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Recent Methodological Developments of Dam Failure Detection: A Systematic Literature Review

Riefda Novikarany[1*], Aris Poniman[2]
Defence University
Coressponding Author: Riefda Novikarany riefda.novikarany@tp.idu.ac.id

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A B S T R A C T

Dam failures have a significant impact on the economy and the community environment. This research aims to map recent developments in the context of triggers and impacts of dam failure conducted by previous researchers, including finding basic methodologies to determine the influence of triggers and impacts through a systematic literature search. The literature search utilized major academic databases, covering the period 2019 - 2023. Inclusion criteria included reputable journals in Q1, Q2 and Q3, relevant publication titles and abstracts, namely "risk assessment", "impact" and "dam failure". The results of the study showed that the triggers of dam failure are the material parameters of the dam and high rainfall or extreme weather and the impacts include flooding, river blockage due to landslides, impacts on housing and casualties. In addition, this study found that the methodologies with probabilistic approaches, hydrological modelling, material mechanics, and risk and safety analysis used to address the reliability and risk aspects associated with dam failure can be findings that provide important insights for academics and policymakers in the future

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INTRODUCTION

Dams are used for several national needs and in their construction can be adapted to use, among others as soil and water conservation (Yuan et al., 2022) as irrigation for thousands of hectares (Bagwan & Sopan Gavali, 2023) as a power plant (Igliński et al., 2022) with a very high capacity, as a flood control (Yin et al., 2022) (such as the Jatiluhur dam for flood shields in Karawang and Bekasi Regencies), as well as a water reservoir for the fulfilment of water supply for households, industries and urban sewerage (Kåresdotter et al., 2022), and some dams were also built as *multipurpose* dams (such as the Jatigede and Jatiluhur Dams) and *specific purposes* Such as for the supply of water for aquaculture of salty water and many more uses for dam construction. However, the value of the benefits of the dam is also overshadowed by potential problems.

Dams are also one of the human activities that can be destructive, one of which is damaging the watershed (DAS) (Brakenridge et al., 2017) because it can change the physiology of the watershed around the dam both at the time of construction and when it has functioned and other potential problems can arise, especially when the dam has changed its function or experienced dam failure. Dam failure is a serious event that causes major damage and significant environmental impacts. In Indonesia, several cases of dam failure have been recorded, in 2009 the failure of the Situ Gintung dam located in South Tangerang, Banten. The failure of this dam is suspected to be caused by one of them due to very high rainfall that causes water to overflow (Andriawan, 2020) and the ability of the dam to hold the water is inadequate, in addition to structural factors and dam maintenance (Andriawan, 2020). The impact of the dam failure recorded more than 100 deaths, damage to houses and infrastructure around the dam area and widespread flooding that caused environmental damage. The failure of the dam was also experienced in Central Maluku at the Way Ela dam in 2013, where the failure of the dam had a major flood impact that swept away hundreds of houses and thousands of residents displaced and lost their property and agricultural land, many village infrastructure was damaged and no longer in good condition. From this event, it is necessary to map the factors that are at risk of becoming the cause of dam failure and the impact of the risk of dam failure.

In fact, from the dam risk assessment in Indonesia analyzed in 2008, sourced from the *Project Implementation Plan for DAM Operational Improvement and Safety Project*, the risk of dam failure that occurs in Indonesia can be classified into *low, moderate, high and extreme* levels with a low assessment range between 0 – 15 values, moderate assessment between 16 – 45 values, high assessment between 46 – 75, and *an extreme* assessment between 76 – 90. The risk criteria are based on two conditions, namely economic risk and physical risk.

LITERATURE REVIEW

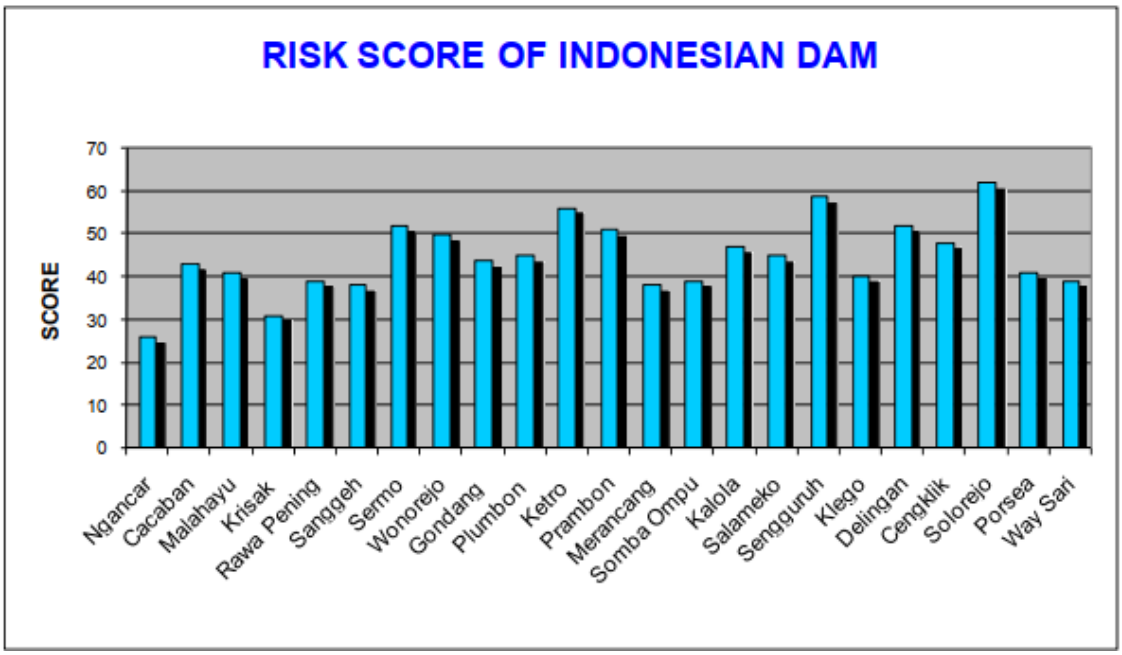

Figure 1. Dam Risk Assessment in Indonesia

From this data, information was obtained that there is a high risk of failure potentially occurring in most dams in Indonesia. In general, dam failure factors are caused by erosion (G. Wang et al., 2022), *cracks* or cracks that cause leakage (C. Wang et al., 2021), and avalanches(Bolgiani et al., 2018), especially those that occur in the type of dam failure, *overtopping* or overflowing of reservoir/dam water through the top of the dam due to flooding or water accumulation that exceeds the capacity of the reservoir/dam to exceed the top of the dam (Hu et al., 2022), because of the earthquake (Peng & Zhang, 2013) and so on. From the physical factor, the threat of dam failure can also be caused by sedimentation factors caused by the high level of erosion in the upstream area of the dam, due to the rampant conversion of forest land into residential land (Long et al., 2008) or new agricultural areas. This sediment pile causes the water capacity of reservoirs or dams to decrease, especially during the rainy season which has the potential to flood. Then the impact that can occur from the collapse of the dam or the damage to the function of the dam is another potential problem that needs to be anticipated, especially considering that the function of the dam is quite large, *multipurpose* and extensive.

Literature review is a research method conducted by collecting, analyzing, and synthesizing various literature sources relevant to the topic under study. This method aims to understand the development of previous research, identify study gaps, and obtain a strong theoretical foundation in answering research questions. In the process, literature review involves a critical review of scientific journals, books, research reports, and policy documents in order to obtain a comprehensive and evidence-based understanding of a particular field of study. the literature review method is expected to bridge any studies that discuss various factors that can trigger dam failure. Through the analysis of scientific

journals, technical reports, and policy documents, this approach enables a comprehensive understanding of dam stability impacts, providing insights that support more effective critical infrastructure management strategies.

This study aims to conduct a systematic mapping of the latest research developments that discuss the factors causing and impacting dam failure. Through *this systematic literature review*, this study will identify and analyze the methodology that has been used by previous researchers in determining the influence of various factors on dam failure, as well as their impact on the environment and society. The results of this study are expected to make a significant contribution to academics in developing further studies and for the government in formulating dam development and management strategies both for new dams and maintenance of existing dams.

METHODOLOGY

This researcher uses a quantitative literature review as a form of *secondary studies* (Nourani et al., 2021) which does not conduct direct research but reviews research that other researchers have conducted to answer research questions that have been determined from the methodology and research results. This systematic review method is detailed in the framework of Preferred Items for Systematic Review and Meta-Analysis of PRISMA (Vaingankar et al., 2022). This method is often used for systematic literature in analyzing and selecting relevant research articles with a series of formulations according to the understanding of the field studied. All article search flows in the PRISMA method are used to minimize potential bias and duplication of article selection.

Search Strategy Using The PRISMA Method

Online databases are selected for searches tailored to the theme of the article and its popularity. The online databases selected for the search are listed below:

Table 1. Literature Library Arrangement

Literature Library	Journal Online Database
Journal search platform	*Mendeley, Scopus and Google Scholar*
Search Year	2019 - 2023
Search schema	*Open Access*
Document Type	Article

Definition of information sources Literature search (García Rellán et al., 2023) Various topics from online databases with large *repositories* for academic studies can be done from the three sources of literature used as well as searches on the article reference list to mark the existence of articles/research that are related and have considerable relevance to the research theme.

Research Questions

To help provide an overview of the scope and limitations of *this Systematic Literature review*, the PICOC method [18] is used, as follows:

1. *Population* (P) is a topic to be researched, namely the function of dams
2. *Intervention* (I) is a specific aspect to be studied, namely the failure of the dam
3. *Comparison and Outcome* (C&O) is a measure of the aspects that are said to be successful, namely the factors and impacts of dam failure
4. *Context* (C) is the scope to be reviewed, namely the failure of the dam from the journal reviewed in the world.

From this PICOC method, several points were obtained that can be developed into search keywords and research questions. Research questions are the most important part of a *systematic literature review*. This *Systematic Literature Review* was searched using the keywords "*risk assessment*", "*model*", *and* "*dam*" on the literature search page until as many as 176 journals of research articles related to extraction were obtained using the PRISMA *flow* method. Research Questions (RQ) have been determined (Gil-Fernández et al., 2023), including:

Research question 1: Factors influencing dam failure and the impact of such failure

Research question 2: Approach used in simulating the factors and impacts of dam failure globally

Research question 3: Development of methodology in overcoming the problem of changing the function of dams.

Read the complete or partial research article that was set aside in the previous preview stage to determine whether the research can answer the specified research question with a predetermined method and pattern of thinking.

Inclusion/Exclusion Criteria

The systematic review guideline method described in the *Preferred Items for Systematic Review and Meta-Analysis* of PRISMA framework requires inclusion (Lohmann et al., 2023) to review the results of primary research so that facts that follow the desired complexity and balance are presented. Meanwhile, *meta-analysis* (Marchenko & Temeljotov-Salaj, 2020) is a method used to synthesize the results of primary research previews statistically (quantitatively) as part of the *systematic review* method to answer the specified research questions

The definition of eligibility criteria or inclusion used in this *systematic literature review* is listed below:

Table 2. Screening Arrangements with Inclusion/Exclusion Library

Criteria	Decision
Reputable journals Q1, Q2 and Q3	Inclusion
The research theme is contained in the article: Title, Abstract and Keywords	Inclusion
Full-text Article	Inclusion
Duplication in article search	Exclusion
Dam Construction Factors	Exclusion

The literature found aims to investigate the factors that affect the change of dam function with the following thinking patterns: Factor X causes dam failure and results in the impact of Y. The selection of titles in reputable journals in Q1, Q2 and Q3 is limited to the research themes, namely "*dam failure*", "*impact*" *and* "*risk assessment*". Then the abstract is limited to the calculation of risk to changes in the function of the dam from external factors and keywords that are limited to the words "*dam*", "*impact*", *and* "*risk assessment method*". A complete article is also one of the inclusions in the systematic determination of articles.

Literature Selection Process

The process of selecting literature/articles using the PRISMA method is carried out with a flow chart as follows:

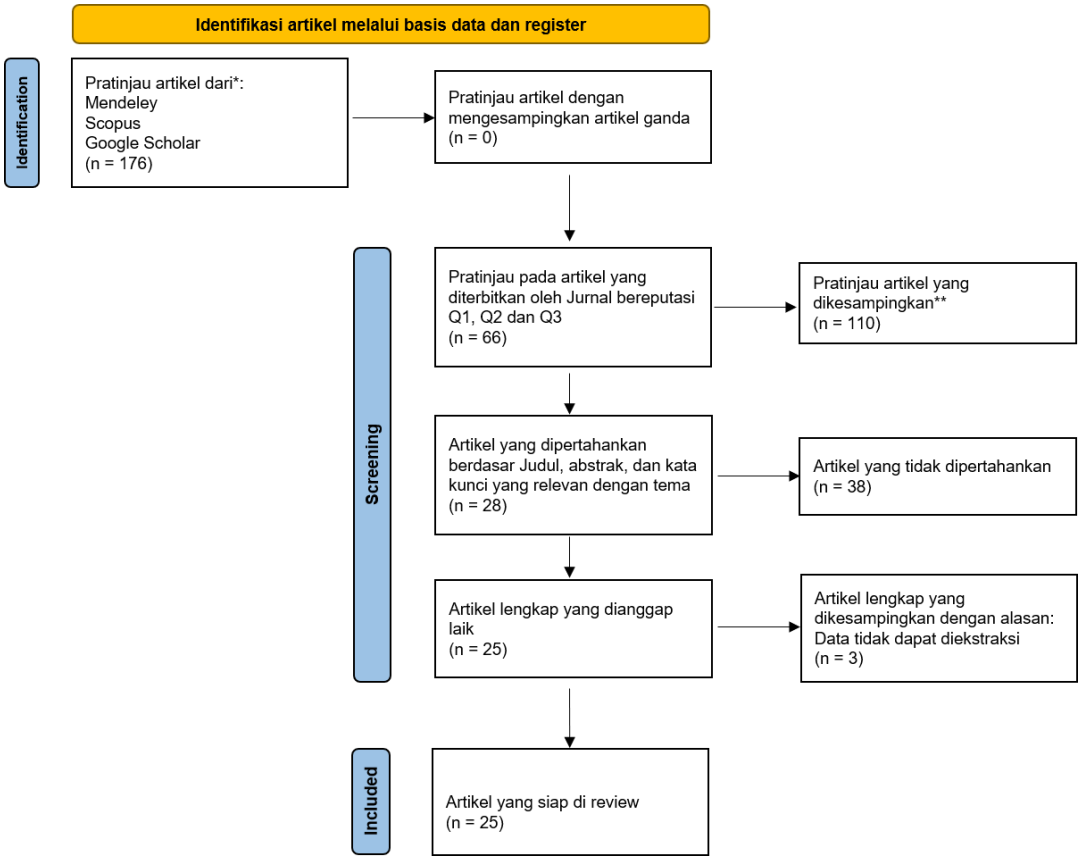

Figure 2. Flow Diagram of the PRISMA Method for Systematic Literature Review

Data Analysis Methods and Synthesis Processes in Systematic Literature Review

There were 25 selected research articles, using analysis and synthesis methods to process, analyze and combine findings from various selected articles. The analysis method is divided into 2 stages of the process, namely, systematic analysis using VOSViewer and Bibliometrix (Budianto & Dewi, 2023) to identify patterns, themes and relationships between articles and narrative analysis to answer research questions (Lekkas et al., 2007). Furthermore, from the results of the analysis, a synthesis of existing findings will be carried out to be combined into information that provides a comprehensive understanding of the factors and impacts of dam failure. Generally, bibliometrix analysis is used to see the distribution of the number of publications and citations from several research articles qualitatively and quantitatively. The VOSviewer application is used to assist in bibliometrix analysis by visualizing a bibliometrix map so that it is easier to translate a relationship between aspects of the selected research article.

Table 3. List of Selected Articles/Literature

No Literature	Literature Title
1	The Risk-Level Change of Dam Break Due to Population Growth in the Dam Downstream
2	Modelling and analysis of the Brumadinho tailings disaster using advanced geospatial analytics
3	A Risk Assessment Model for Dam Combining the Probabilistic and the Nonprobabilistic Methods
4	Modelling the Strength and Fracture Parameters of Dam Gallery Concrete Considering Ambient Temperature and Humidity
5	A spatio-temporal dam deformation zoning method considering non-uniform distribution of monitoring information
6	Effective Safety Assessment of Aged Concrete Gravity Dam based on the Reliability Index in a Seismically Induced Site
7	A Statistical Risk Assessment Model of the Hazard Chain Induced by Landslides and Its Application to the Baige Landslide
8	Blasts from the Past Reimagining Historical Storms with Model Simulations to Modernize Dam Safety and Flood Risk Assessment
9	Assessment of Digital Terrain Models in Dam Break Simulation Studies
10	Hydrological risk of dam failure under climate change
11	Metamodeling for Uncertainty Quantification of a Flood Wave Model for Concrete Dam Breaks
12	New hybrid method for vulnerability assessment in floodplain areas exposed to dam break
13	Analysis of Dam Overtopping Failure Risks Caused by Landslide-Induced Surges Considering Spatial Variability of Material Parameters
14	Anomaly Identification of Monitoring Data and Safety Evaluation Method of Tailings Dam
15	Risk Assessment of Dam-Breach Flood Under Extreme Storm Events
16	Development of an agent-based model to improve emergency planning for floods and dam failures
17	Comparative analysis and risk assessment of dam-break floods: Taking Pingshuijiang Reservoir as an example
18	The Development and Demonstration of a Semi-Automated Regional Hazard Mapping Tool for Tailings Storage Facility Failures
19	Assessment of life loss due to dam breach using improved variable fuzzy method
20	Validation of an Empirical Model with Risk Assessment Functionalities to Simulate and Evaluate the Tailings Dam Failure in Brumadinho

21	Flash Flood Risk Assessment Due to a Possible Dam Break in Urban Arid Environment, the New Um Al-Khair Dam Case Study, Jeddah, Saudi Arabia
22	Evaluation of Dam Break Social Impact Assessments Based on an Improved Variable Fuzzy Set Model
23	Potential Dam Breach Analysis and Flood Wave Risk Assessment Using HEC-RAS and Remote Sensing Data: A Multicriteria Approach
24	Quantitative Assessment of Uncertainties and Sensitivities in the Estimation of Life Loss Due to the Instantaneous Break of a Hypothetical Dam in Switzerland
25	Probabilistic Analysis of Floods from Tailings Dam Failures: A Method to Analyze the Impact of Rheological Parameters on the HEC-RAS Bingham and Herschel-Bulkley Models

RESULTS

Literature Extraction Analysis

All literature found in the last search (25 selected articles) is saved in Bibtex format (. Bib) and .ris to be run with VOSViewer and Bibliometric analysis, previously all literature has been confirmed in full text and has complete information through the Mendeley application. Extraction was carried out in stages in tables 4 and 5 where selected literature was collected based on Thematic Map, and Word Cloud in Bibliometric and based on *Most Relevant Sources, Network Visualization Author, and Cluster Occurrence* in VOSViewer for research topics on dam failure.

Table 4. Stages of Literature Extraction

Software	Formulas
R (4.3.1)	install.packages("bibliometrix")
	library(bibliometrix)
	biblioshiny()
	Ctrl+A and Run
Bibliometrix	Data
	Load Data
	"import raw file(s)"
	Choose "Scopus", "Google Scholar" on the Database
	Choose file .Bib
	Start
VOSViewer	Create map based on bibliographic data
	Choose file .ris
	Choose treshold "1"
	create layout

Fig 3 shows the analysis of the Thematic map depicting the theme in each quadrant. Quadrant I describes trending themes, quadrant II describes special themes, quadrant III describes abandoned themes and quadrant IV describes basic themes.

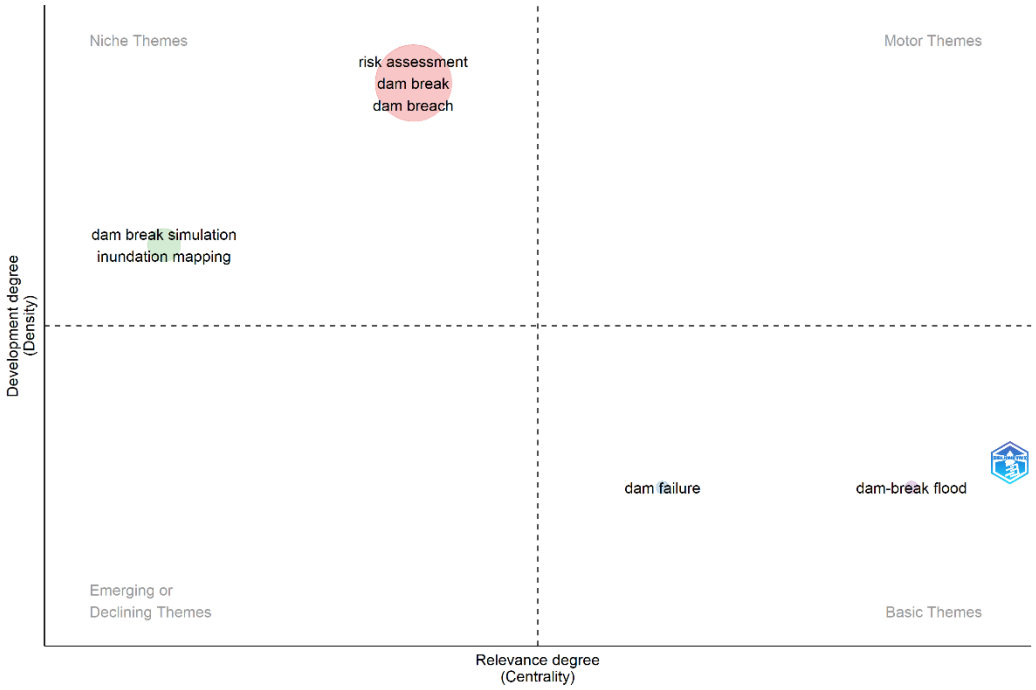

Figure 3. Thematic Map Analysis

From the literature reviewed, quadrant I is related to the trending theme in dam failure does not exist, quadrant II discusses the specific theme of dam failure which is divided into 2 cluster themes, namely the dam break simulation and inundation mapping clusters, then the risk assessment cluster, dam break and dam breach where from the quadrant it shows that this theme cluster includes themes that are widely extracted. In quadrant III which describes the themes that are left out there is also no and in quadrant IV similar to quadrant II there are 2 themes, namely dam failure and dam-break flood.

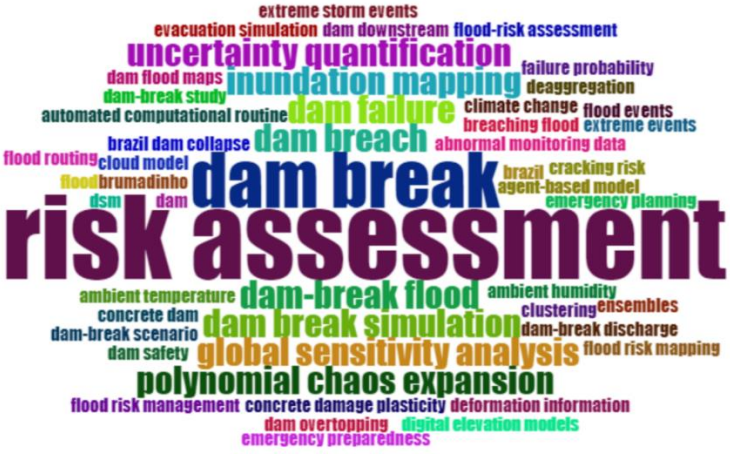

Figure 4. Word Cloud Analytics

Fig 4 shows the relationship between one word and another or interrelated. The extraction results showed that the word risk assessment was the word that looked the largest compared to other words. This means that there is a mutual relationship between the word risk assessment and the words dam break, dam breach, dam failure, inundation mapping, uncertainty quantification, dam-break flood, dam-break simulation, global sensitivity analysis, and polynomial chaos expansion. Meanwhile, the words risk assessment and dam break are some of the words that have a high relationship compared to other words. This is possible because the two words have close specifications in the context of dams and dam management.

The affiliation documents of 25 selected research articles based on *Most Relevant Sources* were obtained that articles on dam functions came from the journal *Water of Switzerland,* followed by the journals *Applied Science, Frontier in Earth Science*, and *Sustainability* from Switzerland.

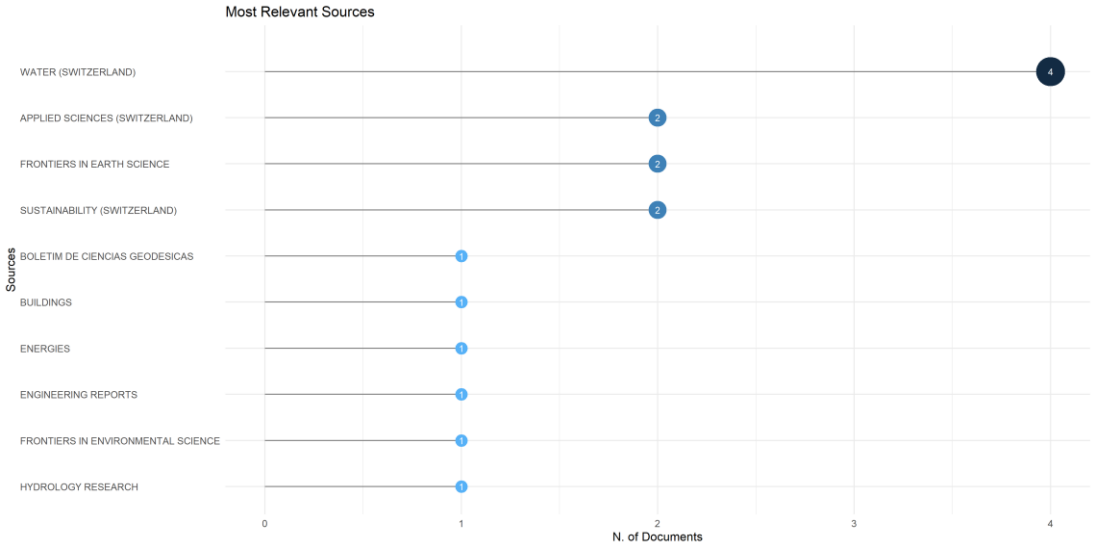

Figure 5. Bibliometrix Visualization of Affiliation Documents by Theme: Function of the Dam

Of the 25 selected research articles, based on *Network Visualization Author*, 12 authors have a strong association, the author's collaboration is described using the VOSviewer application and produces 2 different colours, (1) the red colour group totals 6 authors, and (2) the green colour group also amounts to 6 authors. Each writer links to each other, and the author with the most links is Gu, Chongshi. The research theme on the function of this dam is often discussed and published as a research article in a journal in 2021 – 2022. For other authors, there is a less strong connection, which is possible because the field of study or research theme of the authors is not related to each other. A clearer visualization can be seen in the image below

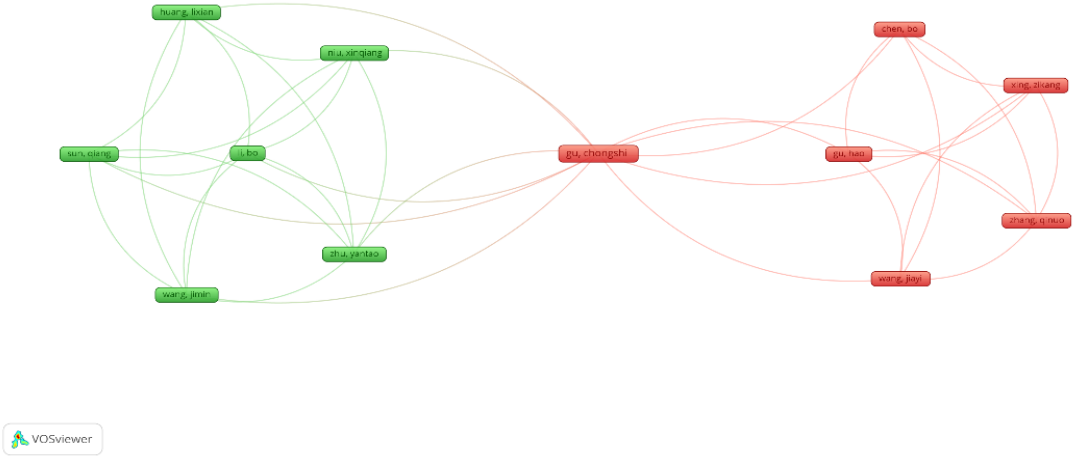

Figure 6. VOSviewer Visualization for Collaboration Networks between Authors

Of the 25 selected research articles, based on *Cluster Occurrenceence*, many terms appeared in articles about dam functions and were widely discussed by the authors. There are 4 clusters, namely cluster (1) in red with the most keywords or terms appearing, namely *risk assessment, and dam failure*; cluster (2) in yellow with the most keywords or terms appearing, namely *population, dam break and methodology*; cluster (3) in blue with the most keywords or terms appearing, namely *assessment and analysis*; and cluster (4) is green with the most keywords or terms appearing, namely *model, dam and study*. It can be concluded that the research sub-theme about the function of dams that stands out is about *risk assessment, methodology, analysis and model*. Then the research sub-theme that is rarely or still not widely discussed is about *variability, accuracy, structure, water, and tailings flow* as seen in the figure below

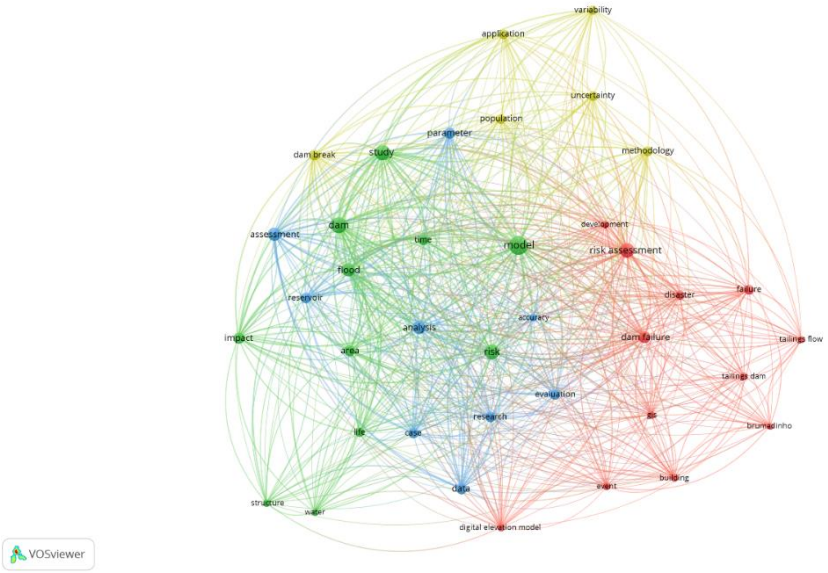

Figure 7. VOSviewer Visualization for Research Topic Density Network

Literature Narrative Analysis

From the results of the literature extraction analysis, it can be described that the risk and impact of dam failure can be assessed through several methodological approaches, this is divided into two main thoughts, namely:

The Method of Assessing the Risk of Dam Failure is Reviewed from the Causal Factors

These studies evaluate various aspects of dam reliability and safety, as well as flood risk due to dam failure under extreme weather conditions. Literature no. 4 (Zhu et al., 2020) and 5 (Gao et al., 2022) use probabilistic and non-probabilistic methods to overcome the uncertainty of dam parameter information. Then literature no. 6 (J. Wang et al., 2021) and 7 (Nahar et al., 2021) evaluate the deformation and seismic performance of dams, using zoning methods and fractionality analysis for more accurate risk assessment. Literature no 15 (Dong et al., 2022) uses *an enhanced* cloud model and *Radial Basis Function* (RBF) neural network to identify tailings dam monitoring data anomalies, while literature no 16 (Lin et al., 2021) models flood risk with two-dimensional simulation for downstream vulnerability assessment.

In addition, the study also highlights the impact of climate change on flood risk and dam safety. Literature no. 9 (Mahoney et al., n.d.) emphasizes the importance of accurate estimation of the maximum limit of extreme CH for dam safety, using a better *downscaling* method than conventional methods. Literature no. 11 (Carneiro et al., 2022) suggests that climate change increases the risk of water infrastructure failure with a higher probability of extreme flood events in the SSP5 8.5 climate scenario. Literature no. 12 (Kalinina et al., 2020) and 14 (Dong et al., 2021) use *polynomial chaos expansion* (PCE) and *Monte Carlo* methods for flood risk analysis and slope instability due to landslides, emphasizing the importance of considering the spatial variability of material parameters in risk assessment for dam energy and safety policies.

The Method of Assessing the Risk of Dam Failure is Reviewed from the Impact That Can Be Caused

These studies evaluate the impact and risk of dam failure with various simulation or modelling approaches. The study of the failure of the Brumadinho dam in Brazil (Dedring et al., 2022) and the simulation of the *tailings runoff path (* TSP) (Atif et al., 2020) model based on GIS with the help of Python programming showed a good correlation between the simulation results and satellite imagery after the dam failure. Another literature compared the flood map from the simulation with the flood event map due to the Vale SA dam failure in 2019, where the *Airborne Laser Scanning* (ALS) model [36] showed the most appropriate results. A hybrid method that combines *Security Vulnerability Assessment* (SVA) and *Source-Pathway-Receptor-Consequences* (SPRC) hydraulic analysis showed that residential areas have the highest vulnerability to flooding due to dam failure [33]. Empirical models to simulate the impact of tailings dam failures show areas with different potential impacts. Studies that use *the fuzzy variable* model to evaluate social impacts show their effectiveness in disaster mitigation and response (Melo & Eleutério, 2023).

The evaluation of flood risk due to river blockage by landslides shows the ability of statistical models to predict flood impacts (Yang et al., 2023). Two-dimensional hydrodynamic simulations underscore the importance of emergency planning based on dam failure scenarios. The tailings flow risk assessment of tailings storage facility failure emphasizes the importance of hazard zone mapping. Evaluation of flood risk due to dam collapse using GIS and hydrological modelling shows variations in risk levels in various recurrence periods. A comparison of the *Bingham* and *Herschel-Bulkley* models with the *Latin Hypercube Sampling* (LHS) technique shows the sensitivity of the model to flood parameters (Melo & Eleutério, 2023). The literature on the impact of dam failure on fatalities using agent-based modelling and HEC-LIFESim devices shows the factors that affect mortality rates and the importance of effective emergency response (Kalinina et al., 2021).

Dam Failure Risk Assessment Method

a) Probabilistic and Non-probabilistic theory, methods combine statistical and deterministic analysis to handle parameter uncertainty
b) Cloud models and neural networks of radial base functions (RBF) for time series data analysis and anomaly identification of monitoring data. This model helps in the real-time safety evaluation of tailings dams
c) Downscaling methods are performed to provide a better representation of extreme rainfall and hydrodynamic models (HEC-RAS and ArcGIS) to simulate flooding under dam failure scenarios caused by extreme rainfall, this helps in estimating the maximum limit of rainfall and assessing the vulnerability of downstream areas.
d) Polynomial chaos expansion (PCE) and metamodelling, to reduce computational costs in flood models due to dam failures. This method facilitates the analysis of sensitivity and propagation of uncertainty in hydrological models.
e) Monte Carlo method, to simulate the spatial variability of material parameters in the risk analysis of slope instability and dam runoff failure.
f) Equivalent distance (EQMM) quantality-adjustment method for adjusting historical maximum daily precipitation data and projections, to account for climate change in flood risk planning and management.

Literature Synthesis Analysis

This narrative analysis of the literature has provided in-depth insights into the factors that affect dam failure and the impact caused. The main findings show that dam failure can be influenced by various factors, namely the material and spatial parameters of the dam as well as high rainfall or extreme weather. These factors play an important role in dam safety, where extreme rainfall can cause increased loads on the dam structure, while material conditions and spatial design can determine the dam's resistance to such pressure. The impact of dam failure is significant, including flooding, river blockage by avalanche of dam material, impact on housing and casualties. These findings are in line with previous literature that shows that dam failures often result in major natural disasters, affect socio-economic life, and require serious attention in dam planning and maintenance.

In the context of the theory used to understand and address dam failure problems, the probabilistic, deterministic, hydrological and material mechanics modelling, as well as risk and safety analysis used have proven effective in addressing various aspects of reliability and risks associated with dam failure. These theories are also able to answer research questions about the approach used in simulating the factors and impacts of dam failure globally and about the development of methodologies in overcoming the problem of changing the function of dams from this literature search. These theories offer a variety of methods for addressing aspects of dam reliability including failure risk prediction, impact assessment, and mitigation strategy development. For example, hydrological modelling helps in analyzing high rainfall that can affect the volume and flow of water that tests the resilience of dams, while risk analysis allows the evaluation of potential dam failures based on various scenarios.

Previous literature has also shown that these approaches not only strengthen the understanding of dam failure but also contribute to the development of methodologies to address changes in dam function over time.

DISCUSSION

This study provides a comprehensive mapping of the latest research developments regarding the causative factors and impacts of dam failure and the methodology used in determining the influence of these factors. Based on the analysis of the three main research questions, the following conclusions can be drawn:

1. Research question 1: Factors influencing dam failure and the impact caused by such failure. The results of the literature review show that the parameters of dam materials and high rainfall or extreme weather are significant factors affecting dam failure. The impact of this dam failure is not only limited to flooding but also includes river blockages due to landslides, impact on housing and casualties.
2. Research question 2: Approach used in simulating the factors and impacts of dam failure globally. This study found that methodologies with probabilistic approaches, deterministic approaches, hydrological modelling and material mechanics as well as risk and safety analysis have been used effectively to simulate various aspects of reliability and risks associated with dam failure.
3. Research question 3: Development of methodology in overcoming the problem of changing the function of dams. The development of more integrated methods and approaches in risk assessment and mitigation of dam failures is essential. The study confirms that a scientific evidence-based approach can minimize the negative impacts caused by dam failures.

CONCLUSIONS AND RECOMMENDATIONS

This literature review provides a comprehensive overview of how existing theories and methods can be applied globally to simulate the factors and impacts of dam failure and how these theories contribute to the development of strategies and policies for handling dam failures. These findings provide important insights for academics and policymakers, to maintain the safety of dam functions and minimize impacts so that the safety of the community and the environment can be more guaranteed in the future.

ACKNOWLEDGMENT

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