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Analysis of dam safety as critical infrasucture: systemic risks, adaptive governance, and geopolitical implications

Abstract

In recent years, the relationship between environmental risks and national security has become increasingly evident, particularly in relation to the occurrence of tailings dam failures around the world. This article investigates the relationship between these disasters and the safety of these dams, analyzing how the collapse of these structures directly and indirectly impacts the geopolitical stability and international reputation of the affected countries. Initially, a systematic literature review was conducted on the topic, covering the years 2000 to 2025. Conflicting geopolitical contexts were taken into account, as failures and disasters in large strategic dams have the potential to compromise the achievement of the Sustainable Development Goals, particularly those related to clean water, action against global climate change, and life on Earth. In their discussion, it is noted that historical cases, including disasters in Brazil, China, the USA, and Europe, have demonstrated that the collapse of large dams has the potential to provoke diplomatic crises, compromising national and international alliances, and influencing foreign policy. It was concluded that the risk management of these structures should be treated as a matter of national security, demanding monitoring and management policies that incorporate increasing climate variability to mitigate future catastrophes.

Keywords: climate change and dam failure, dam management and geopolitical stability, sustainable development goals

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Introduction

National security is a broad and dynamic concept, described by various authors in the world's technical-scientific literature, generally as a set of strategies, policies and measures adopted by a State to protect its essential interests, its territorial integrity and its sovereignty.[1–4] This also includes the security and well-being of the population, as well as aiming to manage imminent and imminent risks, both from actors within the nation itself and from non-state actors.[2–4] Beyond conventional military activities and threats to a nation, the broad concept of national security also includes risks ranging from economic crises, technological and cyber threats, and even environmental catastrophes.[5–7]

In this sense, the relationship between environmental risks associated with dams and national security has gained relevance as environmental disasters and failures in the infrastructure projects of these types of constructions become more frequent and serious.

Exacerbated by climate change,[8–15] these types of disasters not only affect the environment and public health, but also tend to compromise other sectors, such as socioeconomic, health and the environment.[16–19] However, the vulnerability of critical infrastructure, such as dams, and catastrophes that have occurred or may occur, can reveal a relationship between environmental risks and a government's ability to maintain order and confidence both internally and externally in a nation.

The tailings dam collapses that occurred in Brazil, specifically in 2015, in Fundão, Mariana, and in 2019, in Brumadinho, both in the state of Minas Gerais[20–32] highlighted not only the weaknesses in the tailings control infrastructures, but also exposed significant gaps in the capacity of governments and institutions to respond to these events, especially those involving environmental disasters with large-scale dams.[33,34]

The collapse of the Fundão dam, located in the municipality of Mariana-MG, belonging to the mining company Samarco, released millions of cubic meters of mining tailings, and this directly affected the Rio Doce and a wide area of aquatic and terrestrial ecosystems, being considered one of the biggest environmental disasters in Brazil.[35–37]

The Brumadinho-MG disaster, also occurring in Brazil, associated with the mining company Vale SA, in 2019, also resulted in the release of millions of cubic meters of tailings and caused not only large-scale environmental damage, but also caused the death of 272 people,[38–42] therefore being considered one of the biggest industrial disasters in the history of Brazil.[43]

Regarding the disaster resulting from the collapse of the Ferro Carvão Dam in Brumadinho-MG, it is worth highlighting the work carried out with the simulation of a dam collapse in comparison with the real results, where the authors used geotechnologies, employing QGIS[44] and ArcGIS/tools[45] and in conjunction with free software, such as HEC-RAS (Hydrologic Engineering Center-river Analysis System),[46,47] these authors carried out tests with varying spatial resolutions of different DEMs (Digital Terrain Models)[48] and also employing various spatial resolutions, degraded from the original DEM.[49,50] In these tests, the extent of the affected areas was evaluated, as well as the propagation speed of the flood wave. The application of these tools allows for the accurate assessment of the extent of potentially affected areas and the propagation speed of tailings, providing technical support for comparison between simulated results and real events.

Thus, the Mariana-MG and Brumadinho-MG disasters, both occurring in the Southeast Region of Brazil, are interrelated not only by the similarity of their causes and socio-environmental consequences, but also by having fostered the development of more

robust and scientifically tested scientific methodologies for the analysis, prediction and management of risks associated with tailings dams.[51–53] In addition, they revealed the need to reassess regulatory and oversight systems, both at the local and national levels, to prevent the occurrence of new disasters and ensure population and environmental safety.

The responses to the aforementioned disasters at the time were marked by a series of criticisms, both regarding the slowness of emergency actions and the insufficiency of environmental and social recovery measures.[54–56] These events received extensive media coverage, being reported in various news outlets, both national and international.[57–60] However, it was not only Brazil that suffered from dam collapses. An example of this was the rupture of a water dam in Orsk in 2024, which occurred in south-central Russia, generating a large-scale flood, leading to the declaration of a state of emergency, as well as the evacuation of more than 10,000 people and the mobilization of rescue teams.[61,62]

In Laos (Southeast Asia), in 2018, the collapse of the Xe-Pian Xe-Namnoy dam, in the south of that country, resulted in hundreds of deaths and thousands of homeless people.[63–67]

In the year 2023, it is worth highlighting the rupture of the Kakhovka dam, located in Southern Ukraine, which, as reported,[65,68] resulted in flooding along the Dnipro River, compromising the supply of drinking water to the population.

The dam failures mentioned above share common characteristics that highlight global deficiencies in the management of critical infrastructure such as water and tailings dams. This is because, in all these events, there were failures in preventive monitoring and maintenance of structures, despite the fact that all the countries involved in the aforementioned disasters have laws and regulations on dams. Such concerns are reported and commented on by several authors, namely.[33,34]

Thus, the present work has the general objective of carrying out a scientific, historical and geopolitical analysis of dam safety on a global scale, identifying the technical, institutional and strategic patterns that determine the occurrence of disasters associated with the rupture of these critical infrastructures between the years 2000 and 2025.

Therefore, a systematic scoping review of the main international scientific publications on dam safety within this period was carried out, categorizing them into thematic axes that express the technical, normative, and geopolitical dimensions of the problem; comparatively analyzing dam failures that occurred, in order to identify historical trends, recurring failures, and possible evolutions in prevention and response mechanisms; examining the socioeconomic, environmental, and strategic impacts resulting from these disasters, highlighting the implications for environmental governance, energy security, and the geopolitical stability of countries; and proposing an integrated reading of dam safety as an essential component of national and international security policies, incorporating Artificial Intelligence (AI) and risk intelligence approaches, economic valuation of damages, and preventive environmental diplomacy.

The rationale for this is related to the need to understand dams from an integrated environmental security perspective in order to anticipate threats in contexts of hybrid warfare, water scarcity, and climate change, since these are infrastructures that, depending on their size and importance, can be considered strategic and critical structures for a nation.

Materials and methods

This research adopted a Systematic Literature Review (SLR) based on scoping, structured according to the PRISMA-ScR (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) protocol.[69,70] The choice of this method is based on its recognized rigor and transparency in identifying, selecting, and critically evaluating scientific evidence in complex and multidisciplinary research fields.[71] This approach is particularly suitable for the present study, which is situated at the interface between environmental engineering, disaster risk management, and national security, areas that remain fragmented both conceptually and empirically.

Therefore, a systematic search was conducted between September and October 2025 in three scientific databases with broad coverage and international relevance: Scopus, Web of Science, and SciELO. These platforms were selected because they include peer-reviewed publications in the areas of environmental science, engineering, and international security studies.

The search strategy was outlined, as shown in the diagram below and Figure 1, in three complementary analytical axes, with the aim of capturing isolated and interconnected dimensions of the research problem:

a) Axis I – National Security and Critical Infrastructure: Keywords: "dam safety" AND "critical infrastructure" AND "environmental security"

b) Axis II – Dam Safety and Environmental Disasters: Keywords: "dam safety" AND "dam failure" AND "risks and implications for society"

c) Axis III – Integrative Axis (Intersection): Combination of the two previous axes using Boolean operators: "geopolitical risk" AND "dam safety" AND "dam failure".

Figure 1 Axes defined for literature search.

Source: By the authors. Drawing generated using the website Napkin.com

The use of these three axes allowed for mapping the existing scientific production both in each domain individually and at the point of intersection between them, where the relationship between dam safety and national security could be explored directly or indirectly. To ensure the consistency and thematic relevance of the analysis corpus, the following inclusion criteria were adopted:

1) Publications (articles, theses, reports and reviews) from 2000 to 2025, a period that reflects the strengthening of international discussions on environmental governance and dam safety after the turn of the millennium;
2) Reading the title, abstract, objectives, methodology, results, and discussion;
3) Papers written in English, Portuguese, or Spanish;
4) Studies that address environmental risks, infrastructure governance, climate disasters, or implications for national security, involving dams of different types (containment of tailings, water, or sediments);
5) Research that discusses, explicitly or inferentially, the geopolitical, economic, or social implications resulting from dam failures.

Following the selection process, publications that were excluded were:

a) They dealt exclusively with technical or structural engineering aspects, without any connection to dimensions of risk, governance, or safety;
b) These were duplicate entries in the databases;
c) They did not address the implications or impacts of dam failures in areas that could affect governments.

In view of this, the identification and selection of studies followed the four classic steps of the PRISMA-ScR protocol,[60–71] as can be seen in the flowchart in Figure 2, below:

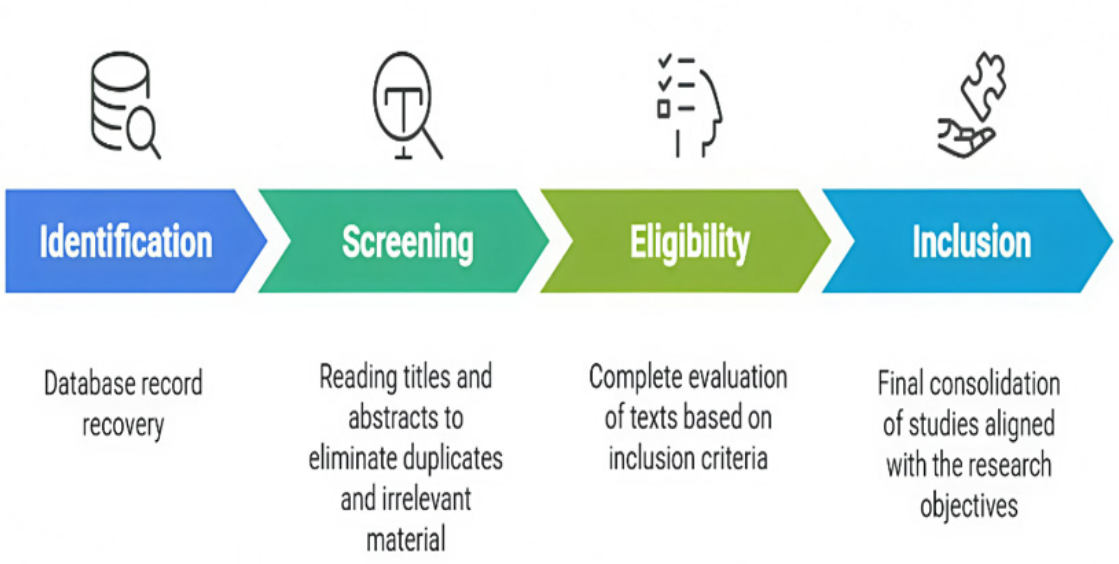

Figure 2 Systematic literature review.

Source: By the authors. Drawing generated using the website Napkin.com

For the continuation of the studies, a comparative analysis of historical dam failures around the world was carried out using scientific and journalistic texts. In this way, the aim was to understand the influence of major dam disasters worldwide and how this knowledge could contribute to consolidating the hypothesis that the collapse of large dams represents not only an environmental and socioeconomic problem, but also a strategic risk to the security and geopolitical stability of nations.

Results

Through searches in scientific databases for Axis I - National Security and Critical Infrastructure, 100 publications were found. Thus, by refining the searches, specifically focusing on scientific works from 2000 to 2025, the databases returned 80 works, the vast majority of which were in English. From these 80 works, after reading the title, abstract, methodology, and results and discussions, only those addressing environmental risks, infrastructure governance, the implications of dam failures for national security, and research that explicitly or inferentially discusses the geopolitical, economic, or social implications of dam failures were selected. This resulted in 20 publications.

For Axis II (Dam Safety and Environmental Disasters), 103 publications were found through keyword searches. Of these 103 publications, 45 were selected because they were most similar to the keywords. Following this, through reading the title, abstract, methodology, and results and discussions, 15 works were selected that presented discussions closest to thematic axis II.

Finally, for Axis III (Integrative Axis), that is, the intersection between the themes of the previous axes, 73 scientific publications were found, of which, similarly to the processes mentioned above for Axes I and II, 13 works were found.

Tables 1–3 below list the selected scientific publications, separated by thematic areas:

Table 1 Selected publications from Axis I[72–90]

● Tailings give failures: A critical evaluation of current policies and practices. Results in Engineering, vol. 25, 2025
● Cyber defense as a part of hazard mitigation: Comparing high hazard potential dam safety programs in the United States and Sweden. Journal of Homeland Security and Emergency Management, 2016.
● Review of studies on risk factors in critical infrastructure projects from 2011 to 2023. Smart and Sustainable Built Environment, 2025.
● Enhancing dam safety: an integrated framework for dam safety management. International Journal of Disaster Resilience in the Built Environment, 2025.
● Comprehensive Review on Sustainable Dam Infrastructure: Issues and Challenges, Factors Causing Dam Failure and Future Direction in a Globally Changing Climate, 2025.
● Enhancing dam safety through contractual strategies. In: Role of Dams and Reservoirs in a Successful Energy Transition, 2023.
● Review of climate change impacts on dam safety and flood mitigation issues in India. Water and Energy International, 2019.
● Dam Safety Legislation: a focus on the different approaches. In: Advances in Water Resources and Hydraulic Engineering: Proceedings of 16th IAHR-APD Congress and 3rd Symposium of IAHR-ISHS. Berlin, Heidelberg: Springer Berlin Heidelberg, 2009.
● Estimating life loss for dam safety and risk assessment: Lessons from case histories. In: Proceedings of the 2000 Annual USCOLD Conference, US Society on Dams (formerly US Committee on Large Dams), Denver, CO. 2000.
● Safety assessment for dams of the cascade reservoirs system of Lancang River in extreme situations. Stochastic Environmental Research and Risk Assessment, 2017.
● Safety monitoring and management of reservoirs and dams. Water, 2023.
● A study of safety evaluation and early-warning methods for global behavior. Structural Health Monitoring, 2012.
● Analysis and application of international dam safety policy benchmarks. Benchmarking: An International Journal, 2011.
● Dam risk management. In: ISRM international symposium. ISRM, 2000.
● Statistical Analysis of Global Dam Accidents in the 21st Century: A Focus on Common Features and Causes. Water Resources Management, p. 1-24, 2025.
● Comprehensive Review on Sustainable Dam Infrastructure: Issues and Challenges, Factors Causing Dam Failure and Future Direction in a Globally Changing Climate. Pertanika Journal of Science & Technology, 2025.
● Comprehensive assessment of dam safety using a game-theory-based dam safety performance measure. Water, 2024.
● Methodology to evaluate cascade dams breaks for analysis and safety design. RBRH, 2023.
● Investigation of damage incidents and failures. Proceedings of the Institution of Civil Engineers-Forensic Engineering, 2011.
● Reviewing arch-dams' building risk reduction through a sustainability–safety management approach. Sustainability, 2020.

Source: By the authors (2025)

Table 2 Selected publications from Axis II[91–105]

● Analysis of damage failure and incident investigations in the United States from 1960 through 2022: framework for improving future investigations. Journal of Water Resources Planning and Management, 2024.
● An innovative methodology for establishing societal life risk criteria for dams: A case study to reservoir dam failure events in China. International journal of disaster risk reduction, 2020.
● Dam failure risk factor analysis using AHP method. In: IOP Conference Series: Earth and Environmental Science. IOP Publishing, 2021.
● An improved method for estimating life losses from dam failure in China. Stochastic Environmental Research and Risk Assessment, 2020.
● Calculation method and application of loss of life caused by dam break in China. Natural Hazards, 2017.
● Loss of life estimation and risk level classification due to a dam break. Heliyon, vol. 2022.
● Tolerable risk for dams: How safe is safe enough. In: US Society on dams annual conference. 2007.
● International small dam safety assurance policy benchmarks to avoid dam failure flood disasters in developing countries. Journal of Hydrology, 2015.
● Incorporating on-farm water storage safety into catchment policy frameworks: International best practice policy for private dam safety accountability and assurance. Land Use Policy, 2013.
● Risk and uncertainty in giving safety. Thomas Telford, 2004.
● Risk analysis is fundamentally changing the landscape of dam safety in the United States. 2017.
● Challenges in preparation and implementation of dam safety emergency plan for hydroelectric plants in Sarawak. In: International Conference on Dam Safety Management and Engineering. Singapore: Springer Singapore, 2019. p. 1-9.
● Geotechnical risk, regulation, and public policy. 2018.
● Understanding future safety of dams in a changing climate. Bulletin of the American Meteorological Society, 2019.
● Dams and floods. Engineering, 2017.

Source: By the authors (2025)

Table 3 Selected publications from Axis III[106–119]

● Developments in legislation giving security in India: a tale of ifs and buts? Asia Pacific Journal of Environmental Law, 2022.
● Dam safety: hazards created by human failures and actions. Journal of Earth Sciences and Geotechnical Engineering, 2021.
● Critical infrastructure protection: Maintenance is national security. Journal of Strategic Security, 2015.
● What Was Actually the Disaster? Flood and Reconstruction in a Bulgarian Village in 2012. JAHRBUCHER FUR GESCHICHTE OSTEUROPAS, 2014
● Biophysical, socioeconomic and geopolitical impacts assessments of large dams: an overview. MegaDam Overview, 2014.
● Introduction to the special issue: Understanding and linking the biophysical, socioeconomic and geopolitical effects of dams. Journal of Environmental Management, 2009.
● Biophysical, socioeconomic, and geopolitical vulnerabilities to hydropower development on the Nu River, China. Ecology and Society, vol. 18, no. 3, 2013.
● Risk modeling in nuclear tailings dams: an Economic Valuation of Environmental Damages (EVED) and hydrological approach. MOJ Eco Environ Sci, 2025.
● Disasters across borders: Borderlands as spaces of hope and innovation in the geopolitics of environmental disasters. In: Crossing Borders: Governing Environmental Disasters in a Global Urban Age in Asia and the Pacific. Singapore: Springer Singapore, 2017
● Environmental peacebuilding: Yesterday, today, and tomorrow. The Journal of Social Encounters, 2024.
● Integrative Dam Assessment Model (IDAM) Documentation: Users Guide to the IDAM Methodology and a Case Study from Southwestern China. Oregon State University, Corvallis, Oregon, 2012.
● Dams, terrorism, and water nationalism's response to globalization and development: the case of South Asia. Terrorism and political violence, 2022.
● The Struggles for Corporate Accountability in the UN: A Global South Perspective. In: The Wretched of the Global South: Critical Approaches to International Human Rights Law. Singapore: Springer Nature Singapore, 2024.
● Dams and floods. Engineering, 2017.

Source: By the authors (2025)

The studies selected through the keywords of Axis I present a multidimensional and comparative approach to dam safety, integrating perspectives from engineering, public policies, risk management, and climate change. In general, the selected publications demonstrate a conceptual and methodological evolution in the assessment of the safety of hydraulic structures, with an emphasis on resilience, sustainability, and institutional governance.[72,78,82,86,88] The investigations range from global statistical analyses of dam accidents and a review of risk factors in critical infrastructures,[79,85] to the development of integrated knowledge for the management and monitoring of the safety of the structures in question.[73,74,77,80,89,90] It is also worth highlighting the contributions aimed at incorporating contractual strategies and public policies for risk mitigation and strengthening cyber defense in systems with high potential for danger.[73]

Furthermore, systematic review studies have shown the challenges posed by climate change and the degradation of water infrastructure[76,86] suggesting future guidelines for improving dam safety legislation and practices on a global scale.

Consequently, scientific literature emphasizes the necessity of adaptive, technical, and scientific governance. This approach must be supported by advanced analytical tools, such as modeling based on game theory, probabilistic assessments, and early warning systems which are essential to enable the proactive management of dam safety and sustainability amidst a changing climate and institutional landscape.

With respect to axis II, Table 2 is presented, which is similar to what was presented for axis I.

In the analysis of Table 2, focused on Axis II, the publications gathered and selected comprehensively address the evolution of methods for analyzing, managing and mitigating risks associated with dam failures, focusing on estimating loss of human lives, formulating socially acceptable risk criteria and improving public water security policies, which is particularly noticeable.[94–96]

Studies are moving towards developing quantitative and multicriteria approaches, such as the use of the AHP method[93] and statistical modeling,[93] which allow for a more precise assessment of risk factors and the probability of dam failure.

Furthermore, normative and comparative research explores the definition of tolerable risk criteria and the role of international security policies, especially in developing countries, in preventing large-scale hydrological disasters.[97–105]

The literature also highlights the incorporation of geotechnical uncertainty analysis and climate change as central elements in the contemporary redefinition of dam safety, pointing to the need for policies and emergency plans in contexts of increasing environmental and institutional complexity, which is evident.[103]

In summary, the works selected for Axis II consolidate a scientific agenda focused on the integration between risk engineering, public management, and sustainability, reinforcing that dam safety should be conceived not only as a technical problem, but as a matter of socio-environmental and ethical governance in the face of uncertainty and human vulnerability.

Continuing with this analysis, now with respect to axis III, Table 3 is presented.

Analyzing Table 3, corresponding to the publications that make up Axis III, it can be seen that these reflect a geopolitical approach to dam safety, articulating legal, socioeconomic, environmental and ethical dimensions in the analysis of the risks associated with these critical infrastructures, notably.[110–115]

Taken together, the selected studies emphasize that dam safety transcends the technical field of engineering,[113] configuring itself as a strategic issue of environmental governance, national security, and socio-environmental justice.

Recent studies have addressed the evolution and challenges of national dam safety legislation, revealing normative and institutional gaps that compromise the effectiveness of preventive policies.[106–109,114]

In parallel, geopolitical and humanitarian studies examine the biogeophysical, socioeconomic and transboundary impacts of large

hydroelectric projects, as well as the reconstruction and resilience processes in areas affected by disasters.[118]

The literature also highlights the growing connection between water security, terrorism and water nationalism, emphasizing emerging geopolitical tensions in the Global South and the need for international mechanisms for corporate accountability and environmental cooperation.[118]

Furthermore, innovative methodological proposals emerge,[120] and the Economic Valuation of Environmental Damage (EVED) model,[113] which integrate hydrological, economic and social analyses to quantify risks and support strategic decisions in contexts of environmental and energy vulnerability.

Finally, by articulating concepts of environmental peace and transboundary disaster governance, the works in this area demonstrated a systemic vision in which dam safety is understood as a fundamental pillar of ecological stability, social cohesion, and environmental peace in a globally interdependent world.

Discussion

Scientifically, the results of this research, obtained through a search of scientific literature, revealed the existence of knowledge about dam safety, positioning such infrastructures as strategic assets for national and international security, and not merely as civil engineering works.

The integration between the three axes identified as technical-managerial, analytical-normative, and geopolitical-strategic demonstrates that dam safety constitutes a node of interdependence between energy, water, territory, and political stability.

The results of this research demonstrate that dam safety must be understood as a complex, multidimensional, and interdependent system, in which technical, environmental, legal, socioeconomic, and geopolitical aspects intertwine in the production and mitigation of risk. This is because the integrated analysis of scientific publications, organized into thematic axes I, II, and III, demonstrates the existence of an initiative for conceptual and methodological maturation, oriented towards the transition from a reactive paradigm, based on disaster responses, to a predictive and adaptive paradigm, grounded in scientific governance, risk intelligence, and institutional sustainability, at least when referring to the scientific texts found in this search.

The study reveals in Axis I that technological advances and innovations in public policies have contributed to improved dam safety management; however, structural limitations persist in the articulation between engineering, legislation, and oversight. Axis II demonstrated increasing sophistication in risk assessment and quantification methodologies, particularly concerning the estimation of human life losses, tolerable risk criteria, and the incorporation of geotechnical and climatic uncertainties. Finally, Axis III broadened the analytical scope, placing dams at the center of discussions on water security, energy sovereignty, environmental governance, and geopolitical stability, demonstrating that these infrastructures are both symbols of power and development and potential vectors of vulnerability and conflict.

This systemic view can elevate the topic of dam safety to the same level as contemporary discussions on critical infrastructure, cyber defense and the protection of essential assets, areas of direct interest to intelligence services, armed forces and multilateral global security organizations, as evidenced.[108–111,113–119]

However, this research considers it necessary to incorporate systemic risk assessment methodologies and economic valuation of environmental damage into defense and security protocols, in order to support decisions, not only institutional but also governmental, based on quantitative evidence and probabilistic scenario studies.

In the field of international security, dams represent infrastructures of power and vulnerability simultaneously. This is evident in the account of the destruction of the Kakhovka dam,[65–68] where it is proven that dams have definitively surpassed the field of civil engineering, configuring themselves as critical infrastructures of national and international security, capable of strategic use in scenarios of hybrid warfare and geopolitical manipulation of water resources.

Conclusion and recommendation

The historical and comparative analysis of dam break failures, systematized in the supplementary tables, affirmed that the recurrence of disasters over more than a century underscores a structural pattern of global negligence in preventive risk management. Despite regulatory and technological advances, effective mitigation of failures is observed to depend on institutional and cultural factors, such as transparency, accountability, and international cooperation, which have proven consistently insufficient.

The integrative methodological framework presented in this research, that is, the most comprehensive thinking on the topic of dam safety, allows us to understand, model, and predict the risks associated with these structures in multiple dimensions: physical, social, economic, and also geopolitical. This allows us to anticipate structural and institutional vulnerabilities, strengthening the capacity for predictive intelligence and strategic response to hybrid threats, which can range from technical failures and cyberattacks to deliberate sabotage in conflict contexts.

Therefore, the main scientific contribution of this research is to demonstrate that dam safety should be treated as a central axis of environmental security and global defense policies, integrating science, technology, and diplomacy into a single area of concern. Dam disaster prevention is not merely a technical issue, but an ethical and civilizational imperative.

Thus, based on everything studied so far, it is proposed to strengthen governance based on environmental intelligence, capable of anticipating systemic risks, protecting populations, and ensuring ecological and geopolitical stability in a century marked by the convergence of environmental, energy, and security crises.

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Conflicts of interest

There is no conflict of interest.

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