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Review Article

Comprehensive Review on Sustainable Dam Infrastructure: Issues and Challenges, Factors Causing Dam Failure and Future Direction in a Globally Changing Climate

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ABSTRACT

A dam is a hydraulic structure built to achieve the Sustainable Development Goals (SDGs) and provide a safe and reliable water supply in a world where climate change is severe. This article provides a comprehensive review of the sustainability aspects of dams in terms of current issues and challenges in dam safety and factors causing dam failure based on the selected case studies. In addition, the selected dam safety guidelines are compared and addressed with the studied issues, challenges and factors leading to dam failure, as these two elements represent an integrated relationship. Future directions are identified to highlight high-risk scenarios and fascinating research areas for dam sustainability. The issues and challenges identified are mainly related to climate change impacts and operations. This study offers a wealth of benefits, such as the identification of factors leading to a failure

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(hydrological impacts, geotechnical condition, geological characteristics and ageing of the structure), improvements in decision-making (shortened time scale) and important fundamental research (fluid-structure interactions) for the modification of emergency plans and the development of early warning systems. In addition, the current study could provide a solid reference for accurate formulation and amendment of design standards, selection of reliable dam construction methods based on the factors of previous dam failures, and appropriate dam safety measures (monitoring and emergency response). In a nutshell, dam safety evaluation is crucial for the sustainability of dams, for accurate engineering decisions on regular maintenance measures and for protection against dam failures.

Keywords: Climate change, dam failure, dam safety, dam sustainability, failure factor

INTRODUCTION

The dam provides an alternative to clean hydropower for a continuous energy supply from an emission-free source, water. Dam infrastructures also serve as a solution to global water scarcity, severe droughts and flood mitigation. However, the constant stress of global climate change has significant disadvantages for these megastructures, particularly limited water storage capacity and structural ageing (Concha et al., 2023; Fluixá-Sanmartín et al., 2018; Islam et al., 2024; Lazin et al., 2023; Liu et al., 2022; Ma et al., 2024; Milly et al., 2002; Mortey et al., 2019; Sun et al., 2022). Climate change has caused hydro-geo-meteorological disasters such as earthquakes and extreme rainfall patterns (leading to flooding and flash floods) (Al-Fugara et al., 2023; Alcocer-Yamanaka et al., 2020; Hasan, 2015; Lee et al., 2022; Wieland, 2016), as well as seasonal flooding and landslides triggered by debris flows (Bocchiola & Rosso, 2014; Carneiro et al., 2022; Chang et al., 2022; Hirabayashi et al., 2013; Hu & Huang, 2017; Lee et al., 2022; Milly et al., 2002; Saber et al., 2022). Soil erosion has led to a sedimentation problem in the downstream section of the dam (Bai et al., 2020; Kondolf & Yi, 2022; Saber et al., 2022). Therefore, a holistic integration of sustainable dam management, monitoring and surveillance approaches is equally important. The adverse effects of climate change are manageable. Continuous inspection, monitoring, and data analysis over a certain period guarantee the long-term viability of the infrastructure and provide a control plan for the early prevention of structural damage, which is crucial as part of the technical measures (Yavaşoğlu et al., 2018). This initiative is in line with the United Nations Sustainable Development Goals (SDGs): No. 6 (Clean Water and Sanitation) and No. 13 (Climate Action) (Jensen, 2022; SPANCOLD, 2017).

The safety of dams has been an important issue for operators, engineers and policymakers around the world for several years, as it can harm socio-economic aspects. The sustainability of dams, especially the structural aspect, is crucial for the smooth operation of dams, operational safety, adequate maintenance and suggestions for short and long-term emergency planning (Wieland, 2016). Safety has been an issue in the construction of dams for almost half a century; for example several high-profile dam failures, such as the collapse of the 230-metre-high Oroville Dam in 2017 (France et al., 2018; Stelloh et al., 2017; White et al., 2019) and the concrete slab spillway-2 of the Toddbrook Dam in England during the flood in August 2019 (Heidarzadeh & Feizi, 2022). Another dam failure event is the collapse of the Niedów earth fill dam due to extreme rainfall and flooding in 2010 (Kostecki & Banasiak, 2021; Kostecki & Rędowicz, 2014). Several deficiencies were identified in the reported incidents: insufficient design capacity, substandard material, environmental aspects, hydraulic impact and geotechnical failure of the dam. Consequently, the development of future dams (design and construction) and renovation works should prioritise the amendment of design standards, real-time monitoring, on-site inspection and maintenance to meet current and future conditions.

The spillway was built primarily to channel and control the flow of water from the reservoir into the downstream and lower reaches (Chanson, 1994). This structure should be operated efficiently to ensure its stability and minimise the impact of dam overtopping (Gu et al., 2017). Proper design of the spillway is, therefore, crucial to guarantee the functionality of the structure throughout its operational life (Kocaer & Yarar, 2020). Conventionally, the spillway was designed based on the PMF (Probable Maximum Flood) criteria and the meteorological and hydrological conditions of the site. The flow over the spillway has a higher velocity and high kinetic energy, namely turbulence. Therefore, a sedimentation basin was provided at the end of the spillway to minimise this turbulent effect and avoid erosion and sedimentation problems in the downstream part of the dam. The design of the sedimentation basin depends on the hydraulic jump characteristics and the underwater depth (Peterka, 1984).

This article aims to shed light on the overall concept of sustainability for hydraulic structures and water supply conservation under changing climatic conditions. Furthermore, the trending and rising issues of climate change uncertainties, ageing infrastructure, especially high dams, dams without any real-time monitoring system, requirement on the revised design guidelines and rising concern on the environmental standards challenge the sustainability, safety and security of the dam sustainability. This study aims to conduct a comprehensive review of the published and current literature related to dam sustainability, particularly dam safety and security. The specific objectives of this study are (1) to identify the key issues and challenges which may jeopardise the dam sustainability, (2) to evaluate the factors causing dam failure based on the analysed key issues and challenges and (3) To evaluate the adequacy of selected established dam safety guidelines on addressing the climate change based on reviewed issues and challenges as well as factors causing dam failure. It provides a comprehensive overview of dam safety by highlighting the causes of threats and challenges to dam safety through selected case studies. Additionally, it is a good reference source for stakeholders (authorities, policymakers, planners, technical experts, designers and consultants) in the decision-making process for selecting appropriate measures, constructing new dams and/or rehabilitating damaged or ageing dam infrastructure.

MATERIAL AND METHODS

This study aims to provide a comprehensive study: a systematic review of recent research on dam safety aspects of supporting dam sustainability under climate change uncertainties. This study emphasises the current dam safety aspect, including dam safety guidelines, the issues and challenges of dam safety and dam failure mechanisms based on the existing monitoring effort, which compromises the structural integrity of the dam. This study preferred to apply the reporting style based on the systematic reviews and meta-analyses (PRISMA) method (Moher et al., 2009). The chosen method is reliable and feasible as it covers the appropriate approach for disaster management (Shaffril et al., 2021). This study intends to delve into the following specific questions: What factors affect the safety, particularly dam safety issues, and what are the challenges that can jeopardise the sustainability of dams? Are there specific factors causing dam failure based on the issues and challenges analysed? Are the available dam safety guidelines adequate to address the safety issues caused by climate change? What is the current approach and future direction to promote dam sustainability?

Identification

The systematic review comprises four key stages in the selection of appropriate articles to be considered in this study. The first stage started with choosing a recent researchable study title based on the current issue in the disaster management field. The process followed at the second stage with the selection and decision of the appropriate keywords using an authorised medium such as act, regulation, guidelines, independent expert report, previous research, database suggestion (e.g. SCOPUS), thesauruses.com, encyclopaedias, and dictionaries. Several applicable electronic databases, such as official government websites and the Web of Science (WOS), were used for the search process after the final decision on the main keywords and associated keywords (similar to the main keywords) at the third stage. In the fourth stage, the search process was conducted based on the decided keywords based on the designed search string.

Searching Strategy

This study used two searching techniques (systematic and manual searching) and numerous electronic databases to ensure a rigorous search process and data validity. The explored electronic databases used were the Official Regulated Body or Government Website (Federal

Emergency Management Agency, International Commission on Large Dams, Department of Irrigation and Drainage Malaysia, United States Society on Dams, The British Dam Society, New South Wales Government, India Government, WOS, SCOPUS, ScienceDirect, Taylor and Francis, Emerald, Springer, American Society of Civil Engineers (ASCE). The search process was conducted in three stages: January 2024 (first searching process), August 2024 (Subsequent searching process), and October 2024 (based on the suggestion for this study). The main keywords such as *climate change, dam failure*, *dam safety, dam sustainability and failure factor* were searched in the electronic databases based on the proposed title and the research question developed. Several additional keywords similar to the main keywords in the second stage were identified, including *climate uncertainty, climate risks, catastrophic failure, dam failure, dam safety guidelines, dam security, earthquake, extreme weather, flood, flooding, hydraulic structure, spillway, and structural integrity*. The single and combinations of these keywords were processed using several search functions, for example, field code function (TITLE-ABS-KEY and TS) and Boolean operators ('AND' or 'OR') in two databases: WOS and SCOPUS. Manual searching: Handpicking was used in databases other than WOS and SCOPUS (Shaffril et al., 2021).

Screening

The screening process involves the selection of the related paper based on criteria such as type of material, year of publication, language and scope of the paper. In this study, the chosen materials were safety guidelines, research-based, systematic review, literature review, and scoping review, published in English between 2014 and 2024. Additionally, the scope of the selected paper should be aligned with the identified main and associated keywords. Additionally, in WOS, the consideration of search criteria is followed in specific editions: Science Citation Index Expanded (SCI-EXPANDED), Conference Proceedings Citation Index-Science (CPCI-S), and Emerging Sources Citation Index (ESCI). A total of 4968 potential materials were identified from the listed databases based on the two applied methods and the first on-site database screening process.

Eligibility Criteria

Several eligibility criteria were determined in this study to ensure the study is specific and aligned with the title and objectives. Criteria such as the scope of the paper, including the title and research content, are compulsory to ensure the clarity, quality and consideration of exclusion criteria (as mentioned in the screening stage) for the current study.

Data Abstraction and Analysis

Several extensive assessment approaches followed carefully based on PRISMA guidelines were considered repetitively for the screening, analysis, and synthesised processes to ensure the validity and exclusiveness of the current study (Moher et al., 2009). Notably, the selected papers should align with the scope of the current study. Figure 1 illustrates the comprehensive process of paper selection for the current study. A total of 1098 papers (including dam safety guidelines) were selected and compiled in the Endnote. Subsequently, 1080 papers were eliminated due to being outside the scope and inaccessible and ended up with 18 papers (including dam safety guidelines) that were considered eligible for the critical review.

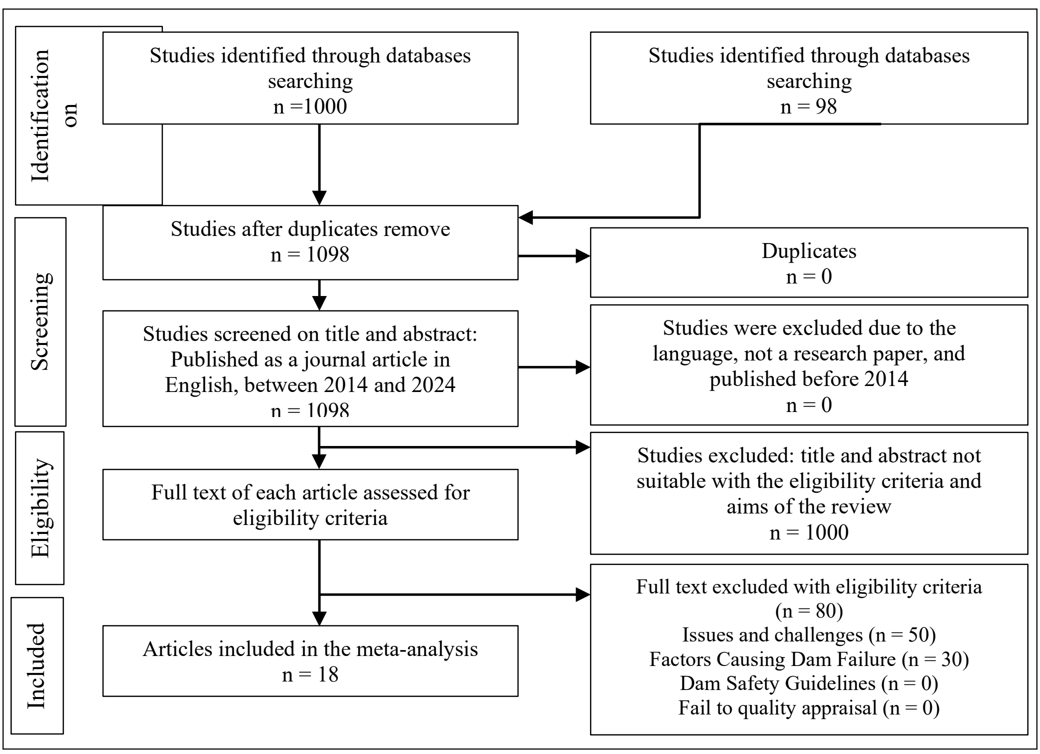

Figure 1. PRISMA flow diagram of dam sustainability: issues and challenges on dam safety, factors leading to dam failure and current approaches to promoting the sustainability of dams

RESULT AND DISCUSSION

Identification of reliable dam safety issues and challenges is critical to supporting dam sustainability and keeping it in line with the SDGs. The issues and challenges are related to the mechanism of dam failure, as the key factors have been identified based on the published and reported case studies. The combination of issues and challenges and the factors causing dam failure were combined to provide an extensive explanation of the focus area. In addition, the guidelines published by the authorised organisation are considered important and appropriate in addressing the issues and challenges related to the mechanism of dam failure. These contexts may provide a future direction for the fascinating research in this area by highlighting the limitations and gaps in the reviewed literature.

ISSUES AND CHALLENGES OF DAM SAFETY

The safety of dams is an important element in ensuring the sustainability of critical infrastructure. Therefore, rigorous measures are required to preserve the infrastructure and ensure the continuous operation of the system. Diverse research has been conducted on non-structural and structural measures to support the sustainability of dams. However, the criteria for dam sustainability should be linked to the root cause, namely the issues and challenges. Identifying issues and challenges can reveal the scope of the main problem and the associated factors causing the dam failure and lead to an appropriate technical decision-making process.

The identified factors that potentially jeopardise sustainable dams can be divided into environmental, structural integrity, structural design and operational, management and maintenance factors as summarised in Table 1 (Balmforth, 2020; France et al., 2018; Goodling et al., 2018; Heidarzadeh & Feizi, 2022; Hollins et al., 2018; Hughes, 2020; Koskinas et al., 2019; Kostecki & Rędowicz, 2014; Patra et al., 2024; Vahedifard et al., 2017; White et al., 2019; Xiao et al., 2022; Xie et al., 2022; Yang et al., 2024). The environmental factor, namely climate change (CC), which is closely related to the rising hydrological stress, is known to be the most important among the others (Heidarzadeh & Feizi, 2022). The hydrological factors, such as extreme precipitation and flooding, lead to runoff fluctuations and the failure of structures, especially ageing and deteriorated dams (Heidarzadeh & Feizi, 2022; Hollins et al., 2018; Koskinas et al., 2019). In addition, soil erosion and sedimentation occur downstream due to the high flow velocity during floods (Heidarzadeh & Feizi, 2022). These factors jeopardise the safety and sustainability of the dams. Therefore, the triangular relationship between the concept of dam sustainability and the exact relationship between the SDGs and dam sustainability is emphasised. The increasing trend of hydrological factors leading to dam failures is alarming, as this has enormous implications for the entire system, such as socio-economic and ecological aspects.

FACTORS CAUSING DAM FAILURE

The factors of dam failure can be viewed from different angles and analysed according to geometric characteristics (type of dam, height of dam, size of dam), hydro-meteorological characteristics (climatic conditions: persistent rainfall, natural hazards, earthquakes, infiltration of seepage water: internal erosion), geotechnical characteristics (type of rock, type of soil), structural characteristics (ageing) and type of failure mode (cascade failure, partial failure and total failure). These factors of dam failure are derived from the issues and challenges in dam safety, as in Table 1. Hydro-meteorological and geotechnical characteristics have a significant influence on the factors and mechanisms of dam failure. Controlling these factors is a challenge due to the severe effects of climate change. However, the exacerbated impacts can be minimised with appropriate controlled measures, and intervention can be made. This approach can reduce the devastating effects on the safety of dams in the short or long term. Therefore, a holistic methodological framework for dealing with the factors of dam failure is required for failure control right from the planning stage. Consequently, this factor deeply contributed to analysing and managing the dam failure mechanism.

The condition of the construction site and the behaviour of the structure should be recorded with real-time monitoring instruments, and possible malfunctions should be eliminated to ensure the highest safety of the dam. Based on the collected or historical data, prediction models can be proposed for early failure prediction, e.g., dam failure simulation. However, careful data management (up-to-date data, error-free data, accurate processing medium) is essential to avoid incorrect predictions of events and types of failure modes. In this way, a dam failure can be predicted at an early stage, an early warning system can be developed, and a warning message can be reliably disseminated. Catastrophic events could be controlled, and the massive losses associated with a dam failure could be minimised. Socio-economic losses and environmental impacts are also minimised.

Climate Change, Hydrological and Hydraulic Factors

The current and future effects of climate change are devastating worldwide. Climate change can drive and contribute to changes in hydrological patterns, e.g. from low to high rainfall (extreme) within a short period. For example, extreme precipitation patterns and capacities change the hydraulic flow patterns in surface reservoirs (reservoirs) and rivers, e.g., turbulent and high-velocity flows.

The 29-metre-high Sardoba Dam in Uzbekistan was supposed to hold 922 million cubic metres of water. Unfortunately, the dam burst on 1 May 2020 after several days of extreme rainfall and strong winds. The incidents began with the breach of the western embankment wall of the Sardoba Dam due to the effects of uncontrolled water loading. The Niedów Dam collapsed due to extreme rainfall and the 100-year flood (Kostecki & Banasiak, 2021). The gate was under maintenance and was closed during the catastrophic event. Therefore, the upper banks were flooded with massive amounts of water, which had an impact on the roads and other facilities.

The Toddbrook Dam partially collapsed, mainly at the auxiliary spillway, because floodwaters flowed uncontrollably through the spillway at a high velocity of 15 m/s due to rainfall and flooding (Heidarzadeh & Feizi, 2022). In the case of the spillway problem at Oroville Dam, Lake Oroville released water over the main spillway a few days before the incident to prepare for an additional inflow of 1550 m^3/s (Koskinas et al., 2019). The discharge was released due to the rise in water levels in Lake Oroville as a result of the effects of the prolonged and extreme rainfall (White et al., 2019).

To summarise, most of these incidents are due to the effects of global climate change caused by human intervention. Therefore, protecting the global climate is essential to preserving and prolonging the sustainability of dams. In the case of a new project, a thorough environmental impact assessment and cost-benefit analysis should be considered to understand the post-construction impacts on the existing system in the vicinity of the proposed project.

Geological and Geotechnical Conditions

A site investigation from a geological and geotechnical point of perspective is important to ensure the rock identification and soil stability of the selected site, especially for hydraulic engineering projects. The factors identified are important for the selection of the correct foundation size, the reinforcement works for soil strengthening and the settlement value over the years. Therefore, a special assessment is carried out before, during, and after construction to avoid any disadvantages to the structure. The physical assessment was compiled together with the robust equipment (i.e. satellite and radar data) for the site inspection and simulation work to determine and predict the difference between the two factors.

Three data sets from Google Earth, namely ICESat-2 data (satellite-based medium), Sentinel-1 SAR data (multi-geometry) and optical images from Sentinel-2 satellites, were used together with global precipitation measurements (GPM) to determine factor-induced damage for the Sardoba Dam in Uzbekistan. The observed images and the collected analyses identified internal erosion as the main cause of failure (Xiao et al., 2022). Other studies showed that the breached section of the Sardoba Dam in Uzbekistan had a settlement difference of about 4.7 cm. Secondary consolidation contributes to post-construction deformations. In addition, the differential settlement and water loads lead to structural transverse cracks in the dam. The recent study relied on hybrid methods: hazard framework, dam-related hazard investigation (RSDHI) and numerical modelling (Xie et al., 2022).

Several landslides occurred at Toddbrook, with the critical area being on the upstream slope of the dam. Long-term systemic design and construction issues, including poor site investigation and foundation stability (poor bedrock condition), have been identified as a possible partial failure factor of the 49-year-old Oroville Spillway (Koskinas et al., 2019). Rapid water runoff triggered landslides and erosion during prolonged heavy rainfall (Heidarzadeh & Feizi, 2022; Koskinas et al., 2019; Martin et al., 2024).

Overall, a proper site investigation and evaluation is required to understand the geographical condition of the site. This is crucial for proper site selection to avoid future incidents. Once the work is completed, the selected project site should be compared with other similar project sites in the vicinity and a critical technical assessment should be carried out by a certified person (geotechnical engineer/geologist). In addition, appropriate numerical simulation and assessment tools are required, which will have a major impact on the project and allow precautions to be taken if the project decides to proceed with construction work.

Inadequate Design Capacity, Design Flaws, Ageing and Structural Failure

Structural design has proven to be an important criterion for the functionality, safety and sustainability of infrastructures. With the help of numerical simulations, malfunctions can now be recognised early. However, the effects of climate change, hydrological influences and hydraulic factors are rarely predicted. Therefore, the dynamic properties of the structure are most strongly influenced by the changing static and dynamic loads.

In the case of the Niedów Dam, the foundation of the Niedów Dam was eroded by a catastrophic flood. The concrete crown had broken and was washed away terribly quickly into the downstream section (Kostecki & Rędowicz, 2014). The breach damaged the concrete slab first, followed by the abutments and the retaining wall. These structures could not withstand the increased flow and water pressure upstream. The shorter event caused a massive flood wave in the downstream section (Kostecki & Banasiak, 2021).

Hybrid methods (field studies, desk studies and numerical modelling) and cascade models focusing on the failure mechanism of the Toddbrook Dam were investigated (Heidarzadeh & Feizi, 2022). The capacity of the auxiliary spillway was unable to withstand the unprecedented extreme rainfall, resulting in overtopping and failure of the structure. The slabs on the surface of the spillway were breached by the combined effects of physical problems and internal forces (dense vegetation), water injection between the slab spacing and uplift pressure within the slabs. The lightweight, thin slab section (15.0 cm) was designed and constructed with limited steel reinforcement and poor joints between slab sections (without water bars and in vertical joints). Therefore, the supported slabs shrank and moved due to the uplift pressure within the slab section. In addition, the eroded foundation is affected by the high flow velocity and water injection into the slab and foundation.

Furthermore, no sedimentation basin was constructed to control the scour problem caused by the water transfer upstream and across the spillway. Another independent checker (Balmforth, 2020) came to the same conclusion as (Hughes, 2020) that the failure was due to design problems (thin concrete slabs and no internal pipework system for water flow to the spillway) and poor maintenance (insufficient sealant between the joints with the concrete slabs, severe cracking in the concrete slabs and dam crest, and dense vegetation between the slab joints). In another case, the formation of a large hole on the surface of the concrete spillway at Oroville Dam was noted due to the intermittent pattern of flowing water (Hollins et al., 2018; Koskinas et al., 2019). Theoretically, the continuous inflow into Lake Oroville exceeds the minimum flood control elevation, resulting in frequent overflows. This situation limits repair time and eliminates the need for remedial measures. As a result, the increased flood water flows continuously over the main spillway and the unclosed weir. The flowing water then moves dramatically over the collapsed concrete partition wall to the slope and experiences soil erosion. The additional spillway (without a closed weir) was built to absorb the overflow from the main spillway and has never been tested on actual events (Koskinas et al., 2019).

Poor Maintenance and Operation

Excellent and smooth management of spillway maintenance is required to ensure the optimal operating condition of the hydraulic infrastructure. Therefore, an appropriate time base (weekly inspection or case-by-case inspection of the changes in discharge and built infrastructure elements) is required to avoid shock incidents. Toddbrook has experienced two spillway incidents, the first in 1964 and the most recent during the 2019 flood (Hughes, 2020). The capacity of the main spillway was supplemented by an additional spillway that could be used for overflow or maintenance purposes. Unfortunately, the constructed auxiliary spillway also failed due to poor monitoring and maintenance, resulting in a dense cover of vegetation on the surface of the concrete spillway (Balmforth, 2020; Heidarzadeh & Feizi, 2022; Hughes, 2020). The frightening incident at the highest dam in the USA, the Oroville Dam (235 m), was taken seriously, especially the emergency measures and the management and maintenance of the spillway. The presence of a hole on the surface of the spillway remained undetected. However, the water flowing over the spillway showed a rare pattern during the incident (Hollins et al., 2018; Koskinas et al., 2019).

Seepage and Drain Failure

A reliable and robust pipework and drainage system is essential for the smooth operation of the spillway. However, this system is not easily visible during physical inspection. The removal of the slabs on the surface of the spillway during the Oroville incident shows internal erosion due to seepage and failure of the internal drainage (Hollins et al., 2018; Koskinas et al., 2019). This poses a high risk to the dam and can lead to its catastrophic failure.

Table 1
Safety issues and challenges in dam engineering

Category/ Issue(s)	**Challenge(s)**	**Parameter(s)/ Variable(s)**	**Quantitative Data**	**Qualitative Data**	**Method**	**Dam and Country (size and type)**	**Researcher**
Environmental Factor	Hydrological stress	Precipitation Water speed Reservoir volume	Rainfall rate Velocity (15 m/s) Volume (1.29 million m^3)	Flooding frequency Maximum capacity of reservoir	Physical Inspection (on-site evaluation)	Toddbrook Dam, England, United Kingdom (24-m high and zoned earth-fill dam with a clay core)	(Balmforth, 2020; Heidarzadeh & Feizi, 2022; Hughes, 2020)
Structural Integrity factor	Hydrological stress	Material degradation Concrete cracking Damaged foundation	Level of degradation (severe)	Ageing Infrastructure	Mixed method (qualitative analysis and quantitative modelling, namely cascading risk analysis model)		
Design factor	Flaws in spillway-2 design	Concrete slab	Concrete slabs design (15-m thickness without any reinforcement)	Inadequate concrete design			
Structural Design factor	Flaws in spillway-2 design	Spillway profile	Designed slope (based on the downstream slope of the embankment – 2H:1V)	Inadequate spillway profile			
Design factor	No stilling basin for sediment collection	Erosion Sedimentation	Level of degradation (severe scouring) Sedimentation rate (severe sediment deposition)	Old dam built in 1840			
Operational Factor	Maintenance frequency and cost of repair	Maintenance frequency	Regular maintenance (based on the	Inadequate maintenance (growth of vegetation and trees)			

Table 1 *(continue)*

Category/ Issue(s)	Challenge(s)	Parameter(s)/ Variable(s)	Quantitative Data	Qualitative Data	Method	Dam and Country (size and type)	Researcher
Environmental Factor	Hydrological stress Seismic stress	Precipitation Flood volume Water speed Reservoir volume Type of flow	Annual rainfall Winter Storm 5392 m^3/s (maximum) Velocity (15 m/s) Volume (59.6 million m^3) Turbulent flow	Gradually rainfall pattern Flooding frequency Maximum capacity of reservoir	Case Study (using resilience framework)	Oroville Dam, United States (235-m high and zoned earth-fill embankment structure)	(Goodling et al., 2018; Koskinas et al., 2019; White et al., 2019)
Structural Integrity Factor	Hydrological stress	Material degradation Concrete cracking Damaged spillway surface	Level of degradation (severe)	Ageing Infrastructure	Physical Inspection (on-site evaluation)	Oroville Dam, United States (235-m high and zoned earth-fill embankment structure)	(France et al., 2018; Goodling et al., 2018; Hollins et al., 2018; Koskinas et al., 2019; Vahedifard et al., 2017)
Management and operational Factors	Hydrological stress Severe main spillway damage Untested auxiliary spillway	Decision-making	Not related	The capability of the main spillway and untested auxiliary spillway	Case Study (using resilience framework)		
Environmental Factor	Spillway foundation Hydrological stress Seepage problem	Spillway material	Level of degradation (severe)	Ageing Infrastructure Internal deterioration	Combination of methods (field investigations, failure analysis, and numerical modelling)		
Structural Design factor	Flaws in floor slab design Flaws in drain design	Slab dimension Drain dimension and capacity Pressure	Invert slabs (minimum thickness of 380 mm) Drain capacity (small) Level of water pressure (high)	Inadequate drains capacity			

Table 1 *(continue)*

Category/ Issue(s)	Challenge(s)	Parameter(s)/ Variable(s)	Quantitative Data	Qualitative Data	Method	Dam and Country (size and type)	Researcher
Environmental Factor	Hydrological stress	Precipitation Reservoir volume	Rainfall rate (Heavy rainfall) Volume (922 million m^3)	Flooding frequency Maximum capacity of reservoir	Earth observation techniques Satellite-based monitoring tools Remote sensing-based Multi-platform approach	Sardoba Dam, Uzbekistan (32-m high and U-shaped earthen dam)	(Xiao et al., 2022; Xie et al., 2022)
Environmental Factor	Geotechnical stress	Soil settlement	Local differential settlement (~4.7 cm) Maximum settlement at North Bank (~270 mm)	Settlement frequency			
Structural Integrity Factor	Hydrological stress Structural stress	Transverse structural crack	Deformation	Breaching frequency			
Environmental Factor	Hydrological stress	Precipitation Water level Reservoir volume	Rainfall rate Water level height (fluctuation) Volume capacity (18.5 billion m^3)	Flooding frequency Maximum capacity of reservoir	Multi-source satellite data analysis	Kakhovka Dam, Ukraine (30-m tall and Earth-fill embankment with gravity sections)	(Yang et al., 2024)
Maintenance and Operational Factors	Maintenance frequency Mode of operation (protocol) Military conflict	Maintenance frequency	Restricted Maintenance capacity	Restricted areas and conflicting conditions cause potential maintenance delays and late notification of structural deterioration.	Meteorological reanalysis Dam design criteria assessment		

Table 1 *(continue)*

Category/ Issue(s)	Challenge(s)	Parameter(s)/ Variable(s)	Quantitative Data	Qualitative Data	Method	Dam and Country (size and type)	Researcher
Environmental Factor	Hydrological Stress Seismic Vulnerability	Discharge data Seismic data Volume rate	Discharge capacity (16,500 m^3/s) Seismic rate of Koyna (magnitude ~6.5) Volume capacity (2,780 million m^3)	Flooding frequency Seismic prone area	Parametric analysis 2D structural modelling techniques	Koyna Dam, Maharashtra, India (103-m tall and Concrete Gravity Dam)	(Patra et al., 2024)
Design Factor	Design Limitations (Older Dam) Variability in Material and Structural Parameters (Older Dam)	Seismic data	Not measured	The seismic factor is not included in the design			
Environmental Factor	Hydrological Stress Seismic Vulnerability	Discharge data Seismic data Volume rate	Discharge capacity (5,700 m^3/s) Seismic rate of Pine Flat (not reported) Volume capacity (1,000 million m^3)	Flooding frequency Seismic prone area	Parametric analysis 2D structural modelling techniques Concrete damage plasticity model	Pine Flat Dam, California, United States (122-m tall and Concrete Gravity Dam)	(Patra et al., 2024)
Design Factor	Design limitations (Older Dam) Variability in material and structural parameters (Older Dam)	Seismic data	Not measured	The seismic factor is not included in the design			

Table 1 *(continue)*

Category/ Issue(s)	**Challenge(s)**	**Parameter(s)/ Variable(s)**	**Quantitative Data**	**Qualitative Data**	**Method**	**Dam and Country (size and type)**	**Researcher**
Environmental Factor	Hydrological stress	Precipitation Water level Reservoir volume	Rainfall rate Water level height (fluctuation) Volume capacity (18.5 billion m^3)	High-intensity rainfall Flooding frequency Maximum capacity of reservoir	Hydrodynamic modelling Observational analysis (Collection of Empirical Data)	Niedow Dam, Poland (17-m height and Concrete Gravity Dam)	(Kostecki & Rędowicz, 2014)
Management factor	Flood management and extreme weather (insufficient technical guidelines) Lack of emergency preparedness	Not measured	Not measured	Flooding frequency	Impact Analysis		
Design factor	Structural design limitation (Older Dam)	Structural failure risk Erosion resistance Hydraulic capacity	Lack of new reinforcement size and quantity Erosion rate Flow rate	Structural risk (deterioration) Overflow capacity and not designed to cater to extreme event			

THE ESTABLISHED DAM SAFETY GUIDELINES

The International Commission on Large Dams (ICOLD) is an international non-governmental organisation and was founded with the participation of members from various regions (Europe, Asia, America, Africa, and Oceania) such as the United States Society on Dams (USSD), the British Dam Society (BDS), the Australian National Committee on Large Dams (ANCOLD), and the Malaysian National Committee on Large Dams (MyCOLD). ICOLD has provided general standards and guidelines for the construction of dams and safety guidelines, a valid global database on large dams built, and documentation on dams registered worldwide, including a database on dam failures (data on dam failures and technical reports on dam failures from participating members).

The ICOLD guidelines are comprehensive in a global context but do not address the specific guidelines for participating countries. Participating countries should develop their guidelines based on the main organisation (e.g., MyCOLD) in the participating country or provide internal and extended specific guidelines based on the primary guidelines, which can be adapted to the state or specific organisation. Table 2 shows the global dam safety guidelines and associated parameters for evaluation. Based on the listed guidelines, MyDAMS and Queensland are said to be essential in consideration of climate changes compared to Federal Emergency Management Agency (FEMA) with a specific focus on climate-specific assessment parameters (extreme rainfall and seasonal droughts, which can exacerbate dam strain and potential failure risks) (DRDMW, 2024; FEMA, 2023; Government of Malaysia et al., 2017). Hence, the improvement of FEMA in terms of long-term climate change adaptation is essential to provide a robust framework for dam safety. Another comparison is in terms of incorporating artificial intelligence (AI) in monitoring dam safety. Currently, the MyDAMS is a good digital data collection with an extensive data collection system. However, this guideline has flaws in the framework, such as immediate risk response and coordinated safety protocols. This also applies to the New South Wales (NSW) and Queensland frameworks, where considering AI is vital to provide a robust framework that can be applied as a real-time monitoring system. This improvement is associated with the context of FEMA, which considers the emergency preparedness model to support dam sustainability (DRDMW, 2024; FEMA, 2023; NSW Government, 2021; Government of Malaysia et al., 2017). The guidelines issued by the Central Water Commission on the safety of dams are limited to basic climatic considerations. Therefore, these guidelines should follow other enhanced guidelines.

Table 2
Global dam safety guidelines

Guideline Source	Name of safety guideline	Guideline level	Specific area	Limitations/Gaps	Climate change considerations	Suggestion for Improvement	Reference
MyCOLD	Malaysia Dam Safety Management Guidelines (Mydams)	National	Digital Monitoring	Lack of comprehensive guidelines Risk management is obsolete and not properly addressed	Minimal climate change aspect	Expanding digital monitoring to include the aspect of climate resilience	(Government of Malaysia, 2017)
Federal Emergency Management Agency	Federal Guidelines for Dam Safety	National	Flood Risk Management	Limited focus on the structural aspect	Limited to the flood risk aspect	Integrating proactive flood and structural risk frameworks	(FEMA, 2023)
Central Water Commission, India	Guidelines for Safety Inspection of Dams	National	Routine Inspection Framework	Digital integration of data is limited Lack of quantitative risk aspect	Basic climate consideration	The development of resilience frameworks	(Central Water Commission, 2018)
New South Wales	Dams Safety NSW Guideline Dam safety management system	State/ Regional	Regular Safety Inspections	The emergency aspect is limited Focus on regular inspection	Minimal climate change aspect	Promoting real-time monitoring and a practical flexibility approach	(NSW Government, 2021)
Queensland	Dam Safety Management Guideline	State/ Regional	Risk Assessment and Monitoring	Reactive rather than predictive	Moderate climate considerations	The development of tools to predict extreme climate impacts should follow the ICOLD	(DRDMW, 2024)

FUTURE DIRECTION OF THE RESEARCH WORK

The advantages, constraints, best practices and gaps have been identified and discussed. Therefore, several future research studies can be conducted to address various non-structural measures.

Comprehensive Guidelines for Disaster Preparedness

The current draft of the guidelines should consider disaster risk reduction parameters such as the climate change index, two- and three-dimensional flows, and real-type flows (turbulent) as additional criteria in the disaster risk reduction guidelines. Therefore, after a thorough discussion with the industry and the scientific community (policymakers, engineers and researchers), the published guidelines will be revised to include these parameters. In addition, the prepared guidelines should be carefully reviewed in several stages by a competent person (a professional engineer) and verified by the government authority and the international or national engineering society. The phased approach is crucial to cover the fundamentals and the technical aspects. In addition, major revisions, such as the current extreme indicator and sedimentation accumulation, require new guidelines for designing and managing the specific case study. Therefore, the problem raised can be applied to designing new dams and improving old or ageing dams. This is consistent with the rising issues and challenges as well as the dam failure mechanism aspect related to climate change issues (hydrological factor) (Heidarzadeh & Feizi, 2022; Hollins et al., 2018; Koskinas et al., 2019; Kostecki & Rędowicz, 2014).

Development of a Holistic Framework for Dam Safety Risk and Sustainability Through the Integration of Cycle Approaches with Climate Change Classification

The inclusion of the cause-effect relationship is crucial to ensure a higher level of dam safety and to harmonise the sustainability of dams with climate change. Therefore, stakeholders (policymakers, dam operators, engineers, evaluators, researchers and the public) should play a crucial role in the development of this framework. The framework should consider the fundamental issues and integrate the problem with the associated non-technical or technical solution). The proposed measures should be adapted to climate change, and the remediation criteria should be defined and categorised according to the severity index. Furthermore, it should be based on other proven examples or case studies, critically reviewed, discussed and presented to stakeholders to gather opinions and feedback. In this way, a specific document with technical content can be created. The prepared framework can be included in the national agenda and used as a national practice to improve dam management and operation. The holistic approach is possible since the current dam safety guidelines for the selected country and region are not standardised and focus on the general aspect rather than specific as listed in the issues and challenges, as well as a directed failure mechanism, which is mostly majored by hydrological stress (climate change impact)(Heidarzadeh & Feizi, 2022; Koskinas et al., 2019; Government of Malaysia et al., 2017).

Development, Implementation and Improvement of the Emergency Response and Action Plan Together with the Robust Flood Mitigation Plan

Extreme climatic conditions can alter rainfall patterns and flooding conditions. Therefore, a further study to amend the emergency plan based on the current state of flood defence integration is essential to consider downstream impacts during a flood event (FEMA, 2023; Kostecki & Rędowicz, 2014).

Hydrological Study and Simulation of Dam Failures Considering Climate Change, a Relationship Study (Climate Change-structural Failure), a Real-time Monitoring Tool (Early Warning System) for the Classification of Dam Failure Events, and Preparation of a Flood Mapping (Downstream)

The current forecast for the hydrological study should take into account the parameters of climate change. The input data must be error-free, and problems with missing or outdated data should be avoided. In this case, new inflow and outflow data for the capacity of reservoirs, dams (intake, spillway, stilling basin) and runoff patterns should be taken into account. The current capacity of the dam infrastructure should be evaluated and addressed as a limitation. The inundation map should be created, and the dam failure event should be classified according to the hazard index. In this way, future predictions can be made for the worst event, and an early warning system can be set up for those affected (Heidarzadeh & Feizi, 2022; Kostecki & Rędowicz, 2014).

Socio-economic and Environmental Risk Assessment in the Context of Climate Change

Climate change may affect water storage capacity and mapping downstream. Therefore, a study to integrate socio-economic and environmental linkages is essential due to the impacts that are currently being investigated. The development of models based on a mixed approach (quantitative and qualitative approach) is required to minimise loss of life, loss of property and severe environmental damage (Heidarzadeh & Feizi, 2022). Advanced tools such as satellite and radar-based measurements to identify the most affected areas (Xiao et al., 2022; Xie et al., 2022; Yang et al., 2024). Therefore, an early intervention programme can be predicted.

Vulnerability Assessment of Critical Infrastructure Under Climate Change Impact, Especially Areas Prone to Flooding and Seismic Activities

A dam is a critical infrastructure known as an important source of water supply, flood control and hydropower development. For structured management, smooth operation, and planning of new dams, it is therefore crucial to assess the current state of this infrastructure in terms of the severity of climate change. New dams should be designed to withstand the worst-case scenario of climate change throughout their operational life. An economical and sustainable approach can be proposed for the construction of a new dam without compromising quality. In addition, consideration of areas prone to natural hazards such as floods and earthquakes is recommended to ensure that the critical aspect is taken into account to support the sustainability of dams, especially for new dams. A range of data on the frequency of rainfall and flooding and the prediction of extreme events is essential along with seismic data to support the current and future dam sustainability (Koskinas et al., 2019; Patra et al., 2024; Vahedifard et al., 2017; White et al., 2019).

CONCLUSION

This comprehensive study on dam safety and sustainability applies a systematic review approach to the field of dam safety and sustainability, which makes an important contribution to understanding the challenges, factors causing dam failure, and associated guidelines for dam safety. Interestingly, the environmental factor of climate change seems to be the main factor for the change in hydrological parameters, such as extreme flooding within a short precipitation period. This main factor has been identified as a stress tensor for catastrophic failure of a dam due to deterioration of structural integrity. Another important issue is the structural design factors that deal with the inadequate sizing of structures with the current capacity, such as spillways. In addition, ageing and old dams are highly susceptible to failure due to unprotected environmental criteria such as seismic activity, especially in vulnerable areas. The combination of hydrological (flooding) and seismic loading should be critically considered due to the cyclic or continuous dynamic loading of the dam structure. The concrete and earth fill dams are vulnerable to this source due to the risk to structural integrity, especially the ageing, old, and high dams. The dam safety guidelines issued by selected authorities contain a variety of criteria relevant to the management and operation of dams.

However, most of the published guidelines are limited to specific criteria, such as flood protection and digital data collection tools that cover only a small part of the impacts of climate change (normal hydrological data). To address this problem, robust guidelines with a comprehensive framework are crucial to closing the gaps. In addition, the holistic integration of globally harmonised guidelines suitable for all countries is feasible to ensure the impacts of climate change, especially extreme events and other parameters such as seismic activity, erosion and sedimentation due to the increasing number of natural hazards and to provide an adequate solution during the decision-making process. In addition, the proposed framework should align with the ICOLD Technical Guidelines (to ensure an update of technical information).

In addition, the integration of methods (parametric study, physical experiment, and numerical model simulation) in the assessment and prediction work is proposed to support the conventional measurement, i.e., a physical inspection, and provide a more robust and reliable measurement to avoid misinterpretation of the problems and allow faster identification and prediction of dam failures. The improvement of the structural aspects can thus be carried out before the actual construction of the dam, as the costs are very high due to the specialised and extensive infrastructure. By integrating these elements, the sustainability aspect of dams can be promoted and established. Future work can provide an extension of the hybrid dam safety assessment method (experimental and numerical simulations) that includes structural integrity assessment and fluid-structure interaction study, focusing on the extreme event and dynamic loading (turbulent flow).

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