construction of dams is still being considered for various purposes and to face issues such as flood protection, raw water supply, irrigation, and hydropower requirements. Floating photovoltaics at the dam reservoirs is a new technology that adds the benefit of the dams but also increases the risk at the dam [3]. The authors' interest in studying New Zealand and Spain is due to their experience in developing risk management of dams. India and Indonesia represent the countries with a dense population downstream of the dams, but the development of the dams is still ongoing. First, to understand how the legislation related to dam safety addresses dam risk management, at what stages, and their main similarities and differences. This analysis is made with the belief that if the legislation powerfully addresses dam risk management, the decision-making related to dam safety based on risk-based information is higher. Second, to understand if these countries adopted specific guidelines to incorporate risk management to provide further support to practitioners and stakeholders and how. Third, to understand if the dam safety regulations include risk analysis and are used to improve dam safety, and how the risk reductions are made. This study contributes findings on both similarities and

differences in legislation between Indonesia, as an example of a developing country with a dense population, and other countries, and highlights the relevance of the regulation for dam risk management in the future.

2. Method

The comparative analysis is used to identify similarities and differences in the approach of different countries to the subject [32]. Comparative analysis generally starts with a specific case comparable with specific characteristics guided by a theoretical framework [33]. Qualitative comparative analysis can evolve as a method and technique for investigating theoretical and managerial implications [34]. The comparative analysis was then performed on a set of dam legislation and dam safety regulations published in the official legal channels of each country. The analysis focused on the references to dam risk management in the bill, the supporting guidelines, and the dam safety regulations. The comparative analysis has been structured according to the following steps.

2.1. Identification of the Document

This stage included identifying the legal documents that frame each country's dam risk management process. Only diplomas published by official channels such as the New Zealand Legislation website, the Ministry of the Presidency, the website from the Ministry of Justice, and relations with the courts of Spain (Ministerio de la Presidencia, Justicia Y Relaciones Con la Cortes), National Informatics Centre website of India and the Ministry of Public Works and Housing of Indonesia were considered. In addition, national guidelines for integrating risk management and dam safety regulations were identified in the same official channels and within the web pages of the New Zealand Society on Large Dams, the Central Water Commission of India (Ministry of Jal Shakti), Spain Committee on Large Dams (SPANCOLD). The author obtained guidelines in Indonesia directly from the Dam Safety Unit, Ministry of Public Works and Housing, which prepares guidelines related to risk assessment. For coherence between countries in the comparative process and to reduce the complexity in the analysis of the legislative documents, only legislation at the national level was considered for this paper. The documents considered for the comparative analysis are presented in the following table (Table 1). As can be observed, all four countries have official legislation related to dam safety and technical guidelines to support it.

Table 1.
Document Considered for Comparative Analysis.

New Zealand	India	Spain	Indonesia
Dam Safety Legislation			
Resource Management Act [35]; Building Act [36] and Building (Dam Safety) Regulations [37]	Dam Safety Act [38]	Technical Regulation about safety of dams and reservoirs (RSDR)	Ministerial regulation of the Ministry of Public Works and Housing 9MR MPWH) No. 27/2015 about dams, 2015
Guidelines related to dam risk management			
Dam Safety Act [38] Module 2: Consequence Assesment and Dam Module 7: Life Cycle Management	Guidelines for assessing and managing Guidelines for Classifying the Hazard	Technical Guide on Operation of Dams and Reservoirs, Volume 1: Risk Analysis Applied Dam classification according to potential risk	Technical guidelines: Dam Hazard Technical guidelines: Dam Risk Assessment
Guidelines incorporating risk management into dam safety			
Dam Safety Act [38]: Module 5: Dam Safety Management Module 6: Emergency Preparedness	Dam Safety Act [38] Guidelines For Safety Inspection of Dams Guidelines for Developing Emergency Action Plan for Dams Guidelines for instrumentation of Large Dams	Technical Guidelines: Elaboration of Emergency Action Plans Technical Regulatin about safety of dams and reservoirs (RSDR)	Indonesia National Standard: procedure of determination of Flood Design and spillway capacity for dams

2.2. Document Analysis

Subsequently, the whole text of each document was analyzed in search of keywords that included ‘risk management, ‘risk, ‘hazard,’ and ‘hazard classification.’ The search for the terms in each document was done with the help of the PDF search function, which does a simple search for the number of occurrences and identifies their location within the text.

2.3. Analysis of Results

Each document recorded references to dam risk management. The legal article in which the reference appeared and the context in which it appeared were registered. The references were categorized according to the scope of work related to risk management, the Hazard potential classification system, the actor, and decision-making.

2.4. Comparative Analysis

A comparative analysis of the references to dam risk management identified in the previous step was performed considering its context within the legal document related to dam safety and in the guidelines related to risk management, such as risk assessment. In addition, the context of the references in each document was compared considering the questions in the following table (Table 2). Several questions were set up based on previous comparative analyses of dam risk management and legislation that have been collected [33, 39, 40]. The criteria for comparing legislation in these studies varies according to the conceptual framework [41] and is related to dam safety, focusing on risk management [42]. The questions were prepared and formed the basis of the comparative analysis of the legal framework of risk management in New Zealand, Spain, India, and Indonesia, presented in this paper. The results of the comparative analysis are presented in Section 4. The following section (Section 3) presents a brief overview of each country's risk management legislative framework, guidelines, and existing dams' safety regulations.

Table 2.
The question that formed the basis of comparative analysis.

1. Risk Management Framework in Dam Safety Legislation
1.a Does the country have dam safety regulation and are these mandatory?
1.b is the risk management stated in Dam Safety legislation?
1.c Who is responsible to implement dam risk menagement?
2. Guidelines about Dam Risk Management
2.a Does the country have the specific national guidelines concerning about dam risk management?
2.b How is risk management framework reffered in the guidelines?
2.c Is the hazard classification statde clearly in the guidelines?
2.d What are the factors to determine hazard classification?
2.e Are there any consequences regarding to the hazard classification?
3. Guidelines reffered to risk Assesment in dam safety framework
3.a Is the Process of risk assesment describe clearly in the guidelines?
3.b Are the risk indocator stated in the guidelines?
3.c Do the guidelines provide recommendation for the results of risk assesment?

3. Country Overview

3.1. New Zealand

The legal obligations and liabilities used to control and regulate dam safety it at the national level in New Zealand were the Resource Management Act [35]. In 2021, the Government announced plans to repeal the RMA and replace it with three new pieces of legislation: Natural and Built Environments Act, Spatial Planning Act, and Climate Change Adaptation Act. The RMA applies for resource consents relating to dams to have dam safety-related consent conditions. In the RMA consent process, the applicant must demonstrate that the dam's design, construction, and operation practices will address hazards potentially impacting the environment.

The Building Act [36] provides for the control of building work and is focused on performance-based criteria relating to construction methods. The RMA governs land and water use, and the Building Act [36] governs construction and subsequent use. The Building Act [36] contains extensive provisions for dam construction and safety, which must be read together with the Building (Dam Safety) Regulations [37]. This Act also sets the requirements from the owner to the regional government, such as notification of the size and location of classifiable or referable dams and the preparation and maintenance of dam safety assurance programs. These programs also include the evaluation of each dam every 5 (five) years.

The Building (Dam Safety) Regulations [37] includes a specified methodology for determining dam classifications, criteria, and standards for dam safety assurance programs, which provide a basis for Recognised Engineers to certify dam classifications and certify dam safety assurance programs. The Building (Dam Safety) Regulations [37] enables the implementation of the legislation requirements relating to classifiable dams contained within the Building Act [36]. The Building (Dam Safety) Regulations [37] includes A framework for the classification of dams, according to the potential downstream effects that would result from a dam failure; Competency requirements for Recognised Engineers; Criteria and standards for dam safety assurance programs; Dam classification, dam safety assurance, and annual compliance certificate requirements.

3.2. India

The dam safety regulation in India was stated in the Dam Safety Act [38] by the Ministry of Jal Shakti. The Bill declares that dam owners must prepare an emergency action plan and conduct risk assessment studies for each dam at specified intervals. The guidelines related to risk management were explained in Guidelines for Dam Safety Act [38] which explains how to classify risk hazards in India. These hazard classifications are used as the basis for analyzing Inflow Design Flood, Requirement of Dam Instrumentation and Frequency of Monitoring, Inspection, and Maintenance, Requirement for Emergency Action Plans (EAP) and their revision, Dam Safety Risk Assessment, and Seismic Hazard Assessment (SHA).

Guidelines for Dam Safety Act [38] have been established to calculate dam risk assessment. These guidelines explain how to do it step by step.

The risk management program safeguards dams' value, explicitly addresses uncertainty, relies on the best available information, promotes continuous improvement and organizational enhancement, and offers a structured, transparent, dynamic, and iterative framework for informed decision-making.

3.3. Spain

The Ministerio de Agricultura, Alimentación y Medio Ambiente (MAGRAMA) oversees the legal framework for dam safety in Spain. It has evolved from the 1967 'Instrucción para el Proyecto, Construcción y Explotación de Grandes Presas' to the 1996 'Reglamento Técnico sobre Seguridad de Presas y Embalses,' which places a greater emphasis on safety aspects.

Due to overlapping applications of the 'Instrucción' and 'Reglamento,' MAGRAMA developed the Normas Técnicas de Seguridad (NTS) to create a unified legal framework for dam safety regulations. The Dam Safety Technical Guides, created by SPANCOLD and ICOLD in collaboration with the Spanish Professional Association of Civil Engineers, provide essential guidelines and best practices for achieving the safety goals outlined in the legal documents. These guides, developed by experienced professionals, serve as a reference for the technological advancement of normative criteria in dam safety, benefiting professionals worldwide.

3.4. Indonesia

Regulations regarding dam safety in Indonesia are contained in the Minister of Public Works and Public Housing Regulation No. 27/2015 about dams. Generally, this regulation discusses the dam construction and management process, including license at the dam's design, construction, impounding, operation and maintenance, and closure stages. To support the implementation of dam safety, the Indonesian government, through the Ministry of Public Works, has issued several guidelines related to risk management, such as Technical Guidelines: Dam Safety Act [38] and Technical Guidelines: Dam Safety Act [38].

Determining dam hazard classification is used in determining dam design, such as the design of flood capacity for spillways. Risk-based decision-making is still not a reference in regulations. However, it has been implemented in several projects.

4. Results

The comparative analysis was conducted following the methodology outlined in Section 2. First, the findings focus on the references to dam risk management in dam safety legislation, then in the dam risk management guidelines, and finally, in the dam risk management incorporation into dam safety guidelines. Table 3 summarises the references about risk management concerning dam safety in the legal documents that frame the dam risk management of New Zealand, India, Spain, and Indonesia. Table 4 compares the guidelines for integrating risk assessment into risk management followed by those countries. The following paragraphs analyze the results observed for each significant question in Table 2 (Section 2), as describe in Table 5.

4.1. Risk Management Framework in Dam Safety Legislation

4.1.1. Does the Country Have Dam Safety Regulations, and are These Mandatory?

New Zealand, Spain, India, and Indonesia legislation addresses dam safety.

4.1.2. Is the Risk Management Stated in Dam Safety Legislation?

The dam risk management framework is referred to in dam safety legislation in all countries. New Zealand law acknowledges hazard classification in medium and high Potential Impact Classification (PIC) dams, which require a dam safety assurance program to fulfill dam safety functions, post-earthquake inspection procedures, and emergency preparedness procedures. India highlights that dam owners must prepare an emergency action plan and conduct risk assessment studies for each dam at specified intervals. Spain is determined to establish the safety criteria that must be considered to prevent and socially and environmentally limit the potential risks that these infrastructures may represent. In contrast, Indonesia stated that dams with high-risk hazards should have a license from the Ministry of Public Works and Housing in every stage, such as design, construction, impounding, operation, and maintenance. Finally, it includes the fact that risk management has been a concern in dam safety regulations in all countries.

Table 3.
References of Risk Management Framework in Dam Safety Legislation.

Scope of Works	New Zealand (BDSR, 2022)	India (DSA, 2021)	Spain (RSDR, 1996)	Indonesia (MR MPWH No. 27/2015)
Scope of regulation related to risk management	Medium and High Potential Impact Classification dams are required to have a dam safety assurance programme to fulfil dam safety functions, post earthquake inspection procedures, and emergency preparedness procedures.	Dam owners will be required to prepare an emergency action plan, and carry out risk assessment studies for each dam at specified regular intervals.	To establish the safety criteria that must be taken into account to prevent and socially and environmentally limit the potential risks that these infrastructures may represent.	Dams which have high risk hazard should have license from Ministry of Public Work and Housing in every stage such as design, construction, importing, operation and maintenance.
Hazard potential classification system	(...) requires a dam owner to give the dam one of the following classifications: (a) low potential impact (b) medium potential impact (c) high potential impact. (Section 8)	"The State Dam Safety Organisation shall classify each dam under their jurisdiction as per such vulnerability and hazard classification criteria as may be specified by the regulations." (Section 17)	Depending on the potential risk that may arise from their possible breakage or incorrect operation, all dams must be classified, in accordance with the Civil Protection Planning Directive against Flood Risk, in one of the following categories: Category A, (..)B, and C (..) (Section 3.2)	-
The Actor	The owner of a dam must, (..) '(e) determine the dam's potential impact classification by correlating the damage level (..) with the estimated population at risk and the estimated potential loss of life.' (Section 9-1)	Every owner of a specified dam, for each of its dam shall, carry out risk assessment studies at such interval as may be specified by the regulations (..) (Section 35-2)	The owner will prepare and keep updated a Technical File of the dam (..): a. Classify the category of dam by determining the people at risk category, according to the risk; (..) (Section 5.5)	In order to fulfill the dam safety, dam safety unit should (..): (f) dam inventory and registration and hazard classification. (Section 148-2)
Decision making	Hazard classification related to identifying an earthquake or a flood of a particular intensity or flow rate. (Section 19)	Hazard classification is used to determine the competent levels of engineers in the dam safety units; the time interval for the risk assessment studies updating the emergency action plans, and the comprehensive safety evaluation. (Section 9;1 additional note)	(...) The period of inspection of dams (Section 5.8); (...) Check compliance with the loading program by monitoring its process and its incident (Section 6.1); (...) flood hydrograph (Section 10.5); spillway capacity (Section 15.3); structural safety (Section 16.1); seismicity (Section 18.2); hydromechanical and electricity (...) (Section 23.1)	-

Table 4.
Brief comparison of guidelines about integrating risk assessment into risk management.

Scope of Works	New Zealand (DSG, 2023)	India (AMARD, 2019)	Spain (RAAMDS, 2013)	Indonesia (DRAJ, 2011)
Scope of regulation related to risk management	• As part of wider infrastructure systems, dams should incorporate resilient features to safely withstand unusual and unexpected events. • A high standard of care should be adopted during the design, construction and rehabilitation of any dam and, where appropriate, additional resilient features should be provided to reflect the consequences of dam failure. • If the consequences of a dam failure are major and extend well beyond the downstream river, additional risk management procedures and resilient features should be included to reduce the likelihood of a dam failure.	• Integrate the dam's design, construction and operation in framework of risk management that ensure effective mitigations of natural and anthropic threats. • Risk Management encompasses activities related to making risk-informed decisions by prioritizing new studies and instrumentation, prioritizing risk reduction actions (structural and non-structural), and making program decisions associated with managing a portfolio of dams.	• Integrated safety management of infrastructures which are relevant for the society focusing on identification, analysis and evaluation of dam safety risk analysis. • The risk management approach: the approach creates and protects value; is an integral part of organizational processes; is part of decision making; explicitly address uncertainty; is systematic, structured and timely; is based on the best available information; is tailored; takes human and cultural factors; is transparent and inclusive; is dynamic, iterative and responsive to change.	• To preserve the existence of the dam, various maintenance, repair and rehabilitation efforts on the dam must be carried out to improve the safety of the dam and its performance. • Due to the large number of dams that must be repaired which requires large costs, this cost efficiency can be achieved by implementing a priority system by considering the hazard status of the dam in terms of safety or the magnitude of the risk of dam failure due to natural disasters such as earthquakes, floods, etc.
Risk Management Process	**Figure 1**	**Figure 2**	**Figure 3**	**Figure 4**
The Actor	The Dam Owners manage their dam safety deficiencies using a risk management process	Dam owners are responsible to develop modern dam safety programs including dam safety evaluations and risk assessments.	The dam owners deal fundamentally with the management of the structure's response against adverse loads, the consequences of the flood.	The owner's should be carried out at least once every 10 years for dams with a high hazard classification.
Decision making	The use of risk informed decision making to identify preferred options, design solutions and construction methods. • Risk-informed' implies using risk assessments as an input to decision making.	The main inputs for risk-informed decision making are: • Prioritization queue of potential risk reduction actions in the Portfolio, obtained from Quantitative Risk Assessment • Prioritization queue of new studies and instrumentation in the Portfolio, obtained from Semi-Quantitative Risk Analysis	• Decision-making must be done in order to reach a proper balance between equity and efficiency • The risk model of the dam is the tool that allows the integration of all information concerning safety and decision making	• determine priorities for dam safety investigations • determine priorities for rehabilitation action • organize dam monitoring and surveillance programs

Table 5.
Summary of the major findings.

Question	New Zealand	India	Spain	Indonesia
1.Risk Management Framework in Dam safety Legislation	Yes	Yes	Yes	Yes
1.a Does the country have dam safety regulation and are these mandatory?				No
1.b Is the risk management srated in dam safety legislation?	Yes			
1.c Who is responsible to implement dam risk management	The owner of the dam	Yes The owner of the dam	Yes The owner of the dam	The owner of the dam, and check by dam safety unit
2. Guidelines reffered to risk hazard in dam				
2.a Does the country have the specific national guidelines concerning about dam risk management	Yes	Yes	Yes	Yes
2.b How is risk management framework reffered in the guidelines?	Risk Management as a part of Dam safety Management System which support asset longevity, license to operate. Insurance and lending.	The consequence-based hazard potential classification will be a step forward to wards the implementation of a portfolio risk management	The understanding of the different risk factors present in dams need to contemplate risk management as an essential element on dam dafety.	Dam risk management is a continuous and dynamic process that aims to maintain dam safety by reducing risk to tolerable limits
2.c is the hazard classification stated clearly in the guidelines?	Yes	Yes	Yes, stated in the regulation	
2.d Are there any consequences regarding to the hazard classification?	Yess	Yes	Yes	Yes Yes
3.Guidelines referred to risk assesment in dam safety framework	Yes	Yes	Yes	Yes
3.a Is the process of risk assesment described clearly in the guidelines?				
3.b Are the risk indicators stated in the guidelines?				
3.c Do the guidelines provide recommendation for the result of risk assesment?	Yes Yes	Yes Yes	Yes Yes	Yes Yes

4.1.3. Who Is Responsible for Implementing Dam Risk Management Related to Hazard Classification?

The dam owner was responsible for the safety of the dams, including risk management. It was stated in the regulation of all countries. New Zealand was declared in Building (Dam Safety) Regulations [37] Section 9-1, that 'The owner of a dam must, (…): '(e) determine the dam's potential impact classification by correlating the damage level (…) with the estimated population at risk and the estimated potential loss of life'. In India [38]. Every owner of a specified dam, for each of its dam shall, carry out risk assessment studies at such interval as may be specified by the regulations (…)" was mentioned in Section 35-2. As stated in Dam Safety Act [38]. Spain stipulated that "The owner will prepare and keep updated a Technical File of the dam (…): a. Clasify the category of dam by determining the people at risk category, according to the risk; (…)" as written in Section 5.5. However, in Indonesia, as stated in Building Act [36] said that "In order to fulfill the dam safety, dam safety unit should (..): (f) dam inventory and registration and hazard classification dam (…)" as written in Section 148-2. Their legislation stated in New Zealand, India, and Spain that the dam's owner should classify its hazard. Meanwhile, in Indonesia, the dam safety unit should inventory, register, and classify dams based on their hazards.

4.2. Guidelines Referred to Risk Hazards in the Dam

4.2.1. Does the Country Have Specific National Guidelines Concerning Dam Risk Management?

All the countries have developed specific guidelines for incorporating risk management related to dam safety. The guidelines are mandatory in New Zealand, India, and Spain and voluntary in Indonesia. New Zealand's dam guidelines should incorporate resilient features to withstand unusual and unexpected events safely. The process begins in the design, construction, and rehabilitation of any dam, and, where appropriate, additional resilient features should be provided to reflect the consequences of dam failure. The design, construction, and rehabilitation of any dam and, where appropriate, additional resilient features should be provided to reflect the consequences of dam failure. If the consequences of a dam failure are significant and extend well beyond the downstream river, additional risk management procedures and resilient features should be included to reduce the likelihood of a dam failure. In India, several guidelines were improved during the Dam Safety Act [38] including risk management [9]. Spain has implemented risk management since 1996. Because of public demand for transparency in decision-making, the Technical Guide on Operation of Dams and Reservoirs has been published. Volume 1 of the guidelines discussed Risk Analysis Applied to the Management of Dam Safety, which explains the risk management approach: the approach creates and protects value; is an integral part of the organizational process; is part of decision making, explicitly addresses uncertainty; is systematic, structured and timely; is based on the best available information; is tailored, takes human and cultural factors; is transparent and inclusive; is dynamic, iterative and responsive to change. In Indonesia, due to the large number of dams that must be maintained, repaired, and rehabilitated, which requires high costs, high costs can be achieved by implementing a priority system of dam risk assessment.

4.2.2. How is the Risk Management Framework Referred to in the Guidelines?

The comparative analysis findings show that all countries have risk management processes in the guidelines. The dam safety risk management process in New Zealand, shown in Figure 1 starts with identifying dam safety risk, estimating risk, evaluating dam safety risk, evaluating risk treatment options, communicating intentions to stakeholders, and implementing risk treatment. The last step is monitoring and reviewing.

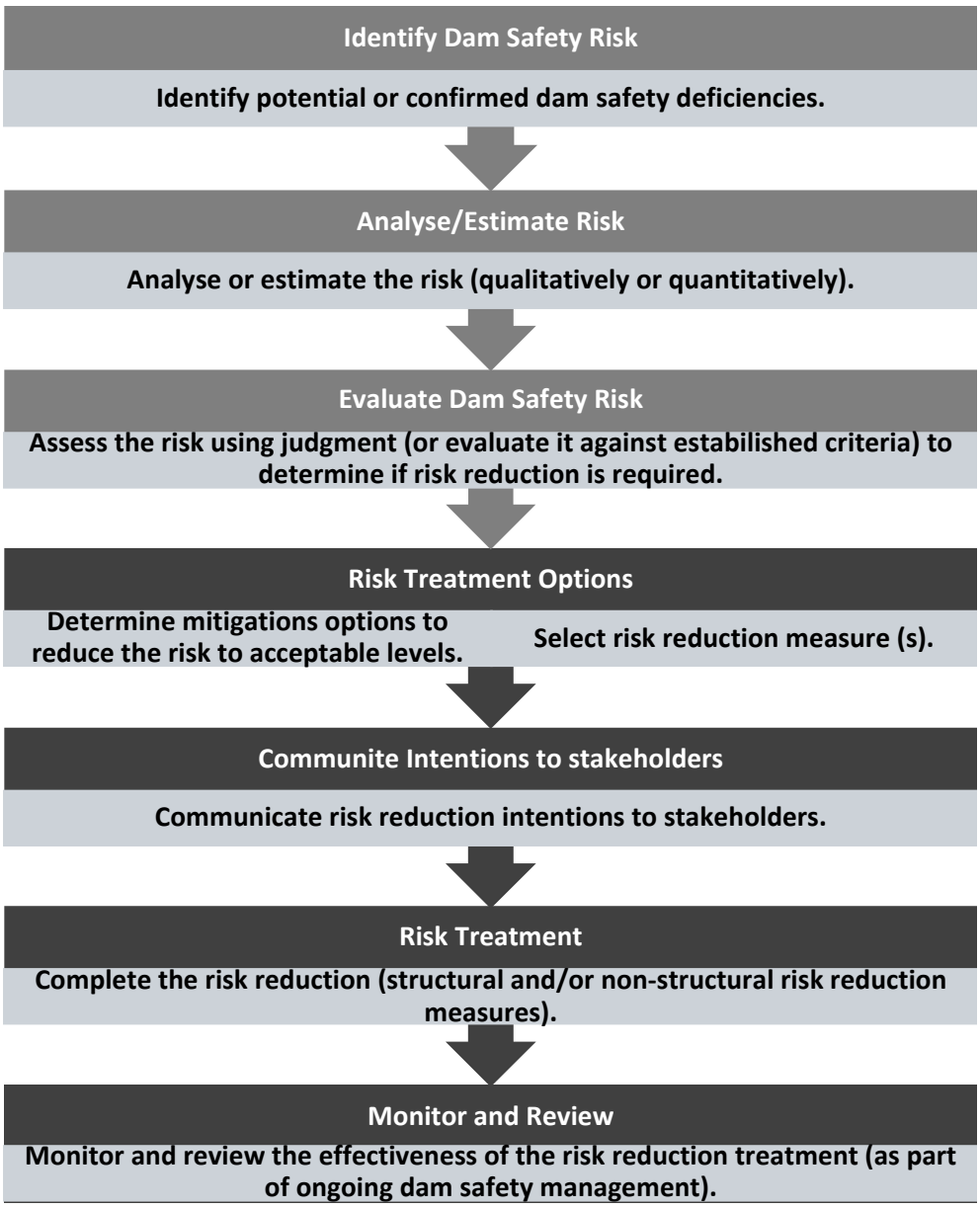

Figure 1.
Dam Safety Risk Management Process in New Zealand**.**
Source: New Zealand Society on Large Dams [43]

Four (four) significant steps were involved in the risk management process in India: initial risk-based screening, dam safety risk assessment, portfolio risk management, and update of reports on dam risk management.

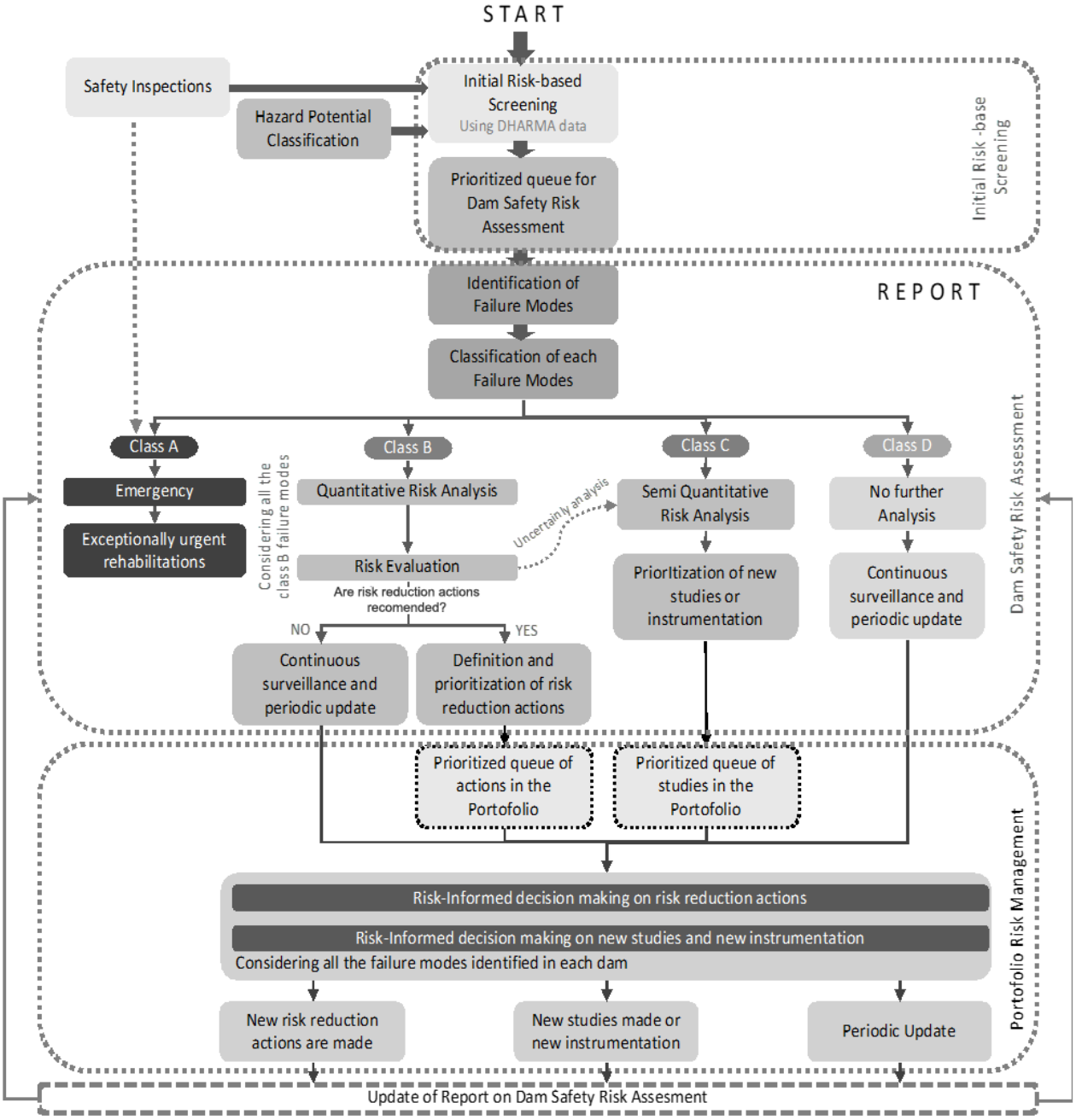

Figure 2.
Risk-Informed Dam Safety Management Program in India**.**
Source: Central Water Commission [9]

The risk model in Spain is shown in Figure 2. It starts with determining the objectives of the risk assessment, followed by a desk study, a site visit to the field, and determining the failure mode analysis. The risk assessment is then continued by determining loads, system response, and sequences. After that, a risk evaluation is carried out. If necessary, the risks are reviewed from the start to ensure that all risks are well known.

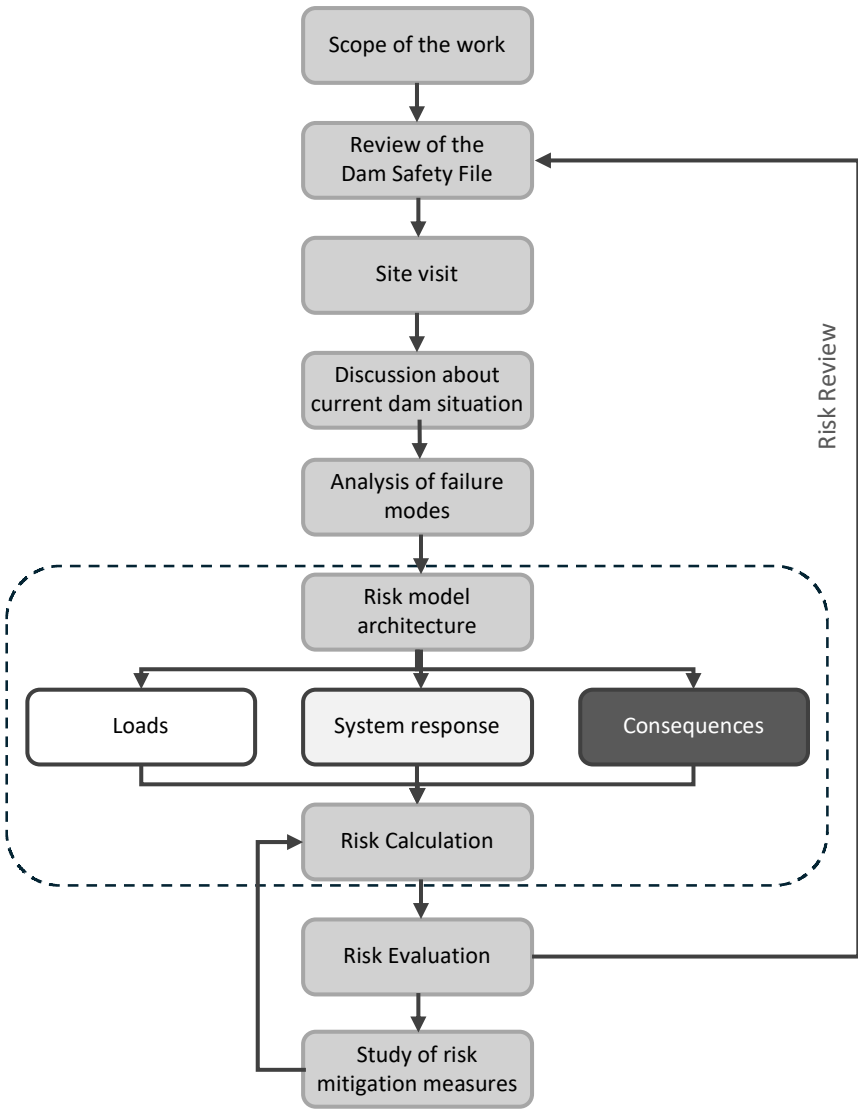

Figure 3.
Scheme of the process of Risk Analysis, highlighting the specific steps of the architecture and calculation of the risk model in Spain**.**
Source: SPANCOLD [15]

The framework for implementing risk management in Indonesia still follows ICOLD as seen in Figure 3. The risk management process is still voluntary in the dam, and the decision-making process still uses standard-based approaches. Indonesia still has difficulty determining which parts fall into the tolerable and non-tolerable categories.

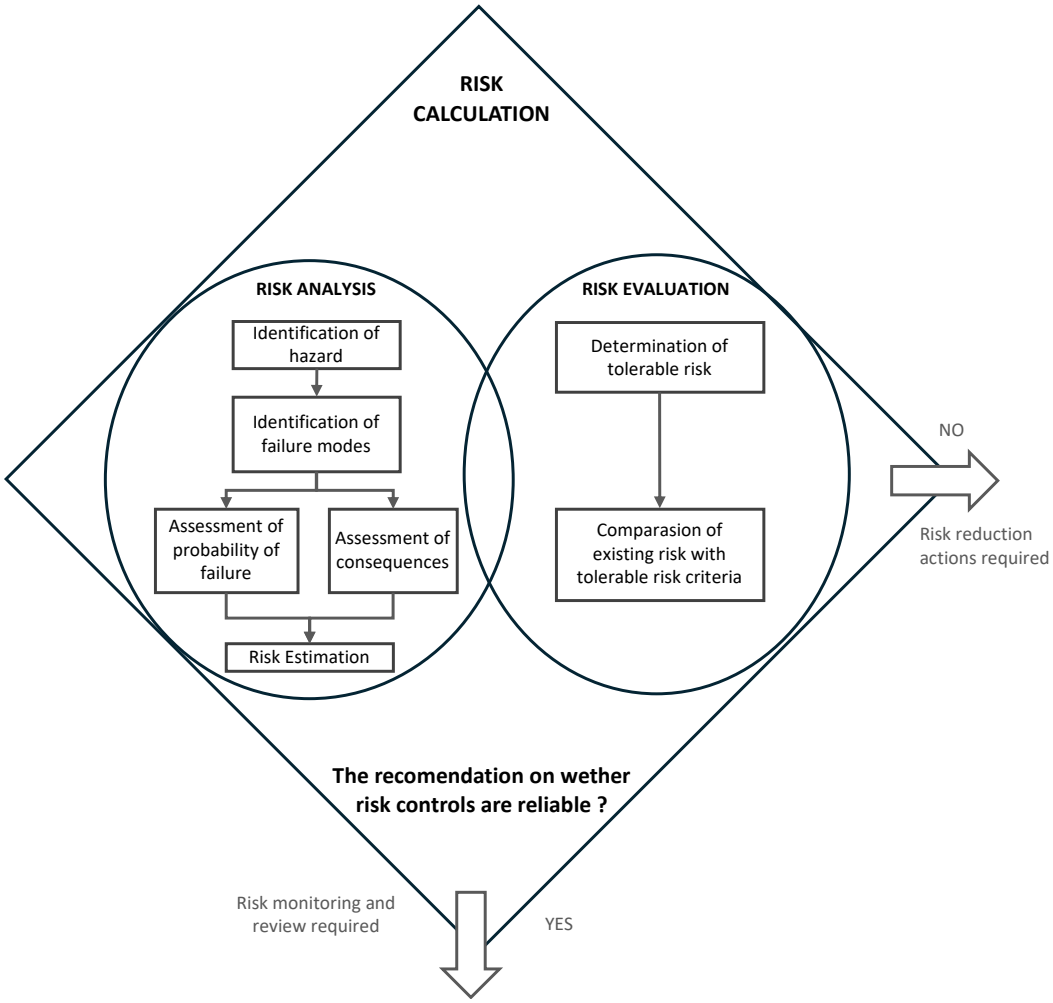

Figure 4.
Dam risk management from ICOLD.
Source: ICOLD [44].

4.2.3. Is The Hazard Classification Stated Clearly in the Guidelines?

Hazard classification is stated clearly in all countries. In Spain, it is stated in the regulation. Dam owners are responsible for ensuring the dams' safety, including risk management. Dam hazard classification is determined based on the population at risk and loss of life. In India and Spain, environmental and property damage determine the classification of dam hazards. Public facilities damage also contributes to dam hazards in Spain.

4.2.4. Are There Any Consequences Regarding the Hazard Classification?

All the guidelines provide consequences regarding hazard classification. As described in Table 3 New Zealand has 3 (three) hazard classification categories related to identifying an earthquake or a flood of a particular intensity or flow rate. India has 4 (four) categories of hazard classification, which are used to determine the competent levels of engineers in the dam safety units, the time interval for the risk assessment studies updating the emergency action plans, and the comprehensive safety evaluation. Spain declared hazard classification in the regulation in 3 (three) categories, which have an impact on specifying the period of inspection of dams, checking compliance with the loading program by monitoring its process and its incident, flood hydrograph, spillway capacity, Structural safety, seismicity; hydromechanical and electricity. Meanwhile, in Indonesia, hazard classification is divided into 4 (four categories, which are stated in hazard classification guidelines and used to determine the flood design used in spillway capacity. Moreover, since risk management is not mandatory in Indonesia, it is recommended that dam owners should be carried out at least once every ten years for dams with a high-hazard classification.

4.3. Guidelines Referred to Risk Assessment in the Dam Safety Framework

4.3.1. Is The Process of Risk Assessment Described Clearly in The Guidelines?

Based on a comparative analysis viewed from the perspective of risk assessment guidelines related to dam safety shows that all countries have well-explained the process of risk assessment for dams. All four guidelines provide a process of risk assessment at the dam. Risk assessment is a qualitative and quantitative method based on how deep the assessment is needed. Usually, the depth of risk assessment on a dam is determined by a predetermined dam hazard class. Generally,

when preparing a dam risk portfolio, the analysis is usually qualitative. However, quantitative analysis with measurable probability values is needed if the dam requires a more complex analysis.

4.3.2. Are The Risk Indicators Stated in the Guidelines?

Each guideline describes risk indicators that need to be included in the risk assessment. Moreover, since every dam has unique problems, risk indicators are not determined as rigid factors. The guidelines recommend identifying potential failure mode analysis as the basis for risk assessment.

4.3.3. Do The Guidelines Provide Recommendations for the Risk Assessment Result?

From the results of this risk assessment process, only New Zealand, India, and Spain explain what needs to be done after the risk assessment results are complete. Risk assessment guidelines in Indonesia only explain the procedures for risk assessment in dams without explaining what should be done with these dams after the risk assessment has been carried out.

5. Discussion

The significant similarities are related to the following: a) dam safety legislation is mandatory. Risk management has become part of the process of realizing dam safety as stipulated in regulations, except in Indonesia, where the implementation of risk management is still voluntary; b) the owner of the dam has the responsibility for implementing risk management to realize dam-safety based on risk inform decision making; c) Dam hazard classification is used as a basis for decision making at the design, operation and maintenance stages; d)the availability of guidelines to support practice and their comprehensiveness regarding the inclusion of risk assessment as part of risk management in dam safety framework. The differences are related to the hazard classification criteria and the guidelines' concurrent assessment of risk and decision-making. These findings bring to the fore a few details worth discussing. The findings of the comparative analysis are synthesized in Table 5.

The comparison of the dam safety legislation of the four countries deserves a few comments. The mentioning of risk management in the dam safety legislation reflects the importance of the matter [45-47] and the recognition of the potential benefits that risk management may offer to foster risk-based decision-making to reduce the risk [48-50]. However, despite these introductory advances, risk management is only included in the dam safety report and decision-making stages, leaving aside other relevant stages like stakeholder communication [51]. Moreover, the degree of detail used by the legislation is also different. The Indian dam safety legislation is less detailed when compared to New Zealand and Spain, leaving doubts about the effectiveness of its implementation by dam safety practitioners. Indonesia is still not clear on what to do about dam risk management in its legislation. Although surprising, given the recognition of the Indian system, this finding can be associated with only the federal legislation being analyzed. Further references to risk management may be included in the dam safety legislation at the provincial level. On the contrary, the Spain legislation is more comprehensive. It references risk management and dam development stages (design, construction, operation, and maintenance). In addition, by referring to the need to thoroughly describe the factors of hazard to be potentially affected by the project, such as population at risk and potential loss of life, as well as to undertake a comprehensive analysis of the projects' vulnerabilities to risk, it presents a solid approach to both mitigation and adaptation perspectives. This strength is likely due to the influence of International Committee on Large Dams (ICOLD) directives as they set the ground for a risk analysis that needs to be thoroughly understood and followed by all Member States.

The comparative analysis shows that all countries developed national guidelines supporting dam risk assessment in the risk management process. However, the depth of analysis in risk assessment varies from country to country. This represents a strength point, as Gonzalez, et al. [31] suggested, the process of risk management considerations in dam safety legislation can minimize the dangers of failure. This condition would be better if it is supported by other measures such as practical guidance [52] training for dam operators[17] and enhanced understanding of the population of downstream residents[53]. It also validates the suggestions of Castillo-Rodríguez, et al. [54] who noticed that the standardization of risk analysis concerning loads, system response, and consequence estimation methods should be supported by practical guidelines. The risk management framework in New Zealand's guidelines states that risk management supports dam asset longevity, license to operate, insurance, and lending. India guidelines determine hazard classification as initial risk-based screening for risk assessment. The output of this process is a portfolio of risk management. As a country that has adapted risk management as early as possible, Spain stated that dam risk factors should be considered in risk management. In Indonesia, risk management is voluntary, including the obligation of dam owners to carry out risk assessments.

Guidelines on risk assessment in New Zealand, India, and Spain explain the follow-up actions after a risk assessment. Since risk management is still voluntary in Indonesia, the guidelines do not explain in detail what to do after a risk assessment and what the owner should do after the risk assessment. In New Zealand, the risk assessment results are used to make more perfect designs and implement construction. In existing dams, risk assessments determine whether the dam needs upgrading, rehabilitating, or other actions to reduce the risk. In India, initial risk-based screening is performed at the hazard classification stage. Identification of failure mode analysis is carried out to start the dam risk assessment to classify the potential danger of the dam, which is divided into four categories that determine how deep the risk assessment needs to be. The risk assessment results are used as a reference for which dam will be prioritized first to reduce risk, add instrumentation to the dam, and determine how often major inspections will be carried out. Risk assessment model in Spain, considering load, system response, and consequences. The results of this assessment are carried out as mitigation in reducing dam risks [14].

6. Conclusion

Dams have enormous benefits, but this infrastructure can become deficient over time, increasing the risk of dam failure. When a dam fails, it will lose of population downstream, cause environmental damage, and harm the economy. Risk management in dams is one of the efforts to mitigate risks. Establishing risk management in regulation is one of the firm efforts so that dam owners pay great attention to mitigating risks in dams. Explanation related to determining dam hazard classification, risk assessment, risk factors that influence dam failure, and risk evaluation is essential in implementing risk management in dams. This paper compares legislation and guidelines related to risk management in New Zealand, India, Spain, and Indonesia. This finding shows that dam risk management has been stipulated in regulations related to dam safety. Determining the dam hazard classification is the primary basis for determining design, construction, operation, and maintenance criteria. However, risk assessment as an effort to mitigate risks in dams has not been fully implemented as in Indonesia. In the technical guidelines, decision-making is based on risk, with the risk assessment results determined. However, decision-making based on standard-based apportionment is also still permitted. Considering the current conditions where society demands transparency in decision-making, dam risk assessment is crucial. In the future, regulations related to risk management should be made mandatory in the construction and management of dams. Training for dam operation and maintenance officers and outreach for dam management staff regarding risk management need to be implemented.

This article also raised a few questions that deserve further research. First, to assess the extent content of laws and guidelines effectively can reduce the risk of failure in the dam by practitioners and what expectations they have regarding the contents of statutory regulations and guidelines. Second, the indication of risk factors in risk assessments in dams should be explained in guidelines that cover the overall analysis, including technical, economic, social, and environmental analysis. Finally, to determine which adjustments should be introduced to existing laws and which harmonization procedures should be considered to ensure that the dam is safe and the risks are acceptable.

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