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Evaluating dam safety in Brazil: a comparative analysis of international classification systems

Avaliação da segurança de barragens no Brasil: uma análise comparativa de sistemas de classificação internacionais

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ABSTRACT

Dams provide essential services to society, but the consequences for downstream communities and the environment can be devastating when safety measures fail. This investigation examines Brazil's dam safety policies, focusing on classification systems and emergency preparedness. Data from 2022 reveals serious shortcomings: over 14,000 dams are unclassified by Risk Category (RC), and more than half lack a Potential Hazard Associated (PHA) rating. Of the 1,235 dams classified as high risk, only 106 have an Emergency Action Plan (EAP). The study compares Brazil's system with international frameworks from institutions such as ICOLD, FEMA, USACE, and countries including Portugal, Spain, New Zealand, Australia, South Africa, Argentina, and Canada. While Brazil's approach aligns with global standards, critical improvements are needed. The study proposes practical adjustments to enhance hazard classification and emergency planning. Future research could explore these proposals through case studies to better guide policy and protect lives.

Keywords: Dam safety; Dam classification; Hazard classification; Emergency preparedness; Policy improvement.

RESUMO

As barragens prestam serviços essenciais à sociedade, mas quando falham em termos de segurança, as consequências para as comunidades a jusante e o meio ambiente podem ser devastadoras. Este estudo analisa as políticas de segurança de barragens no Brasil, com foco nos sistemas de classificação e na preparação para emergências. Dados de 2022 revelam deficiências importantes: mais de 14 mil barragens não possuem classificação por Categoria de Risco (CR) e mais da metade não tem avaliação de Dano Potencial Associado (DPA). Das 1235 barragens classificadas como de alto risco, apenas 106 possuem Plano de Ação de Emergência (PAE). O estudo compara o modelo brasileiro com referências internacionais, como ICOLD, FEMA e USACE, além de países como Portugal, Espanha, Nova Zelândia, Austrália, África do Sul, Argentina e Canadá. Embora o modelo brasileiro siga padrões globais, melhorias críticas ainda são necessárias. Propõem-se ajustes práticos para aprimorar a classificação e o planejamento emergencial. Pesquisas futuras podem explorar essas propostas por meio de estudos de caso, contribuindo para políticas mais eficazes e maior proteção à população.

Palavras-chave: Segurança de barragens; Classificação de barragens; Classificação de dano; Preparação para emergências; Aprimoramento de políticas.

INTRODUCTION

The reservoirs created by dams offer a variety of benefits to society, including water supply, flood control, irrigation, hydroelectric power generation, navigation, and recreation. However, the presence of dams increases the likelihood of accidents owing to the exposure of downstream valleys, populations, infrastructure, and environmentally sensitive areas.

(Viseu & Almeida, 2009).

Although dam failures are rare, their consequences can be catastrophic, causing enormous damage and loss of life (Hariri-Ardebili, 2018; Viseu & Almeida, 2009). Accordingly, dam safety is essential to mitigating social, economic, and environmental risks (Bradlow et al., 2002).

Comparative studies have contributed significantly to shaping the understanding of regulatory frameworks for dam safety. Bradlow et al. (2002) conducted one of the earliest global analyses, outlining essential legal and institutional elements across 22 countries. Building upon this foundation, Wishart et al. (2020) expanded the scope to 51 countries, incorporating a broader analysis of governance structures and operational practices.

Dam safety legislation requires a robust legal framework, the establishment of minimum technical standards, and the definition of roles and responsibilities among dam owners, public authorities, and civil society, aiming to protect public welfare, the environment, and economic stability (Wishart et al., 2020).

A core component of dam safety regulations is the classification system, which determines which dams require monitoring. These systems typically categorize dams based on specific characteristics or potential hazards (Martínez-Gomariz et al., 2023).

In Brazil, this issue is particularly relevant given the existence of 23,977 dams across the country (Agência Nacional de Águas e Saneamento Básico, 2023), serving purposes such as irrigation, water supply, tailings storage, and power generation. In response to past accidents, Brazil established its National Dam Safety Policy (PNSB) in 2010. However, over a decade later, the policy continues to encounter barriers to effective application, as revealed in a post-implementation evaluation by the National School of Public Administration (Escola Nacional de Administração Publicas, 2021).

Under Brazilian legislation, dam classification must be conducted by the relevant supervisory agency, based on three parameters: Risk Category (RC), Potential Hazard Associated (PHA), and reservoir volume. These are defined by general criteria established by the National Water Resources Council (CNRH). Agencies may also apply additional technical criteria. For example, the National Water and Sanitation Agency (ANA) developed complementary PHA evaluation criteria for dams under its jurisdiction (Brasil, 2016).

Dam classification is a fundamental tool for determining the legal obligations of dam owners (Persechini et al., 2015). A salient exemplification of this imperative is the obligation to formulate an Emergency Action Plan (EAP) for dams categorized as High and Medium PHA.

In Brazil, the interaction between RC and PHA exhibits characteristics of a risk index (RI) (World Bank, 2021). However, in practice, this relationship is used primarily to define compliance obligations, rather than for broader policy planning or prioritization.

This analysis presents dam data in Brazil, including the total number of dams, their classification under Brazilian regulations, and the share with EAPs as key indicators of dam safety policy progress. These elements serve as international benchmarks and are commonly used to evaluate the effectiveness of dam safety frameworks (Bradlow et al., 2002; Pisaniello et al., 2012, 2015; Tingey-Holyoak et al., 2011).

This analysis also includes a comparison *of* dam classification systems across countries and institutions, including the International Commission on Large Dams (ICOLD), Federal Emergency Management Agency (FEMA), and the United States Army Corps of Engineers (USACE), as well as countries such as Portugal, Spain, New Zealand, Australia, South Africa, Argentina, and Canada (Québec). These were selected based on the maturity of their regulatory frameworks, global influence, and availability of technical documentation.

This study applies explicitly the classification criteria established in CNRH Resolution No. 143/2012, which was in effect during the analyzed period. Accordingly, the analysis does not cover CNRH Resolution No. 241/2024, enacted afterward.

Furthermore, a comparative perspective is also presented, contrasting Brazil's classification system with international best practices and identifying potential improvements in hazard assessment and dam safety policy.

METODOLOGY

This investigation is structured in two main parts. The first part presents an analysis of data on Brazilian dams, including the total number, classification according to Brazilian regulations, and the percentage with EAP.

The data source is the 2022 Dam Safety Report (RSB), published by ANA. The spreadsheet used to prepare the RSB for 2022 analyzes the situation of dams in Brazil. Data is available for download at https://www.snisb.gov.br/portal-snisb/inicio and includes identification of the dam, owners, geographic coordinates, reservoir's purpose, supervisor agencies, foundation height, height from the riverbed level, reservoir volume, and classification of the dam's risk category and potential hazard.

Additionally, it examines Brazilian dams using the classification criteria of the International Commission on Large Dams (ICOLD). This classification criterion uses a relationship between the height of the dam in meters (H), measured from riverbed level, and the volume of the reservoir at the maximum operating level in million cubic meters (V), based on those proposed the French Committee on Dams and Reservoirs, Equation 1. This constitutes a deterministic relationship aimed at evaluating the potential risk in the flood zone in the event of a dam failure (International Commission on Large Dams, 2011).

$$H^2\sqrt{V} \quad (1)$$

According to ICOLD, small dams are identified when $H^2\sqrt{V}$ is less than 200, with heights ranging from 2.5 to 15 m. Figure 1 illustrates the ICOLD classification of dams.

The second part of this investigation consists of a comparative analysis between Brazil's dam classification system and international models. The selection of countries and organizations for comparison was based on three criteria: (i) global relevance in dam regulation (e.g., ICOLD, FEMA, USACE); (ii) established expertise in dam safety and risk management (e.g., Portugal, Spain, New Zealand, Australia, and Canada); and (iii) availability of official regulations, reports, and technical guidelines.

The comparative analysis was conducted with a focus on five primary dimensions: (1) classification by dam size, (2) environmental impact, (3) socio-economic impact, (4) downstream population affected, and (5) use of flood maps for risk assessment. For each criterion, a comparative analysis was conducted to identify both the similarities and divergences between the Brazilian model and international approaches.

LEGISLATION AND THE DAM CLASSIFICATION PROCESS IN BRAZIL

As in many other nations, Brazil's legislative framework emerged in response to dam-related accidents with severe downstream consequences, including loss of human lives, community displacement, and significant socio-economic and environmental impacts (Wishart et al., 2020). Table 1 presents some dam accidents in Brazil (Agência Nacional de Águas e Saneamento Básico, 2016, 2020; Balbi, 2008; International Commission on Large Dams, 2001, 2011; Mello et al., 2021).

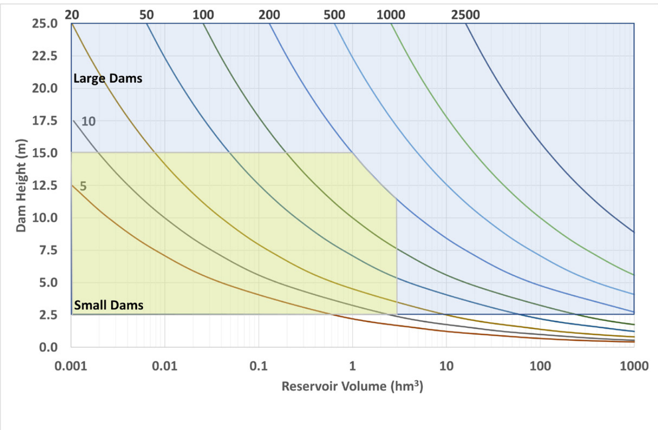

Figure 1. Classification of small and large dams. Adapted from International Commission on Large Dams (2011).

Brazil established the PNSB with the enactment of Law No. 12,334 on September 20, to enhance dam safety standards by reducing the likelihood of accidents and their consequences, promoting a culture of risk management, and clearly defining responsibilities for dam safety across Brazilian territory.

However, even after the establishment of the PNSB in 2010, significant dam failures occurred, including those in Bento Rodrigues, Mariana (2015), and Brumadinho (2019), both related to tailings dam. These disasters led to revisions in the PNSB, culminating in the enactment of Law No. 14,066 on September 30, 2020.

The PNSB applies to various categories of dams, including water storage dams for various purposes, dams for final or temporary disposal of mining waste, dams for the accumulation of industrial residues, and dams for the disposal of nuclear mining waste (Brasil, 2010). This legislation applies to dams that exhibit at least one of the following characteristics:

The PNSB applies to dams for water storage, mining waste, industrial residues, and nuclear waste disposal that meet at least one of the following conditions: height ≥ 15 m, reservoir volume ≥ 3 million m^3, presence of hazardous substances, Medium or High hazard potential, or High Risk Category, as defined by the supervisory authority (Brasil, 2010).

In Brazil, 44 entities have the potential to engage in activities related to dam safety supervision. However, as of 2022, only 33 of these entities were registered for dam safety and were actively involved in the supervision process (Agência Nacional de Águas e Saneamento Básico, 2023).

At the national level, dam safety is overseen by three agencies: the National Mining Agency (ANM) for tailings dams, the National Electric Energy Agency (ANEEL) for hydropower dams, and the National Water and Sanitation Agency (ANA) for non-energy dams located on federal rivers.

State-level supervision is carried out by 30 agencies, generally divided between environmental agencies (responsible for industrial

Table 1. Some notable dam accidents in Brazil and their Consequences.

DAM	Year	Type of dam	Consequences
Euclides da Cunha	1977	Water Storage	Armando Salles Oliveira (Limoeiro) power plant and Coronel Soares hydroelectric plant experienced significant impacts, resulting in their incapacity to operate
Fernandinho	1986	Tailing Dam	7 fatalities
Mineração Rio Verde	2001	Mining Tailings	5 fatalities, along with disruptions to water supply, power, and roadways
Cataguases	2003	Industrial Waste	Disruption of water supply for some cities
Camará	2004	Water Storage	5 fatalities and 800 people left homeless
Rio Pomba Cataguases	2006	Industrial Waste	Disruption of water collection
Rio Pomba Cataguases	2007	Industrial Waste	765 people displaced
Algodões	2009	Water Storage	11 fatalities and 2 500 people left homeless
Fundão	2015	Mining Tailings	19 fatalities, population displacement, disruption of water supply, and environmental degradation along a 600 km stretch from the Doce River to its mouth
Herculano	2014	Mining Tailings	3 fatalities
Brumadinho	2019	Mining Tailings	270 fatalities

Adapted from Agência Nacional de Águas e Saneamento Básico (2016, 2020), Balbi (2008), International Commission on Large Dams (2001, 2011) and Mello et al. (2021).

waste dams) and water agencies (responsible for water storage dams without hydropower generation on state rivers).

Supervisory authorities are responsible for approving dam classifications according to Risk Category (RC), Potential Hazard Associated (PHA), and reservoir capacity, based on general criteria from CNRH and complementary institutional criteria.

This classification is crucial for guiding dam safety policy, as RC and PHA ratings determine the obligations of dam owners. For example, water storage and industrial waste dams must have an EAP if classified as High or Medium PHA, or High RC at the discretion of the supervisory agency. In contrast, all mining tailings dams are required to have an EAP, regardless of their classification.

Brazil dam classification criteria

The first regulation for dam classification was Resolution CNRH No. 143, issued on July 10, 2012. In 2024, this resolution was replaced by Resolution CNRH No. 241, published on September 10, 2024. However, due to its recent publication, the effects of the new resolution on dam safety have yet to be assessed.

Therefore, since the available dam classification data is based on the 2012 resolution, the analysis follows the classification defined in that legal framework. Dams are categorized based on reservoir capacity, according to the criteria outlined in Table 2 (Brasil, 2012).

The RC classification considers technical, safety, and operational aspects of dams that could influence the probability of dam failure (World Bank, 2021). The RC classification process uses three matrices that evaluate and assign scores to aspects of the dam, including the Technical Characteristics Matrix (TCM), Conservation Status Matrix (CSM), and Safety Plan Matrix (SPM). Table 3 summarizes the respective classification matrices and descriptors that define the RC for water storage dam.

After evaluating the scores for each criterion in the matrices, their sum determines the RC of the dam under analysis, as described in Equation 2.

$$RC = \sum TCM + \sum CSM + \sum SPM \quad (2)$$

Dams scoring 35 points or lower are classified as 'Low Risk', while those scoring between 36 and 60 points fall under 'Medium Risk'. Dams with a score of 60 points or higher are categorized as 'High Risk'. Additionally, RC is automatically classified as 'High' if any descriptor in the Conservation Status Matrix receives a score of 8 or higher. Figure 2 provides a summary of the RC scoring and classification.

PHA evaluates the potential downstream damage resulting from dam failure. The impacts are classified based on reservoir capacity, potential loss of life, and socioeconomic and environmental impacts (Brasil, 2012). The PHA classification criteria are presented in Table 4.

Table 2. Classification of Water Accumulation Dams by Reservoir Capacity.

Dam Type	Classification	Reservoir Volume (hm^3)
Water Storage Dam	Small	≤ 5 hm^3
	Medium	> 5 hm^3 and ≤ 75 hm^3
	Large	> 75 hm^3 and ≤ 200 hm^3
	Very Large	> 200 hm^3

Table 3. Summary of RC matrices and scoring parameters for water accumulation dams.

Matrices	Descriptors	Score range
Technical Characteristics Matrix (TCM)	Height (a)	0 to 3
	Length (b)	2 to 3
	Type of construction material (c)	1 to 3
	Type of foundation (d)	1 to 5
	Age (e)	1 to 4
	Design flow conditions (f)	3 to 10
	TC = ∑ (a to f)	8 to 28
Conservation Status Matrix (CSM)	Reliability of spillway structures (g)	0 to 10
	Reliability of outlet structures (h)	0 to 6
	Seepage (i)	0 to 8
	Strains and Settlement (j)	0 to 8
	Slopes or faces deterioration (l)	0 to 7
	Navigation Lock (m)	0 to 4
	CS= ∑ (g to m)	0 to 43
Safety Plan Matrix (SPM)	Existence of project documentation (n)	0 to 10
	Organizational structure and technical qualification of dam's safety staff (o)	0 to 6
	Procedures and routines of dam safety inspections and monitoring (p)	0 to 8
	Operating rules for outlet hydraulic structures (q)	0 to 8
	Dam safety reports with analysis and interpretation (r)	0 to 7
	SP= ∑ (n to r):	0 to 39

Adapted from Viana et al. (2015).

When assessing the potential loss of human life, the analysis considers both permanent and temporary residents in the downstream region of the dam. This includes residential, commercial, agricultural, and industrial infrastructure, as well as navigation services. Additionally, the environmental impact assessment considers the ecological significance and legal protection status of the affected area, without referencing specific legislation.

PHA scores are derived by summing values from each descriptor. Dams scoring less than 10 are designated as Low PHA, while those scoring between 10 and 16 fall under the Medium PHA category. Dams with a total score of 16 or higher are classified as High PHA (Figure 3).

The legislation does not provide clear guidelines for defining the downstream valley or establishing criteria for flood

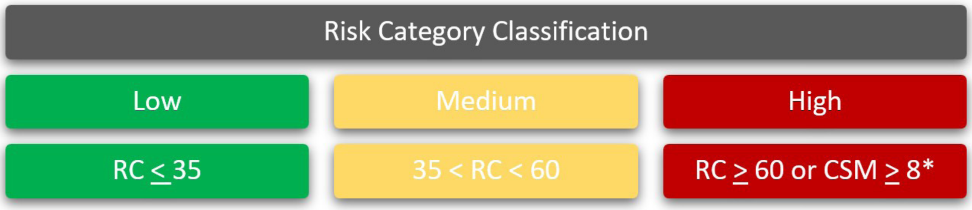

Figure 2. RC classification of water accumulation dams.

Figure 3. PHA classification of water accumulation dams.

Table 4. Summary of PHA Matrix of water accumulation dam and their descriptors and score range of water accumulation dams.

Descriptors	Classification	Description	Score
Reservoir Volume	Small	< = 5hm³	1
	Medium	5 to 75hm³	2
	Large	75 to 200hm³	3
	Very Large	> 200hm³	5
Potential loss of human life	None	There are no permanent/resident or temporary people/transiting in the area downstream of the dam	0
	Infrequent	There are no people permanently occupying the area downstream of the dam, but there is a neighboring road for local use	4
	Frequent	There are no people permanently occupying the area downstream of the dam, but there is a municipal or state or federal highway or other place and/or enterprise where people may be affected	8
	Existing	There are people permanently occupying the area downstream of the dam, therefore, human lives could be affected	12
Environmental impact	Significant	The affected area of the dam does not represent an area of environmental interest, areas protected by specific legislation or is totally out of character for its natural conditions	3
	Very significant	Dam affected area has relevant environmental interest or is protected by specific legislation	5
Socio-economic impact	None	There are no navigation facilities and services in the area affected by the dam accident	0
	Low	There is a small concentration of residential and commercial, agricultural, industrial or infrastructure facilities in the affected area of the dam or port facilities or navigation services	4
	High	There is a large concentration of residential and commercial, agricultural, industrial, infrastructure and leisure and tourism services facilities in the affected area of the dam or port facilities or navigation services	8

wave studies in the PHA analysis. CNRH Resolution defines the affected area as the region potentially impacted in the event of a dam failure but delegates the authority to delineate its boundaries to supervisory agencies.

Brazil – Complementary criteria

Brazilian legislation allows supervisory agencies to propose technically justified complementary criteria for dam classification. For instance, ANEEL incorporates the evaluation of the powerhouse in the Characteristic Matrix, a structure specific to hydropower dams. This adjustment modifies the RC scoring range: dams scoring between 35 and 62 are classified as Medium, and those scoring above 62 as High (Brasil, 2023).

Under ANEEL supervision, the inundation map used for classification and EAP preparation must consider the worst-case scenario. This includes both the flood event predicted by the spillway design or most recent hydrological study, and the flooded area resulting from a dam breach on a dry day, regardless of natural flood occurrence.

Based on practical experience, ANA identified the need to adjust the PHA classification for dams under its jurisdiction. In February 2016, Resolution No. 132 introduced complementary criteria to refine the weighting of environmental and socio-economic impacts, Table 5.

Environmental impact assessment is based on the conservation status of the downstream area and the presence of conservation units protected by specific legislation. For socioeconomic impacts, a medium impact category was established, and quantitative criteria were introduced for distinguishing between "low" and "medium" impacts (Brasil, 2016).

Some regulatory agencies have introduced classification systems that correlate PHA and RC to enhance the enforcement of dam safety regulations. A notable example is the classification system adopted by the federal agencies ANA and ANEEL, as shown in Tables 6 and 7.

STATUS OF DAMS IN BRAZIL: CLASSIFICATION OVERVIEW

The 2022 Dam Safety Report states that Brazil has 23,977 registered dams. Among these, 7,073 have been classified by RC, with 2,635 categorized as High, 2,536 as Medium, and 1,902 as Low RC. In contrast, 16,903 dams remain unclassified. Of these,

Table 5. Complementary criteria PHA classification ANA.

Descriptors	Classification	Description	Score
Environmental impact	Little Significant	when the affected area of the dam does not represent an area of environmental interest, areas protected by specific legislation or is completely deprived of its natural conditions.	1
	Significant	when the affected area includes protected areas of sustainable or when it is an area of environmental interest and is little deprived of its natural conditions	2
	Very significant	when the affected area includes areas of strict protection, including Indigenous Lands – or when it is of great environmental interest in its natural state	5
Socio-economic impact	None	when there are no navigation facilities and services in the area affected by the dam accident	0
	Low	when there are 1 to 5 residential installations and commercial, agricultural, industrial facilities or infrastructure in the affected area of the dam	1
	Medium	when there are more than 5 to 30 residential and commercial, agricultural, industrial or infrastructure facilities in the affected area of the dam.	3
	High	when there is a large concentration of residential and commercial, agricultural, industrial, infrastructure and leisure and tourism services facilities in the affected area of the dam or port facilities or navigation services	8

Adapted from Agência Nacional de Águas e Saneamento Básico (Brasil, 2016).

Table 6. Class for water storage dams.

RC	PHA		
	High	**Medium**	**low**
High	A	B	C
Medium	A	C	D
low	A	D	D

Adapted from Agência Nacional de Águas e Saneamento Básico (Brasil, 2016).

Table 7. Classes for hydroelectric dams.

RC	PHA		
	High	**Medium**	**low**
High	A	B	B
Medium	B	C	C
low	B	C	C

Adapted from Agência Nacional de Energia Elétrica (Brasil, 2023).

14,943 have not been assessed by supervisory agencies, while 1,961 either do not meet the criteria for inclusion under the PNSB or are under construction and listed as "not applied" (Agência Nacional de Águas e Saneamento Básico, 2023).

Notably, water storage dams account for 97.0% (16,397) of the 16,904 dams that have not been classified by RC, as detailed in Table 8. Figure 4 illustrates the geographic distribution of dams in Brazil, categorized by their RC.

Table 8. RC classification by reservoir purpose.

RC	Purpose				Total
	Water storage	Hydroelectric	Mining tailings	Industrial waste	
High	2,254	315	52	14	2,635
Medium	2,345	95	96	-	2,536
low	691	893	307	11	1,902
Not classified	16,397	0	487	20	16,904
Total	**21,687**	**1,303**	**942**	**45**	**23,977**

Adapted from Agência Nacional de Águas e Saneamento Básico (2023).

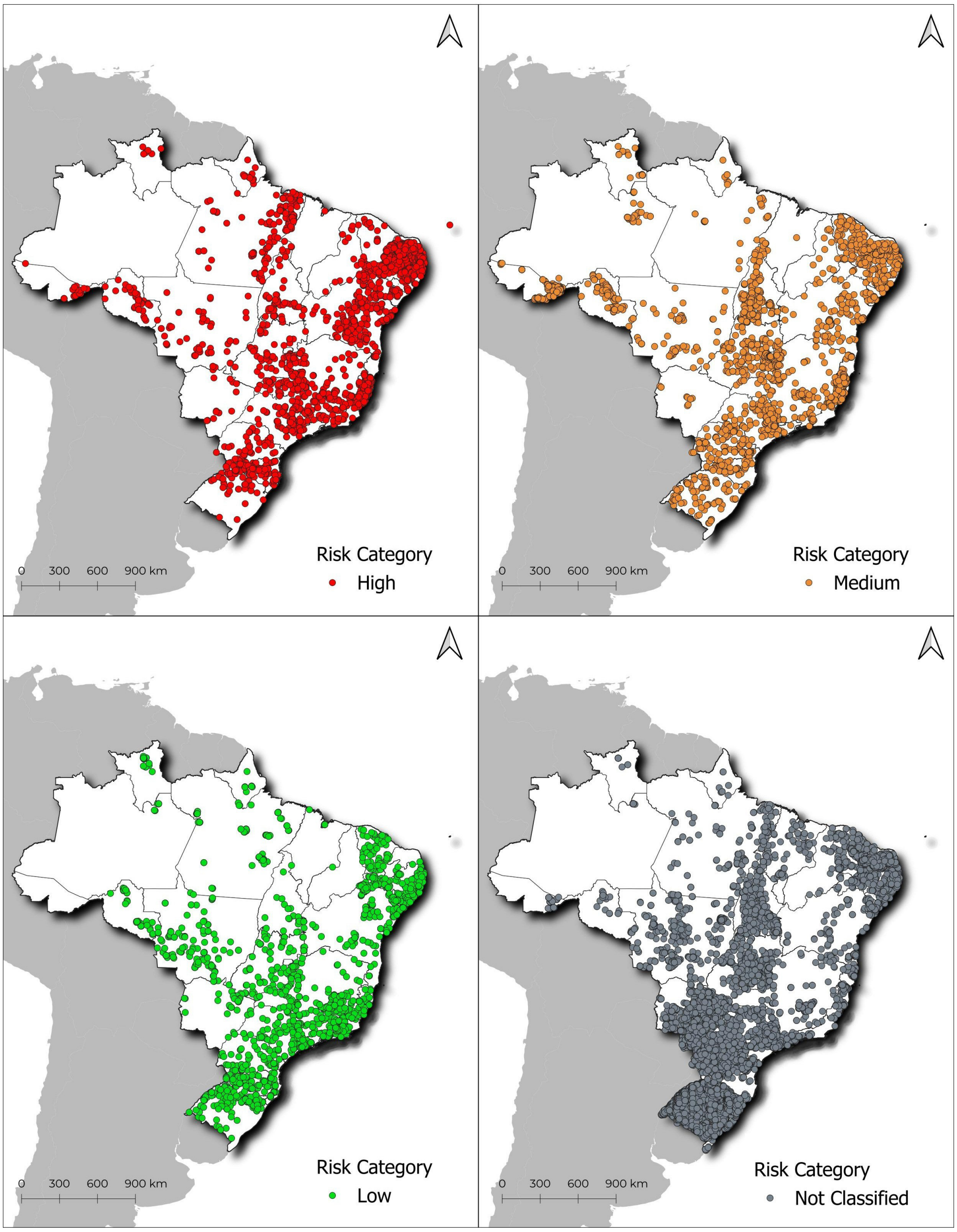

Figure 4. Maps of RC Dam Classification Locations in Brazil.

A total of 10,171 dams have been classified by PHA, with 3,789 considered High PHA, 1,151 Medium, and 5,231 Low. Consequently, 13,806 dams (57.6% of all registered) remain unclassified by PHA. The geographic distribution of dams in Brazil, classified by PHA, is shown in Figure 5. Water storage dams represent 98.7% (13,666) of these unclassified structures. The geographic distribution of dams in Brazil, classified by PHA, is shown in Table 9.

In terms of reservoir capacity classification, small reservoirs (≤ 1 hm^3) account for approximately 73.5% of the 22,990 dams

Table 9. PHA classification by reservoir purpose.

PHA	Purpose				Total
	Water storage	Hydroelectric	Mining tailings	Industrial waste	
High	2,926	588	254	21	3,789
Medium	893	94	164	-	1,151
low	4,202	621	403	5	5,231
Not classified	13,666	-	121	19	13,806
Total	**21,687**	**1,303**	**942**	**45**	**23,977**

Adapted from Agência Nacional de Águas e Saneamento Básico (2023).

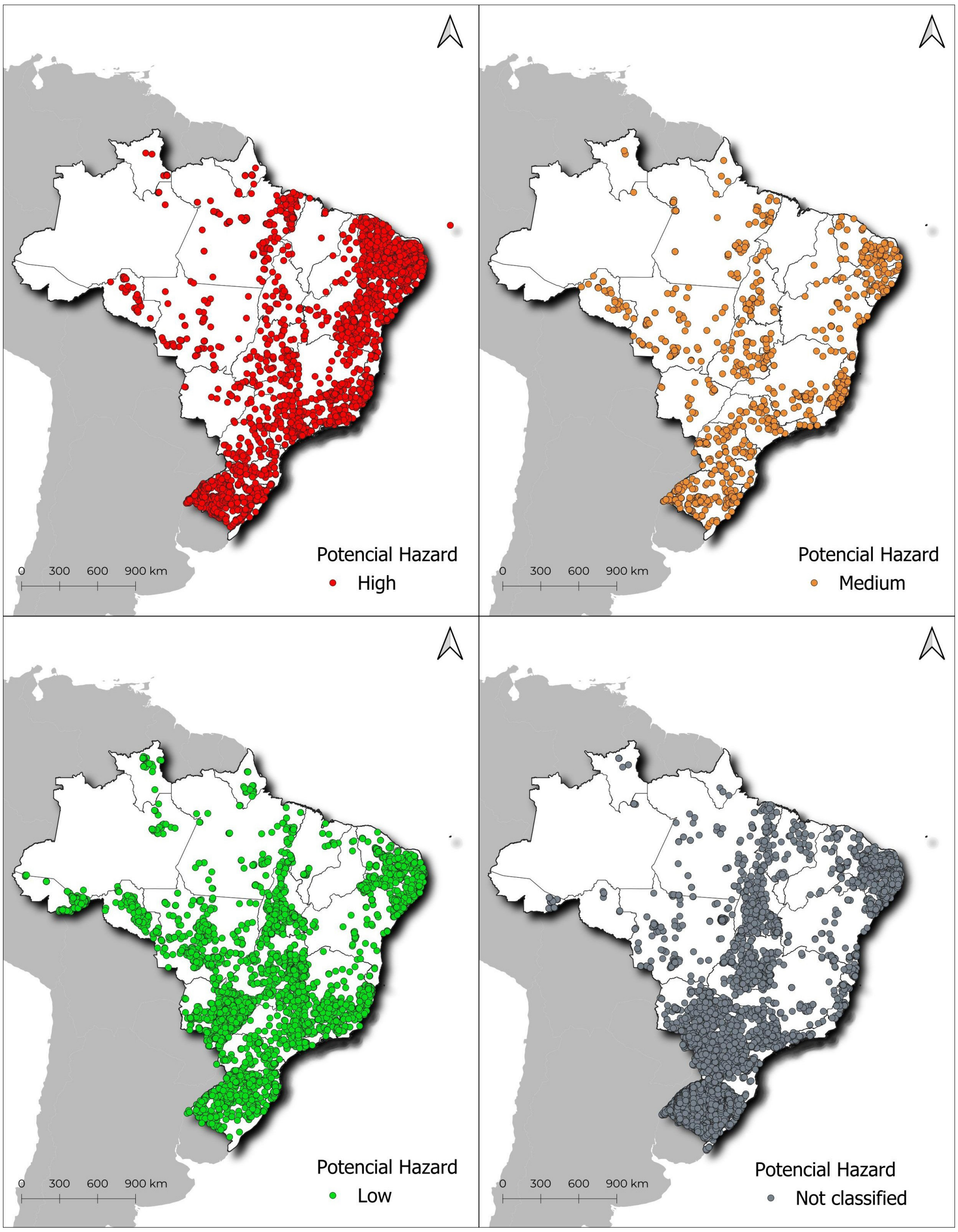

Figure 5. Maps of PHA Dam Classification Locations in Brazil.

designated for water storage. These small dams also represent 46.8% of the High PHA group and 75.6% of Medium PHA dams. Additionally, they represent 75.6% of the 13,666 dams that have not been categorized by PHA, as showed in Table 10.

Regarding the classification of dam reservoir capacities for mining tailings and industrial waste, 154 out of the 275 dams classified under PHA have small to very small reservoirs. Moreover, 101 of the 140 unclassified dams in these categories also fall within these small-size classifications, as shown in Table 11.

ICOLD CRITERIA

Table 12 presents ICOLD's classification for small and large dams (International Commission on Large Dams, 2011) applied to structures under the PNSB. According to this system, 10,263 dams (42.8%) are considered small and 2,057 (8.6%) large. However, 11,657 dams (48.6%) lack height or volume data, preventing their proper classification.

There are 5,665 dams subject to safety legislation, of which 2,013 are classified as large and 2,675 as small. Consequently, 47.2% of regulated dams are considered small. Additionally, 977 dams lack the necessary height or volume data required for size classification. There are also 4,874 unregulated dams, of which 89.9% are classified as small. Finally, 13,438 dams still await eligibility assessment under the PNSB framework.

The analysis of PHA classifications under the PNSB and ICOLD criteria reveals important structural nuances (Table 13). Among the 5,231 dams classified as Low PHA, there is a predominance of small dams in this category. For Medium PHA, there are 1,151 dams, of which 763 (66.3%) are classified as small, emphasizing the prevalence of smaller structures within this hazard designation.

Conversely, 3,789 dams are classified as High PHA. Of these, 1,703 (44.9%) are small, highlighting the significant presence of smaller structures with high hazard potential. Figure 6 illustrates High PHA dams with heights up to 25 m, showing the prevalence of small dams with high hazard potential and the existence of small structures under 2.5 m height, with elevated hazard classification.

Many dams (13,806) remain unclassified under the PHA criteria, with most designated as "Insufficient Data" due to missing information on dam height or reservoir volume. This observation highlights a critical challenge in establishing a comprehensive dam inventory, which affects assessing potential dam-related risks and damages.

Table 10. Reservoir capacity classification by reservoir water storage purpose.

Reservoir capacity	PHA				
	High	**Medium**	**Low**	**Not classified**	**Total**
Very Large (> 200 hm^3)	306	7	11	20	344
Large (> 75 hm^3 and ≤ 200 hm^3)	125	4	11	13	153
Medium (> 5 hm^3 and ≤ 75 hm^3)	613	73	80	82	848
Small (> 3 hm^3 and ≤ 5 hm^3)	202	32	69	116	419
Small (> 1 hm^3 and ≤ 3 hm^3)	521	100	287	485	1393
Small (≤ 1 hm^3)	1,643	746	4,172	10,337	16,898
Without information	104	25	193	2,613	2,935
Total	**3,514**	**987**	**4,823**	**13,666**	**22,990**

Adapted from Agência Nacional de Águas e Saneamento Básico (2023).

Table 11. Reservoir capacity classification by reservoir mining tailings and Industrial waste purpose.

Reservoir capacity	PHA				
	High	**Medium**	**Low**	**Not classified**	**Total**
Very Large (> 50 hm^3)	56	24	21	12	113
Large (> 25 hm^3 and ≤ 50 hm^3)	10	2	-	5	17
Medium (> 5 hm^3 and ≤ 25 hm^3)	55	16	1	2	74
Small (> 0.5 hm^3 and ≤ 5 hm^3)	54	33	17	16	120
Very Small (≤ 0.5 hm^3)	100	87	346	85	618
Without information	-	2	23	20	45
Total	**275**	**164**	**408**	**140**	**987**

Adapted from Agência Nacional de Águas e Saneamento Básico (2023).

Table 12. Dams subject to PNSB regulation and ICOLD classification criteria.

ICOLD	PNSB Regulation			Total	%
Classification	**Regulated**	**Not Regulated**	**Undetermined**		
Large Dams	2,013	29	15	2,057	8.6%
Small Dams	2,675	4,385	3,203	10,263	42.8%
Insufficient data	977	460	10,220	11,657	48.6%
Total	**5,665**	**4,874**	**13,438**	**23,977**	100%

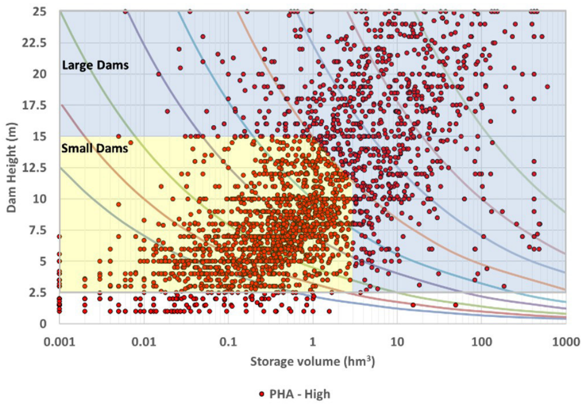

Figure 6. Ratio $H^2\sqrt{V}$ for dams with high PHA.

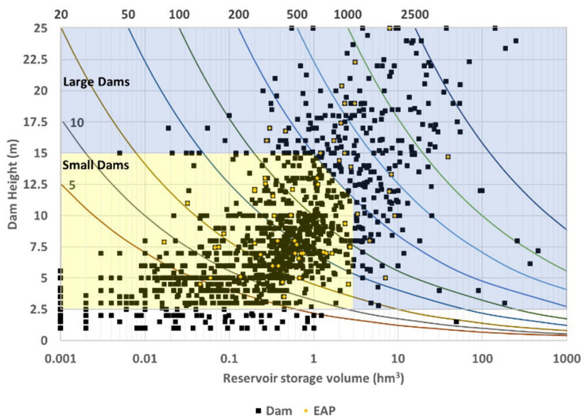

Figure 7. Dams with high RC and high or medium PHA and dams with EAP – up to 25 meters in height.

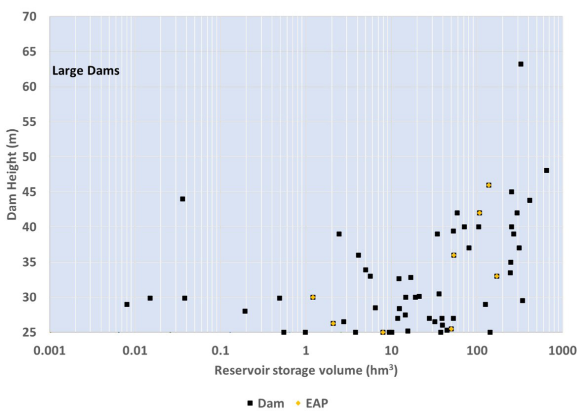

Figure 8. Dams with high RC and high or medium PHA and dams with EAP – over 25 meters in height.

Although the PNSB applies not only to large dams but also to small dams classified as Medium or High PHA, there is a regulatory gap concerning these smaller structures (Nava et al., 2021). This lack of specific regulations may result in an approach that does not adequately reflect the risks associated with such dams.

Regarding emergency preparedness, the data indicate that 1,342 dams have an Emergency Action Plan (EAP). Among Medium PHA dams, just 157 (13.65%) have an EAP, while 1,060 of the 3,789 High PHA dams (27.97%) are covered. Additionally, 90 Low PHA and 35 unclassified dams also have an EAP in place. Figure 7 and 8 illustrate High RC and High or Medium PHA dams with and without EAPs.

The analysis of EAP data raises serious concerns about emergency preparedness and exposes a critical gap in the implementation of the PNSB. Only a small fraction of dams, particularly those with Medium or High PHA, have an EAP, which is alarming and underscores a major weakness in Brazil's dam safety management system.

Effective risk communication and community education are essential for adequate preparedness in the event of a dam failure (Mehta et al., 2020). The lack of EAPs reveals a disconnect between existing regulations and real-world practices, exposing a systemic vulnerability that could lead to severe consequences in the event of a dam failure.

COMPARISON BETWEEN APPROACHES TO DAM CLASSIFICATION

Dam classification aims to identify potential downstream damage by evaluating population exposure, as well as social, economic, and environmental impacts. In many countries, classification serves as the foundation for dam safety regulations, guiding legal obligations and defining the frequency of inspections and reviews.

The following section compares Brazil's classification criteria with international approaches. Table A1 (Appendix A) summarizes key characteristics, including institutions involved, assessment criteria, hazard categories, and notable features of each system.

Flood assessment

Assessing downstream impacts from dam failure requires flood maps that incorporate hydraulic variables such as depth, velocity, and propagation time. Most classification systems consider two standard failure scenarios: "Sunny Day" failures, which occur independently of natural floods, and "Rainy Day" failures, which coincide with flood events (Australia, 2014; Federal Emergency Management Agency, 2004; España, 2023; New South Wales, 2022; New Zealand Society on Large Dams, 2015; Organismo

Table 13. PHA classification dams subject to PNSB regulation and ICOLD classification criteria.

Classification	PHA				
	High	Medium	Low	Not classified	Total
Large Dams	1,474	216	219	148	2,057
Small Dams	1,703	763	4,514	3,283	10,263
Insufficient data	612	172	498	10,375	11,657
Total	**3,789**	**1,151**	**5,231**	**13,806**	**23,977**

Regulador de Seguridad de Presas, 2018; Tasmania, 2015; United States Army Corps of Engineers, 2014).

These maps must reflect the extent and severity of flooding, particularly for identifying the population at risk. Empirical relationships between flood depth and velocity are commonly used to estimate potential human and infrastructure damage (España, 2023; Smith et al., 2014; United States Bureau of Reclamation, 1988).

In Brazil, ANEEL requires such scenarios for hydroelectric dams for hazard classification and EAP development (Brasil, 2023). However, regulations for water storage dams do not mandate failure scenarios for hazard assessments.

ANA employs a simplified methodology to generate inundation maps, relying on empirical equations and free global digital elevation models (DEMs), such as the Shuttle Radar Topography Mission (SRTM). Additionally, this methodology incorporates reservoir elevation and volume data from the Dam Register. The method is also available to other supervisory agencies and is, in theory, easy to apply (Agência Nacional de Águas e Saneamento Básico, 2017; Banco Mundial, 2014; Petry et al., 2018).

However, this simplified method is limited in scope, as it calculates only the flood area elevation and generates a flood map while ignoring other hydraulic variables essential for emergency planning.

This simplified approach aligns with the concept of a screening or tiered method (Federal Emergency Management Agency, 2013) and offers a practical interim solution for the large number of dams that remain unclassified. However, for structures with High or Medium PHA or RC, more advanced tools—such as hydrodynamic modeling and simulations of multiple failure scenarios—are essential to better address uncertainties and enhance risk reliability.

Classification by score

ICOLD's Bulletin 72 outlines a scoring method for preliminary dam safety assessment based on structural characteristics (e.g., height and reservoir capacity) and downstream consequences (e.g., required evacuations and potential damage) (International Commission on Large Dams, 1989). The total score results from summing structural and impact criteria, with greater weight assigned to larger reservoirs and more severe consequences.

The risk assessment is conducted by weighting these components, giving greater emphasis to dams with larger reservoirs. According to the proposed method, dams requiring more extensive evacuations and posing greater downstream damage potential will receive a higher risk score (International Commission on Large Dams, 1989).

Québec applies a similar risk-based approach, where the risk level (P) is calculated by multiplying the dam's vulnerability (V) by the consequences of failure (C) (Québec, 2022). Vulnerability is based on structural parameters (e.g., height, type, capacity, foundation) and operational conditions (e.g., age, seismicity, discharge reliability). Consequences are assessed from population density and critical infrastructure exposed.

$$P = V \times C \tag{3}$$

The dam's vulnerability (V) is calculated by multiplying the average of its physical parameters—height, type, capacity, and foundation type—by the average of its variable parameters, such as age, seismicity, discharge reliability, and conservation conditions. Québec's legislation also defines consequence categories based on population density and the presence of critical infrastructure, including roads, industries, dams, water supply, and hazardous materials (Québec, 2022).

In Brazil, RC and PHA classifications are applied independently, though some agencies use their combination to guide documentation and inspection frequency. Their relationship resembles a Risk Index (RI), which, according to the World Bank (2021), can help prioritize safety interventions across dam portfolios.

A graphical representation can support this use: the y-axis reflects the RC score, indirectly reflects the risk of dam failure, and the x-axis represents the potential hazard, based on the PHA score. Figure 9 shows how ANA applied this model to 104 dams, highlighting Class A dams—those with high RC and PHA—as priorities for stricter oversight.

Though preliminary, this visual model aligns with international practices adopted by ANCOLD, USACE, and USBR, where dam failure probability is plotted against expected loss of life (Australian National Committee on Large Dams, 2003; United States Army Corps of Engineers, 2012; United States Bureau of Reclamation, 2011). These frameworks incorporate principles like acceptable, tolerable, and ALARP risk thresholds, which could inform future classification practices in Brazil and improve decision-making by supervisory agencies.

Dams size

In Brazil, dam height is used to classify (RC), while PHA is scored using total reservoir volume. However, volume has limited influence on final PHA classification, especially for small dams, since human life and socio-economic impact scores tend to dominate. By contrast, FEMA prioritizes downstream threats to life and property regardless of dam size (Federal Emergency Management Agency, 2004).

ICOLD's Bulletin 72 assigns scores based on height and volume, similar to Québec's system, which treats these as key

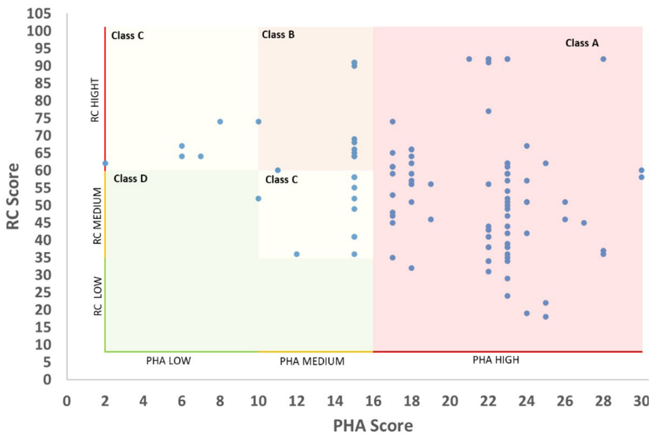

Figure 9. Proposal to graphically represent the use of the RC score and PHA.

physical parameters (International Commission on Large Dams, 1989; Québec, 2022). Bulletin 157 introduces a specific classification for small dams, evaluating risks through life safety, economic, environmental, and social factors, along with the height-to-volume ratio. Dams are classified as high hazard if ($H^2\sqrt{V} > 200$) or if the population at risk exceeds 10 (International Commission on Large Dams, 2011).

Portugal also uses a height-to-volume metric ($X = H^2\sqrt{V}$). classifying dams as Class I if X > 1000 and more than 10 residences lie downstream (Portugal, 2018). In contrast, South Africa relies primarily on dam height, and small dams are not included in the highest hazard category—even if they pose high potential damage (Republic of South Africa, 2012).

In Portugal, dam classification is based on dangerousness (X), calculated using the height-to-volume relationship, similar to the ICOLD classification ($X = H^2\sqrt{V}$). To be classified as Class I—the highest category—a dam must have X > 1000 and impact more than 10 households downstream (Portugal, 2018).

Environmental impact

CNRH adopts a binary environmental impact classification approach— "Significant" or "Very Significant". While simple, this system limits precision and interpretability. To reduce subjectivity, ANA introduced refinements based on the National System of Conservation Units (SNUC), classifying impacts as "Little Significant," "Significant," or "Very Significant",depending on the degree of environmental protection and natural state of the affected area.

The criteria established in Spain determine the severity of environmental damage and the impact on historical, artistic, or cultural heritage. Category A applies to damage affecting elements or territories with legal protection at the state level. At the same time, Category B refers to severe damage to elements protected at the local authority level. In addition to defining these categories, the assessment also considers the size of the affected area (España, 2023). In Australia, systems evaluate recovery time, biodiversity, water quality, and the presence of protected areas (New South Wales, 2022). New Zealand uses a scale-based approach that assesses the severity and reversibility of environmental damage (New Zealand, 2022a).

Socio-economic impact

CNRH assesses socio-economic impacts by considering the density of residential, commercial, agricultural, industrial, infrastructure, and leisure facilities in the potentially affected area. However, its largely qualitative approach introduces subjectivity. ANA improved this by incorporating the number of facilities into the classification, though some subjectivity remains.

In contrast, Australia and New Zealand adopt more detailed, structured assessments. Australian states like Victoria, Tasmania, and New South Wales follow ANCOLD guidelines, which evaluate both infrastructure repair costs and health and social impacts (Australian National Committee on Large Dams, 2012). These include effects on human health, displacement, employment, property loss, and recreational facilities, assessed by the number of people or duration of disruption (Australia, 2014; New South Wales, 2022; Tasmania, 2015).

New Zealand's framework also includes cultural and critical infrastructure impacts, assessing both damage severity and recovery feasibility (New Zealand, 2022a). Spain and the US Army Corps of Engineers (USACE) adopt similar approaches, incorporating damage to water, power, communications, and transportation infrastructure into their evaluations (España, 2023; United States Army Corps of Engineers, 2014).

USACE further analyzes property losses by considering both direct damages—such as physical destruction of facilities and downstream structures—and indirect impacts, including revenue losses from navigation interruptions and service outages. It also accounts for life safety risks related to loss of access to essential services like hospitals, water supply, and energy systems (United States Army Corps of Engineers, 2014).

Downstream population affected

Two fundamental concepts are used to assess the potential risks associated with dam failure: Population at Risk (PAR) and Probable Loss of Life (PLL). PAR estimates the number of people exposed to flooding if a dam fails without warning (Federal Emergency Management Agency, 2004; New Zealand, 2022b; Wishart et al., 2020), while PLL incorporates a mortality rate to estimate expected fatalities, even with evacuation efforts (Federal Emergency Management Agency, 2004; Graham, 1999; Wishart et al., 2020).

PLL estimation depends on dam failure scenarios, flood dynamics, and the exposed population, and must also consider shelter access, warning systems, and evacuation times (United States, 2011; Jonkman et al., 2008). Various methods are available, including analytical models (Graham, 1999), RECEM (United States Bureau of Reclamation, 2015), and simulation tools like LIFEsim (Aboelata & Bowles, 2008).

In Australia, dam classification in states like Victoria, Tasmania, and New South Wales follows ANCOLD guidelines, allowing the use of either Population at Risk (PAR) or Probable Loss of Life (PLL), with PLL taking precedence when available (Australian National Committee on Large Dams, 2012). Queensland applies the Failure Impact Assessment (FIA), which assigns a Failure Impact Rating based on estimated PAR (Australia, 2018).

New Zealand adopts a more comprehensive approach by incorporating both PAR and PLL, offering a fuller assessment of the number of people exposed and the potential fatalities from dam failure (New Zealand, 2022b).

New Zealand and Australia include permanent and transient populations in their PAR calculations (New Zealand, 2022b; New South Wales, 2022). The permanent population comprises individuals in households, commercial and industrial establishments, and community facilities. Meanwhile, the transient population includes recreational users, campers, seasonal agricultural workers, and transit users of highways and bridges (New Zealand, 2022b).

In contrast, FEMA and USACE classification systems do not consider transient populations—such as passersby or occasional recreational users—when estimating potential loss of life (Federal Emergency Management Agency, 2004; United States Army Corps of Engineers, 2014).

Table 14. Recommendations for Enhancing Dam Classification Criteria in Brazil: A Comparative Analysis with International Practices.

Criterion	Suggestion for Improvement	International Example
Dam Size	Assess whether incorporating dam size as a classification criterion would improve risk evaluation.	While dam size is relevant, classification should prioritize potential downstream damage to enhance safety.
Flood Assessment	Establish clear guidelines for "Sunny Day" and "Rainy Day" scenarios, differentiating between failures independent of natural floods and those occurring during floods.	Most international classification systems consider flood scenarios. ANEEL (Brazil) already applies similar criteria to hydroelectric dams; expansion to all dams could improve assessments.
Environmental Impact	Develop more detailed criteria for environmental impact assessment, moving beyond a binary approach.	Some classification systems, such as ANA's, define protected areas, but a more advanced approach could quantify the affected area in the event of a dam breach, as used in Spain.
Socio-economic Impact	Enhance the socio-economic impact assessment by explicitly incorporating key infrastructure that, if affected, would significantly impact society.	Most international classification systems specify which types of infrastructure should be considered in this evaluation.
Population Affected	Introduce quantification of downstream residences for a more objective PHA assessment.	Portugal and Spain use the number of residences downstream as a classification criterion.

Brazil's hazard classification uses the term "potential loss of human life," considering both permanent and temporary residents downstream (Brasil, 2012, 2016). Temporary residents include people in public developments and along roads, aligning the criteria with PAR-based approaches. In the simplified method, downstream population is estimated by counting the number of residences within the inundation area (Agência Nacional de Águas e Saneamento Básico, 2017).

The dam classification system does not distinguish between a single residence and an entire town within the flood zone. As a result, the presence of just one residence is sufficient to increase the "potential loss of human life" score. In practice, this leads to the dam being classified as High PHA under CNRH criteria and as Medium or High PHA according to ANA's complementary criteria.

In this context, the criterion could be revised by formally adopting the number of households as a key parameter and adjusting the score distribution based on the number of households downstream (Salgado & Carvalho, 2023), following the approach used in Portugal and Spain.

The criterion adopted by Spain assesses the presence and impact of population centers and isolated residences located downstream of the dam (España, 2023). The classification of risk conditions in households is structured as follows: Category A applies when the "serious condition" affects more than five households, while Category B is used when the "serious condition" affects between one and five households.

The classification system in Portugal considers the number of permanent residences (Y) in the flood-prone area (Portugal, 2018). A single residence does not lead to the highest classification; to be classified as Class I, the area must have at least 10 residences and a dangerousness factor (X) greater than 1000. Class II applies when there are $\geq$10 residences and X $\leq$1000, or fewer than 10 residences, regardless of X.

The experience of Portugal and Spain suggests that additional criteria could be incorporated into Brazil's dam damage assessment. One such criterion could involve quantifying the number of households downstream of the dam, based on the potential inundation area in the event of a failure.

Improving dam hazard classification

Table 14 presents a structured approach to enhancing dam safety assessments, highlighting areas for improvement based on the characteristics and challenges of Brazil's classification system, as well as international best practices. The table underscores the importance of comprehensive assessment criteria, including dam size, flood scenarios, environmental impacts, socio-economic factors, and downstream population impacts, to ensure a more effective dam classification system.

Some of the recommendations presented in this section have already been partially incorporated into CNRH Resolution No. 241/2024—most notably, the environmental impact criteria, which now include scoring based on the type of protected area, and the socio-economic impact criteria, which consider areas of interest and types of affected infrastructure (Brasil, 2024).

However, the effective implementation of these criteria depends on revising regulatory procedures and strengthening the technical capacity of supervisory agencies. Moreover, key elements—such as the standardization of dam break scenarios, the explicit use of flood maps, and the quantification of downstream populations, as highlighted in international best practices—still lack clear guidance or widely adopted methodologies.

CONCLUSIONS

The RC and PHA classifications have proven to be effective and interpretable indicators of the status of the PNSB. They offer strategic value for guiding the actions of both supervisory agencies and dam owners, encouraging the adoption of good safety practices.

However, the data indicate that fully enforcing the national dam safety policy will require improved dam data collection and refinement of classification criteria—particularly those related to downstream impacts. These steps are essential to identifying risks and ensuring the adoption of appropriate safety measures.

Additionally, large dams may require specific safety strategies, and small dams urgently need proportionate regulatory standards to ensure adequate maintenance and monitoring.

The existence of numerous unclassified dams—especially among water storage structures—underscores gaps in implementation. In contrast, hydroelectric dams tend to present more complete data and classifications.

This discrepancy is especially evident in the widespread absence of EAPs, despite legal mandates, exposing not only regulatory weaknesses but also deficiencies in risk and emergency management.

Improving PHA criteria could enhance alignment between dam characteristics and legal obligations. One such improvement is the explicit inclusion of the number of downstream households as a proxy for potential loss of life, as already practiced in countries like Portugal and Spain.

Defining flood scenarios is another essential factor in assessing damage, as demonstrated by international experience. In the case of hydroelectric plants, this practice has already been incorporated into ANEEL regulations, and its expansion to other dams could strengthen risk analysis. In addition, it is essential to limit the use of simplified methodologies and promote more accurate assessment techniques.

Currently, inspection agencies principally employ the classification to define the frequency and content of the required reports. Nevertheless, there is an opportunity to broaden its application by integrating it into a graphical model that intuitively represents dam failure risk and potential damage, creating a more comprehensive risk index.

Further research could apply the proposed classification improvements through case studies, comparing the current Brazilian model with international frameworks to assess discrepancies and their practical implications for dam safety management.

Investing in these improvements is not exclusively a matter of regulatory compliance; the initiative also presents an essential opportunity to strengthen the implementation of the PNSB, prevent new tragedies, and consolidate a dam safety culture in Brazil.

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DATA AVAILABILITY STATEMENT

Research data is available in the body of the article.

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APPENDIX A - OVERVIEW OF POTENTIAL HAZARD CLASSIFICATION SYSTEM

Table A1 - Overview of Potential Hazard Classification System

Institution/Country	Potential Hazard			Observation
	Criteria	Classes	Max classification	
ICOLD	Dam height, reservoir capacity, evacuation requirements (number of people), and potential damage downstream (socio-economic and environment)	Low, Moderate, High, Extreme	Total risk points = 31 to 36	Bulletin 72 of the ICOLD
ICOLD	Life Safety Risk, economic risk, environmental Risk, and social Risk	High, Medium and Low	PAR > 10 and X > 200, implies high class. $X = H^2\sqrt{V}$ where H is the dam height and V is the reservoir volume.	Bulletin 157 of the ICOLD
Portugal	PAR, dangerousness (X), socio-environmental and economic damage	I, II and III	PAR > 10 e X>1000, results class I. $X = H \sqrt{V}$ where H is the dam height and V is the reservoir volume.	
Argentina	LOL, socio-environmental damage and economic damage	Heigh, Significant and Low,	1 LOL means Class I	
Spain	Urban centers or isolated dwellings, essential services, material damages, and environmental aspects, historical, artistic, or cultural	A, B and C	Impacts more than five residences, impairs essential services, causes significant material damage, or severely impacts areas with legal protection, such as environmental, historical, or cultural sites.	
New Zealand	Assessed damage, PAR and LOL	High, Medium and Low	Damage = Catastrophic: Damage = Major PAR > 11; or LOL > 2 Damage = Moderate or Minimal LOL > 2	Assessed damage: Community impacts, on historical or cultural sites, on critical or important infrastructure, and on the environment
South Africa	PAR, economic losses, and adverse impact on resource quality	I, II and III	PAR > 10 or economic losses = Great or Impacts on environmental resources = Severe	Final classification in 3 levels based on a matrix with size class (Small, Medium, Large) versus hazard (High, Significant, and Low)
Australia/ Victoria, New South Wales and Tasmania	PAR or LOL, health and social impact and environmental impacts	Extreme, High A, High B, High C, Significant, Very low and Low	50 > PAR > 5 and Damage and Loss = Catastrophic PAR > 50 and Damage and Loss = Major or Catastrophic	Classification based on a matrix that relates the severity of damage and loss levels to the LOL or PAR. Classification with LOL overrides any classification based on PAR
Australia/Queensland	PAR	High and Low	PAR > 100	Unregulated DAM in case that PAR < 2
USA/FEMA	LOL and economic, environmental, and vital services losses	High, Significant, and Low	LOL result in high class	

Table A1 - Continued...

Institution/Country	Potential Hazard			Observation
	Criteria	Classes	Max classification	
USA/USACE	LOL and economic, environmental, and vital services losses	High, Significant, and Low	LOL result in high class	
Canada/ Québec	Physical parameters of the dam, population density, infrastructure, and services	A, B, C and D	P ≥ 120 dam's vulnerability (V) by the numerical value of the potential consequences of failure (C)	
Brazil/CNRH	Reservoir volume, potential loss of human life, environmental Impact, Socio-economic Impact	High, medium, and low	PLL result in high class	Dams classified according to the risk category, and can be categorized as: high, medium, and low.
Brazil/ANA	Reservoir volume, potential loss of human life, environmental Impact, socio-economic Impact	High, medium, and low	PLL result high class or Medium Class	Dams classified according to the risk category, and can be categorized as: high, medium, and low. implemented classification classes that correlate PHA and the RC
Brazil/ANEEL	Reservoir Volume, potential loss of human life, environmental impact, socio-economic Impact	High, medium, and low	PLL result in high class	Dams classified according to the risk category, and can be categorized as: high, medium, and low." implemented classification classes that correlate PHA and the RC