EVALUATING NON-STRUCTURAL INTERVENTIONS FOR DAM SAFETY: INSIGHTS FROM HYDRAULIC SIMULATION, STAKEHOLDER PERSPECTIVES, AND COMMUNITY-FOCUSED PROTOTYPES

Rahubadda Vithanage Ashen Dilruksha Rahubadda

248100K

Master’s by Research

Department of Building Economics
Faculty of Architecture

University of Moratuwa
Sri Lanka

October 2025

EVALUATING NON-STRUCTURAL INTERVENTIONS FOR DAM SAFETY: INSIGHTS FROM HYDRAULIC SIMULATION, STAKEHOLDER PERSPECTIVES, AND COMMUNITY-FOCUSED PROTOTYPES

Rahubadda Vithanage Ashen Dilruksha Rahubadda

248100K

Thesis/Dissertation submitted in partial fulfillment of the requirements for the Master of Science (Major Component of Research)

Department of Building Economics

Faculty of Architecture

University of Moratuwa

Sri Lanka

October 2025

DECLERATION

I declare that this is my own work and this thesis/dissertation does not incorporate without acknowledgement any material previously submitted for a degree or diploma in any other University or Institute of higher learning and to the best of my knowledge and belief it does not contain any material previously published or written by another person except where the acknowledgement is made in the text. I retain the right to use this content in whole or part in future works (such as articles or books).

Signature: Date: 01/01/2026

The above candidate has carried out research for the ~~PhD/MPhil~~/Master's thesis/dissertation under my supervision. We confirm that the declaration made above by the student is true and correct.

Name of the Supervisors	Signature of the Supervisor:	Dates
Prof. Udayangani Kulatunga		01/01/2026
Prof. Menaha Thayaparan		01/01/2026
Dr. Sandun Dassanayake		01/01/2026
Dr. Chathura De Silva		01/01/2026

DEDICATION

I DEDICATE THIS STUDY TO ALL WHO WORK TO SAFEGUARD COMMUNITIES BY UNITING HUMAN INNOVATION WITH THE FORCES OF NATURE, TO MY PARENTS, TEACHERS, AND FRIENDS FOR THEIR UNWAVERING SUPPORT, AND TO THE CITIZENS OF SRI LANKA WHOSE RESILIENCE AND CONTRIBUTIONS INSPIRE THIS RESEARCH

ACKNOWLEDGMENT

I wish to express my deepest gratitude to my supervisors, Prof. Udayangani Kulatunga, Prof. Menaha Thayaparan, Dr. Sandun Dassanayake, and Dr. Chatura DeSilva, for their invaluable insights, guidance, encouragement, and constructive feedback throughout this research journey. Their perspectives and support were instrumental in shaping both the direction and the quality of this work.

I am also sincerely thankful to the officers of the Postgraduate Office, Faculty of Architecture, University of Moratuwa, for their kind assistance, timely clarifications, and excellent cooperation, which greatly facilitated the smooth progress of my academic work. My appreciation is further extended to the staff of the Department of Building Economics for their continued support and encouragement.

Special thanks are due to the Senate Research Grants, University of Moratuwa, for providing the financial assistance that made this research possible.

Finally, I wish to acknowledge with heartfelt gratitude the many individuals, friends, and colleagues who have supported me in countless ways during this educational journey. Although I am unable to mention each by name, their encouragement and companionship have been vital to the successful completion of this study.

ABSTRACT

Dam failures pose severe threats to both human life and socio-economic stability, often resulting in catastrophic losses. This study sets out to critically examine the socio-economic impacts of dam failures and to investigate innovative non-structural measures for risk reduction, with a focus on enhancing community preparedness. A mixed-methods approach underpinned by a pragmatist philosophy was adopted, integrating narrative and systematic literature reviews, hydraulic modelling, GIS-based analysis, agent-based modelling (ABM), stakeholder interviews, and gamification. Literature reviews synthesized global evidence on dam failure impacts and identified gaps in existing preparedness strategies. A case study of the Kantale Dam in Sri Lanka was conducted using 2D HEC-RAS modelling to simulate potential dam-break scenarios, producing detailed inundation maps and hazard parameters. These outputs were combined with socio-economic data and validated through semi-structured interviews, which provided insights into vulnerabilities and adaptive capacities of local communities. To translate complex risk information into accessible and participatory formats, the study developed a serious board game as a gamified non-structural intervention. Iteratively refined through pilot studies, the game successfully engaged participants, improved their knowledge of dam-related challenges, and fostered collaborative decision-making. The findings confirm that integrating technical modelling with community-based educational tools significantly enhances disaster preparedness. The research contributes to knowledge by advancing hybrid methodologies, demonstrating the value of ABM in simulating human behavior under disaster conditions, and pioneering a gamified approach to dam safety education. These contributions provide a replicable framework for policymakers and practitioners to strengthen dam safety management and reduce disaster risk in vulnerable regions.

Keywords: *Dam failures; Socio-economic impacts; Hydraulic modelling; Agent-Based Modelling (ABM); Non-structural measures; Gamification*

TABLE OF CONTENTS

LIST OF FIGURES

TABLE OF TABLES

LIST OF ABBREVIATIONS

Abbreviation	Description
ABM	Agent-Based Modelling
BIM	Building Information Modeling
CBEWS	Community-Based Early Warning System
CDA	Canadian Dam Association
DEM	Digital Elevation Model
DRIP	Dam Rehabilitation and Improvement Project
DRR	Disaster Risk Reduction
DSMP(s)	Dam Safety Management Plan(s)
EAP(s)	Emergency Action Plan(s)
EWS	Early Warning System(s)
FLUS	Future Land-Use Simulation
GISTM	Global Industry Standard on Tailings Management
GRCA	Grand River Conservation Authority
HEC-RAS	Hydrologic Engineering Centre's River Analysis System
ICMM	International Council on Mining and Metals
ICOLD	International Commission on Large Dams
MCDA	Multi-Criteria Decision-Making
MNRF	Ontario Ministry of Natural Resources and Forestry
OPG	Ontario Power Generation
PRI	Principles for Responsible Investment
RCC	Roller-Compacted Concrete
RSDHI	Remote Sensing-Based Dam Hazard Investigation
SAR	Synthetic Aperture Radar
TSF(s)	Tailings Storage Facility(ies)
UNEP	United Nations Environment Programme
USACE	United States Army Corps of Engineers

LIST OF APPENDICES

1 CHAPTER 01: INTRODUCTION

Dams are hydraulic structures designed to impound water for irrigation, hydropower, and domestic and industrial supply, while multipurpose reservoirs also provide flood control, drought mitigation, and sediment storage (Di Baldassarre et al., 2021). Although dams offer significant benefits to society (Derdous et al., 2015), floods resulting from dam failures have caused some of the most devastating disasters (Pellicani et al., 2018), leading to extensive property damage, severe threats to human safety, ecological degradation, and lasting impacts on the landscape (Kumar et al., 2017). When a dam fails, it can trigger a catastrophic flood wave that severely impacts downstream activities, accelerates sediment transport, and causes significant morphological changes to the river and surrounding landscape (Cao et al., 2014). Studies done by Adamo et al. (2020) and Ge et al. (2021) highlight that dam failures worldwide, such as Xe-Pian Xe-Namnoy (Laos, 2018), Oroville (USA, 2017), and Machhu-2 (India, 1979), have caused massive loss of life, displacement, and environmental damage. These events are largely attributed to inadequate maintenance, design flaws, insufficient spillway capacity, and extreme weather conditions (Lyu et al., 2019; Vogel, 2013; Wu et al., 2022; Yochum et al., 2008). These failures have led to a significant socio-economic and ecological impact.

Dam failures have profound social, economic, and environmental consequences, significantly affecting communities, economies, and ecosystems. Socially, the most immediate and severe impact is the loss of life (Gu et al., 2020), particularly for those living in downstream inundation areas, as rapid, high-speed floodwaters pose a life-threatening risk. Large-scale displacement and relocation force communities to abandon their homes, leading to social instability, cultural loss, and disruptions in daily life (Lin et al., 2020; Shabu & Musa, 2015), while inadequate public awareness and preparedness exacerbate the risk (Muda et al., 2021). Additionally, dam failures cause severe damage to critical infrastructure such as schools, hospitals, and transportation networks, impairing social stability and quality of life (He et al., 2020). Samsuddin et al. (2024) highlights the need for improved disaster response mechanisms and social protection to mitigate these risks. Economically, dam failures lead to direct and indirect financial losses, including infrastructure damage, business disruptions, and job losses at both local and national levels (Parente et al., 2021). The loss of economic benefits from dams, such as hydropower generation, irrigation, and industrial water supply, further strains national economies (Ellingwood et al., 1993), while the high costs of disaster recovery and reconstruction divert resources from other development projects. Local economies, particularly businesses and agricultural activities, suffer as farmlands, livestock, and supply chains are devastated by floods (Latrubesse et al., 2020), and long-term financial burdens exceed the immediate costs of physical damage, creating economic instability (Wu et al., 2019).

Environmentally, dam failures trigger severe flooding and soil erosion, altering landscapes and riverbanks (He et al., 2020), while biodiversity loss and habitat destruction affect fish populations, aquatic life, and terrestrial wildlife (Lin et al., 2020; Shabu & Musa, 2015). Water contamination from toxic sediments, pollutants, and waste materials deteriorates water quality and poses health risks to humans and wildlife (Parente et al., 2021), while long-term environmental sustainability is jeopardized as ecosystems struggle to recover (Wu et al., 2019). Additionally, disruptions in downstream river systems impact irrigation, fisheries, and ecological equilibrium, causing cascading environmental consequences (Latrubesse et al., 2020). These interconnected social, economic, and environmental impacts underscore the urgency of comprehensive dam risk management strategies to prevent catastrophic consequences and ensure sustainable flood mitigation efforts. As a result, there is a growing awareness of the need to move from a flood prevention paradigm to flood risk management, and both structural and non-structural measures play an important role in mitigating the consequences of dam failure (Dong et al., 2024; Zhang et al., 2024). Accordingly, this highlights the importance of rigorous dam safety protocols, early warning systems, and improved risk management strategies to mitigate future disasters (Seddeek, 2023).

Non-structural measures are additional strategies to enhance dam safety and reduce the risk of disaster without touching the physical structure of the dam (Bashar et al., 2023). These approaches are focused on reducing the vulnerability of communities and enhancing their capacity for effective response in case of potential failures of the dam (Shuka et al., 2024). The most important of these non-structural measures is the formulation and implementation of early warning systems, which would be able to provide early warning in the case of a pending dam breach or flooding (Chan et al., 2020). This, in turn, provides an excellent opportunity for early warning systems to give the necessary time for the relocation of people living downstream, reducing fatalities and injuries to a minimum (Bashar et al., 2023). Furthermore land-use zoning and floodplain management is also a crucial measure to be focused (Tariq et al., 2021). Authorities can decrease exposure whenever there are critical infrastructure, homes, and businesses, through the constraint on development in areas that would most likely get flooded because of a dam (Zio & Duffey, 2021). This helps decrease the human and economic costs whenever a dam fails (Nguyen et al., 2024). In many cases, strict land-use policies in high-risk areas can prohibit new development within floodplains, thus safeguarding communities from disasters that may be perceived in the future (Tariq et al., 2021).

Another significant nonstructural measure pertains to planning evacuations (Seddeek, 2023). In this regard, good plans ensure that communities understand how to act in the event of a dam failure by indicating routes, shelters, and a communication protocol (Sun et al., 2022). To further assist in this regard, the use of public education and awareness programs makes residents aware of the risk from nearby dams and shows them ways to act in an emergency (Persson & Granberg, 2021). The knowledge and preparedness plans make the communities resilient because the availability of information enhances the state of preparedness among members, hence enabling them to respond promptly and as a team in the event of any disaster (Shuka et al., 2024). It is through advanced recovery planning that the governments can minimize socio-economic impacts in the short run and speed up the normalization process for the affected communities (Manzoor et al., 2022).

1.1 Problem Statement

Dams have long been considered critical infrastructure, underpinning water supply, irrigation, hydropower generation, and flood control worldwide. They are also seen as symbols of national development and ecological civilization construction (Wang et al., 2024). Yet, history demonstrates that despite rigorous engineering designs, dams are not immune to failure.

Catastrophic events such as the St. Francis Dam collapse in California (1928), the Teton Dam failure in Idaho (1976), the Machhu II Dam disaster in India (1974), and the Buffalo Creek coal impoundment failure in West Virginia (1972) caused massive fatalities, destruction of property, and long-term socio-economic disruption (Costa, 1985; Davies et al., 1972; Rogers, 2006; Zhang et al., 2022). More than 60% of global fatalities from dam failures have been concentrated in just three such disasters (Costa, 1985), underscoring their disproportionate consequences. In addition to loss of life, these failures cause cascading impacts on agriculture, industry, infrastructure, and ecosystems, making dam safety a global challenge that extends beyond engineering to the broader domains of disaster risk governance and social resilience (Ge et al., 2024; Nielsen et al., 2019; Tortajada, 2015). With climate change intensifying hydrological extremes and many dams worldwide approaching or surpassing their design lifespans, the risk of dam-related disasters is escalating, drawing urgent attention to both preventive and adaptive strategies.

While substantial research has focused on structural measures, such as seepage control, slope stabilization, spillway enlargement, and material innovations, to improve dam resilience, these interventions alone cannot fully eliminate risks from seismic events, extreme weather, operational errors, or aging infrastructure (Khosravi et al., 2019; Seddeek, 2023). Increasingly, scholars and practitioners recognize that structural defenses must be complemented by non-structural measures, including advanced monitoring technologies, early warning systems, land-use planning, emergency preparedness, policy frameworks, and community awareness programs. These interventions not only enhance disaster preparedness but also mitigate the socio-economic impacts of dam failures by strengthening institutional and social capacity to respond effectively (Arlikatti et al., 2018; Wang et al., 2024). Yet, there is a notable research gap in how non-structural measures can be systematically applied to assess and mitigate the potential socio-economic impacts of dam-related disasters. Addressing this gap is essential to framing dam safety not merely as an engineering concern, but as an integrated aspect of disaster risk reduction and sustainable development. Accordingly, the research question has been formulated as;

“How non-structural measures can be used to mitigate the social and economic impacts arising from dam related disasters?”

1.2 Aim and Objectives

1.2.1 Aim

This research aims to minimize the socio-economic impacts of dam failures through non-structural measures.

1.2.2 Objectives

- To critically review:
  - socio-economic impacts of dam failures.
  - non-structural measures for minimizing the impacts of dam failures.

- To investigate the socio-economic impacts due to various dam failure scenarios.
- To develop prototypes for non-structural measures for minimizing the socio-economic impacts of dam failures.
- To evaluate the effectiveness of non-structural measures in minimizing the socio-economic impacts of dam failures through the developed prototypes.

1.3 Scope and Limitations

This study was scoped to examine the socio-economic impacts of dam failures and to evaluate the effectiveness of non-structural measures. By integrating hydraulic and geospatial modelling, expert interviews, agent-based modelling, and a gamified educational tool, the research provided a holistic framework that addressed both technical and community dimensions of disaster preparedness. However, several limitations must be acknowledged: the study employed hydraulic and flood simulations based on available hydrological data and defined breach parameters, with inherent simplifications limiting result precision. Complementary Agent-Based Modelling captured community responses under disaster scenarios but was similarly constrained by its underlying assumptions. Additionally, the board game developed to enhance disaster preparedness demonstrated promise in controlled settings but requires broader validation across diverse populations and real-world contexts.

1.4 Methodology

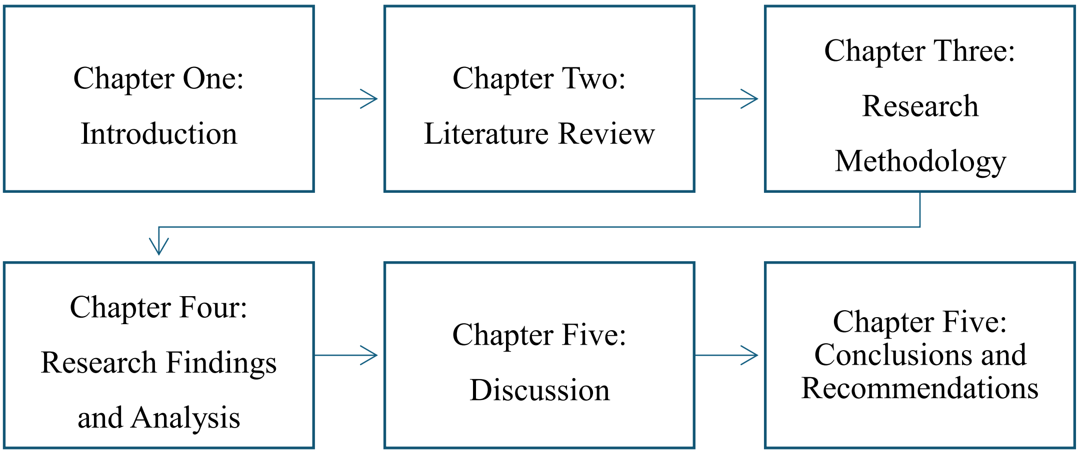
The methodology of this study employed a mixed-methods approach that combined technical modelling with qualitative inquiry to comprehensively assess the socio-economic impacts of dam failures and the role of non-structural measures. Hydraulic and geospatial modelling were first used to simulate potential flood scenarios and delineate inundation zones, providing the technical foundation for impact assessment using Kantale dam in Sri Lanka as a case study. These results were then complemented by expert interviews, which validated the modelling outcomes and offered practical insights into dam safety management and community preparedness. To capture human behavioral dynamics, an agent-based model was developed to simulate evacuation and response patterns under different hazard conditions. Finally, to translate technical findings into an accessible educational tool, a gamified board game was designed and piloted to enhance community awareness of dam safety and disaster preparedness. Together, these methodological components created an integrative framework that addressed both the physical and social dimensions of dam-related risks.

1.5 Chapter Breakdown

Figure 1.1 illustrates the chapter breakdown for this study.

Figure 1.1

Chapter breakdown of the study



1.6 Chapter summary

This chapter provides the background of the study, outlining the risks and socio-economic consequences of dam failures. It further elaborates the aim and objectives of the research, which serve as the guiding framework for achieving the intended outcomes. In addition, the chapter explains the methodology adopted to address these objectives, combining technical modelling with community-focused approaches. Finally, it presents the overall structure of the thesis, indicating how the subsequent chapters develop the study in a logical progression.

2 CHAPTER 02: LITERATURE REVIEW

2.1 Chapter introduction

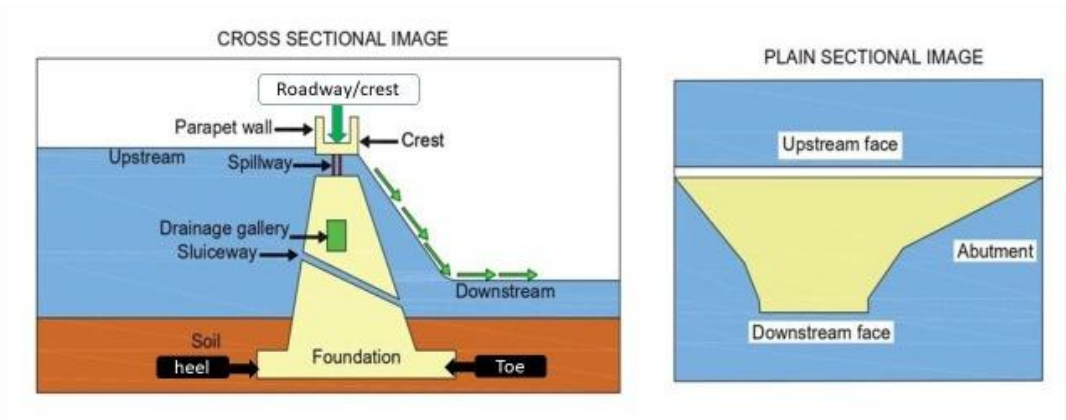
This chapter conducts a comprehensive literature review focusing on dam failures and their impacts on social and economic factors, as well as the existing non-structural measures employed to prevent such disasters. The review critically evaluates and synthesizes the existing body of literature, drawing upon numerous case studies and projects to highlight key insights. It also identifies gaps, contradictions, and emerging trends in the current knowledge landscape. Furthermore, this chapter establishes the foundation for a deeper understanding of how dam failure risks are managed, setting the stage for the subsequent analysis presented in this study.

2.2 Dams and their importance

Dams are engineered structures designed to regulate the natural flow of rivers by impounding water to create reservoirs (Pa & Sin, 2020). These reservoirs serve multiple functions, including flood control, hydropower generation, and the provision of water for municipal, industrial, agricultural, and ecological purposes (Shahraki et al., 2012). Dams are mostly constructed in mountainous river regions, where narrow valleys and stable geological foundations provide favorable conditions for structural stability (Schapper & Urban, 2021). Hydropower facilities are typically co-located with dam sites to capitalize on the hydraulic head and convert the kinetic energy of flowing water into electricity (Smith, 2024). Furthermore, river flows are often diverted, with controlled releases from the reservoir directed into canals and distribution networks to support irrigation and other downstream uses (Tortajada, 2015). Figure 2.1 illustrates the principal components of a dam.

Figure 2.1

Typical components of a dam



Source: (Gopinath, 2022)

Table 2.1 shows the purpose of each component in a dam.

Table 2.1

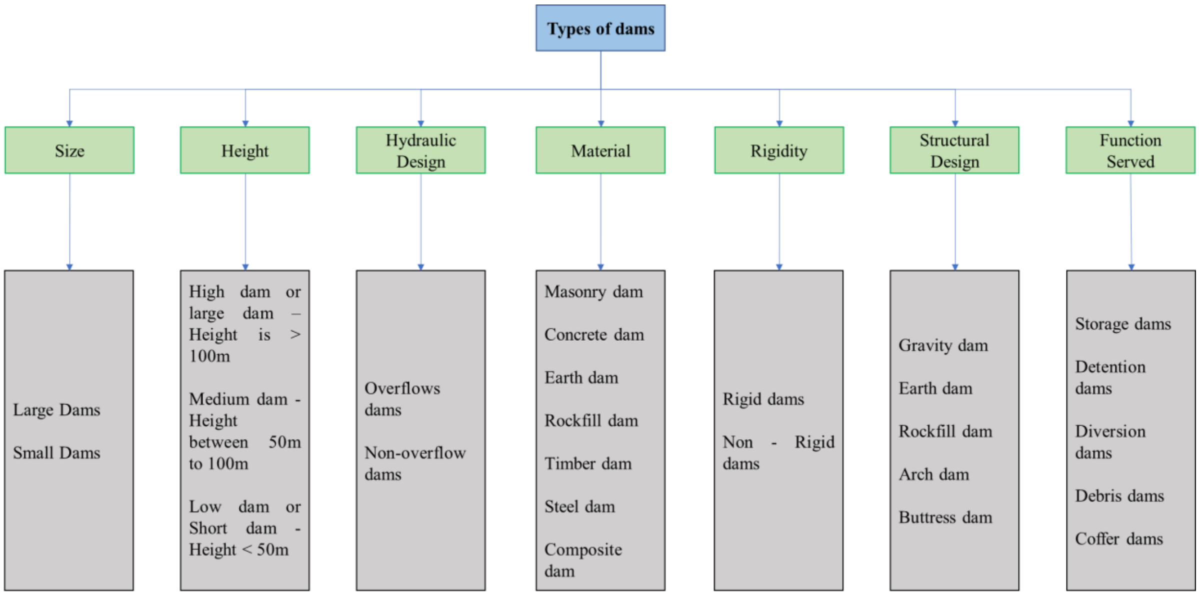
Components of a dam

Component	Purpose
Abutment	An abutment is the valley side or wall that supports a dam. If a natural abutment is unsuitable, an artificial one, typically a concrete gravity section, is built to withstand the thrust of an arch dam and maintain stability.
Gallery	A gallery is a passage within a dam or abutment, used for functions such as grouting, inspection, or drainage.
Spillway	A spillway is a structure that allows floodwaters to be safely discharged from a dam. • Controlled Spillway: Flow is regulated by gates. • Uncontrolled Spillway: Flow is governed solely by the elevation of the spillway crest.
Crest	The crest is the top surface of a dam, which may serve as a roadway or walkway. Parapet walls are low protective barriers built on either side of the crest to ensure safety.
Heel	The upstream face of a dam is the portion in contact with the ground or riverbed on the upstream side, where water is retained.
Toe	The downstream face of a dam is the portion in contact with the ground or riverbed on the downstream side, where water is released.
Sluice way	A sluice is an opening near the base of a dam, designed to remove silt accumulation from the reservoir.

Dams can be classified based on the size, height, function served, hydraulic design, material of construction, rigidity, and the structural design (Bharti et al., 2020). Figure 2.2 showcases the types of dams around the globe.

Figure 2.2

Classification of dams



According to the International Commission on Large Dams (ICOLD) (1995), a dam is classified as "large" if its structural height exceeds 15 meters. However, dams with heights ranging from 10 to 15 meters may also fall within this category when certain criteria are met: a crest length exceeding 500 meters, a reservoir storage capacity greater than one million cubic meters, a flood discharge capacity above 2,000 cubic meters per second, or when foundation conditions present substantial engineering challenges. While dams provide considerable societal benefits, they also pose risks to downstream communities, the environment, and public safety. A dam breach, defined as the formation of an opening in the dam body that permits uncontrolled water flow downstream (Xiong, 2011), produces rapid, turbulent flood waves carrying debris and sediment. These not only cause severe human casualties but also long-lasting socioeconomic and ecological impacts (He et al., 2020).

2.3 Understanding dam-related disasters

Figure 2.3 and Table 2.2 present notable dam failure incidents worldwide, with records extending back over two centuries. These failures reveal that causes are diverse but broadly fall into categories of hydrological (e.g., overtopping due to extreme rainfall), structural (e.g., poor design or foundation flaws), geotechnical (e.g., seismic activity, landslides), and operational (e.g., inadequate maintenance or human error). The St. Francis Dam (1928), Vajont Dam (1963), and Brumadinho Dam (2019) stand out as particularly devastating events, collectively claiming tens of thousands of lives. The high proportion of overtopping and rainfall-related incidents underscores the role of climatic and meteorological variability as decisive triggers.

Figure 2.3

Notable dam failure incidents recorded worldwide

Table 2.2

List of major dam failures and their impacts

Cause of failure	Dam	Date	Country	Fatalities
Overtopping	Iruka lake dam	13/5/1868	Japan	941
	Lower Otay dam	1916	U.S.	14
	Sweetwater dam	27/1/1916	U.S.	0
	Lake Toxaway dam	13/8/1916	U.S.	0
	Horonai dam	1941	Japan	60
	Heiwa lake dam	1951	Japan	117
	Taisho lake dam	1951	Japan	108
	Tous dam	20/10/1982	Spain	8
	Upriver dam	20/5/1986	U.S.	0
	Belci dam	29/7/1991	Romania	25

Cause of failure	Dam	Date	Country	Fatalities
	Virgen dam	1998	Nicaragua	-
	Hope mills dam	26/5/2003	U.S.	0
	Sayano-shushenskaya dam	17/8/2009	Russia	75
	Niedow dam	7/8/2010	Poland	1
	Kopru dam	24/2/2012	Turkey	10
	Panjshir valley dam	11/7/2018	Afghanistan	10
	Sanford dam	15/9/2018	U.S.	0
	Walnut Grove dam	1890	U.S.	100
	Xuriguera dam	1944	Spain	8
	Swift dam	10/6/1964	U.S.	28
Structural / Construction Deficiencies	South fork dam	31/5/1889	U.S.	2208
	Gleno dam	1/12/1923	Italy	356
	Granadillas dam	1934	Spain	8
	St. Francis dam	12/3/1928	U.S.	451+
	Vega de tera	9/1/1959	Spain	144
	Malpaset dam	2/12/1959	France	423
	Val di Stava dam	19/7/1985	Italy	268
	Kantale dam	20/4/1986	Sri Lanka	180
	Dakrong 3 dam	7/10/2012	Vietnam	0
	Austin dam	11/9/1911	U.S.	78

Cause of failure	Dam	Date	Country	Fatalities
Piping / Internal Erosion	Mill river dam	1874	U.S.	139
	Austin dam	11/9/1911	U.S.	78
	Lawn lake dam	15/7/1982	U.S.	3
	Kantale dam	20/4/1986	Sri Lanka	180
	Big bay dam	12/3/2004	U.S.	0
	Taum Sauk reservoir	14/12/2005	U.S.	0
	Hope mills dam	16/6/2010	U.S.	0
Natural Disasters (Landslides, Snowmelt, Seismic Activity)	Vajont dam	9/10/1963	Italy	2000
	Shimantan dams	8/8/1975	China	171000
	Teton dams	5/6/1976	U.S.	11
	Laurel run dam	19/7/1977	U.S.	40
	Shihgang dam	21/9/1999	Taiwan	0
	Fujinuma dam	11/3/2011	Japan	8
	Shakidor dam	10/2/2005	Pakistan	70
	Kyzyl-Agash dam	11/3/2010	Kazakhstan	43
	Ivanovo dam	6/2/2012	Bulgaria	8
	Tokwe mukorsi dam	4/2/2014	Zimbabwe	0
Maintenance & Operational Failures	Canyon lake dam	9/6/1972	U.S.	238
	Val di Stava dam	19/7/1985	Italy	268

Cause of failure	Dam	Date	Country	Fatalities
	Situ gintung dam	27/3/2009	Indonesia	98
	Gusau dam	30/9/2006	Nigeria	40
	Testa Linda dam	13/7/2010	Canada	0
Human or External Interference	Mount polley tailings dam	4/8/2014	Canada	0
	Brumadinho dam	25/1/2019	Brazil	217
	Manana dam	5/11/2015	Brazil	19
	Merrie spruit tailings dam	22/2/1994	South Africa	17
	Mount polley tailings dam	4/8/2014	Canada	0

Notably, Shahraki et al. (2012) observed that earthen dams fail at rates nearly four times higher than concrete or masonry structures, underscoring the vulnerability of embankment dams to hydraulic loading and seepage-induced instabilities. These structural weaknesses are often exacerbated by environmental variability. For instance, the Ram Creek landslide dam in New Zealand collapsed following prolonged rainfall, while Argentina's Rio Barrancas rockslide dam failed after 425 years due to exceptional glacier melt and intense austral summers (Delaney & Evans, 2015).

Collectively, these historical and contemporary events reaffirm that dam failures remain an evolving global threat. They reveal the complex interplay between environmental variability, human oversight, and structural fragility, emphasizing the urgent need for continuous risk assessment, climate-resilient engineering design, and proactive safety management frameworks.

2.4 Impacts of dam failures

Large dams are integral to sustaining social and economic development worldwide International Commission on Large Dams (ICOLD) (1995). Despite the benefits of such dams, the most severe and frequently observed consequence of dam failure is a dam-break flood, as highlighted in numerous hazard risk assessments (Samsuddin et al., 2024). Populations residing downstream face the constant threat of sudden, unpredictable, and potentially catastrophic events. Accordingly, understanding the impacts of dam-break flooding on the social, economic, and environmental fabric of downstream communities is of critical importance.

2.4.1 Social Impact

Dam breaches have catastrophic consequences for downstream communities and their social structures. The most immediate and devastating impact is the loss of human life, as sudden flood surges overwhelm densely populated and low-lying areas (Abdullah & Rahman, 2021). Displacement and forced relocation are also major repercussions, as entire communities are uprooted, often before adequate resettlement arrangements can be secured (Smith, 2024). Globally, dams have displaced an estimated 40–80 million people, with many never fully recovering their livelihoods (Ge et al., 2021; Pérez-Brito, 2018). The aftermath of dam failures frequently includes public health crises, ranging from the outbreak of waterborne diseases to the psychological trauma endured by survivors, which places immense strain on emergency response systems (Lorenzoni et al., 2020). Education is similarly disrupted: school closures, interrupted learning, and the reliance on temporary facilities not only hinder student development but also impose additional financial burdens on families and governments (Lassa et al., 2023). Cultural and social heritage is also at risk, as dam-induced floods can destroy places of worship, burial grounds, and recreational spaces, thereby eroding the communal identity of affected populations (Carmo et al., 2017). In parallel, the collapse of agricultural production and the disruption of food supply chains exacerbate food insecurity, creating shortages and driving up prices (Roulo & Pichuka, 2024). Finally, damage to critical infrastructure, including transportation networks, utilities, and public administration buildings, compounds recovery challenges by delaying access to essential services and prolonging community vulnerability (Gu et al., 2020; He et al., 2020).

2.4.2 Economic Impact

The economic repercussions of dam failures are profound, extending beyond immediate physical destruction to long-term disruptions of livelihoods, business operations, and overall economic stability (Ellingwood et al., 1993). The most immediate impact typically involves the loss of critical infrastructure, such as roads, bridges, power plants, and public buildings, the repair and replacement of which impose substantial financial burdens on governments and affected communities (Al Ruheili et al., 2019). Because dams often provide essential services including irrigation, municipal water supply, and hydroelectric generation, their failure also triggers cascading effects such as water scarcity, flooded agricultural lands, and severe financial losses for farmers and agribusinesses (Al Ruheili et al., 2019; Dolman et al., 2018).

Commercial sectors are similarly vulnerable. Businesses located in inundated regions suffer devastating damage to facilities, interruptions in supply chains, and prolonged revenue losses (Perera & North, 2021; Wilk-Woźniak et al., 2021). In some cases, these shocks lead to bankruptcy, job elimination, and persistent unemployment (Samsuddin et al., 2024). Economic assessments underscore how infrastructure destruction imposes immediate costs, while business closures and reduced productivity deepen inequalities, disproportionately affecting marginalized and low-income populations (Vamvakeridou-Lyroudia et al., 2020). Broader systemic impacts include interruptions in electricity generation, irrigation services, and recreational activities, all of which constrain local and national economies (Perera & North, 2021). Property values in flood-affected areas also decline sharply, limiting recovery options for homeowners and business owners and depleting household financial reserves (Choi et al., 2014). Meanwhile, governments are compelled to redirect public funds toward emergency relief, disaster recovery, and infrastructure rehabilitation, often at the expense of long-term development initiatives and other essential services (Haddad & Teixeira, 2015).

Given these extensive economic consequences, integrating rigorous economic risk assessments into dam safety management is essential. Policymakers and stakeholders must account for both direct and indirect costs when evaluating dam failure risks, thereby strengthening preventive measures, enhancing resilience, and improving disaster preparedness (Manzoor et al., 2022).

2.4.3 Environmental Impact

Dam failures cause profound environmental degradation by reshaping ecosystems and destroying critical natural resources (Shabu & Musa, 2015). One of the most immediate and severe consequences is water contamination, as floodwaters carry debris, chemicals, and sediments into surrounding rivers, lakes, and reservoirs (Silva Rotta et al., 2020; Wu et al., 2019). Such contamination often leads to long-term pollution, threatening potable water supplies and damaging aquatic ecosystems (Wu et al., 2019). The sudden release of vast water volumes also destabilizes riverbanks, alters hydrological regimes, and disrupts wildlife habitats, thereby undermining ecological balance.

The destructive force of floodwaters further accelerates soil erosion and vegetation loss, creating a dual impact: reduced biodiversity and the destruction of fertile agricultural land, which is often extremely difficult to restore (dos Santos Vergilio et al., 2021; Gu et al., 2020; Guimarães et al., 2022). For example, during the Brumadinho tailings dam disaster in Brazil, the release of hazardous materials contaminated entire river systems, causing widespread ecological damage and disrupting the lives and livelihoods of communities dependent on those waters (Silva Rotta et al., 2020).

Sediment dynamics are also significantly disturbed. Dam failures alter natural patterns of sediment transport, causing severe erosion in some regions while depositing excessive sediments in others (Gu et al., 2020). These imbalances obstruct navigation routes, damage fisheries, and undermine wetland ecosystems that play a crucial role in biodiversity preservation. The destruction of wetlands and natural floodplains also removes natural buffers against flooding, increasing vulnerability to future hydrological extremes (Shabu & Musa, 2015).

Perhaps most critically, the ecological consequences of dam failures can persist for decades, with full environmental recovery often unattainable in the short term. This reality highlights the importance of prevention-oriented strategies, including stricter dam safety regulations, effective warning systems, and ecological monitoring programs to minimize risks (De Paiva et al., 2024). Policymakers and stakeholders can contribute to sustainable disaster resilience by incorporating comprehensive environmental impact assessments into dam risk management, ensuring that protection and restoration efforts are aligned with long-term ecological sustainability (Wu et al., 2019).

2.5 Non-Structural Measures for Dam-Related Disaster Mitigation

Building on the limitations of purely engineering-based solutions, non-structural measures play a critical complementary role in reducing dam-related disaster risks (Seddeek, 2023). Rather than reinforcing the physical structure, these strategies focus on managing exposure, vulnerability, and preparedness within downstream communities. Key interventions include integrated flood risk management frameworks, early warning systems, evacuation planning, and land-use regulations that restrict settlements in high-hazard zones (Arlikatti et al., 2018). According to Wang et al. (2024) non-structural measures serve as essential tools for reducing fatal outcomes from dam-break floods through their promotion of preparedness along with response and evacuation system efficiency. Central to these efforts is early hazard detection coupled with reliable and efficient warning dissemination (Perera et al., 2020). Delays in detection or communication significantly increase the risk of fatalities by reducing available evacuation time (Perera et al., 2020). Effective emergency planning must therefore incorporate rapid alert systems, coordinated responder actions, and clear, unambiguous evacuation protocols (Perry & Lindell, 2003). Conversely, poorly designed plans exacerbate risks; inadequate preparation, ineffective coordination, or mismanagement of evacuation routes and shelters can trap people within flood zones, intensify congestion, and render shelters inaccessible or overcrowded (Muda et al., 2020).

Research emphasizes that adaptive management systems, such as two-way traffic designs, flexible road entry points aligned with flood progression, and strategically located shelters above flood levels, can markedly improve evacuation outcomes (Courtnadge et al., 2017). Equally important is sustaining public engagement through education campaigns, preparedness drills, and accessible risk communication, which collectively foster a culture of readiness (Chan et al., 2020; Seddeek, 2023). Ultimately, non-structural measures must operate in tandem with structural defenses such as levees and barriers. A cohesive, integrated strategy that combines robust early-warning systems, well-organized evacuations, efficient traffic management, and community preparedness offers the most effective pathway to reducing fatalities and strengthening resilience to dam-related disasters (Seddeek, 2023; Wang et al., 2024). Such integration ensures that technical safeguards are reinforced by adaptive social and institutional capacities, addressing both the physical and human dimensions of disaster risk.

2.5.1 Early Warning Systems (EWS)

Early Warning Systems (EWS) are a cornerstone of disaster risk reduction (DRR) because of their ability to provide timely alerts that enable both authorities and populations to take proactive protective measures (Weerasinghe et al., 2022). A functional EWS comprises four interlinked elements: risk knowledge, monitoring and forecasting, dissemination, and response capacity (Weerasinghe et al., 2022). Through continuous data collection on hydrological conditions, rainfall, weather patterns, and dam stability, these systems transform scientific monitoring into actionable warnings (Mauney, 2025). When effectively managed, EWS operates not simply as technical infrastructures but as socio-technical systems that connect science, governance, and community preparedness (Ghazali et al., 2018).

Preparedness levels vary significantly within populations, reflecting differences in education, age, gender, and geographic location. A study by Tukiman et al (2017) found that individuals with higher education levels demonstrated greater disaster knowledge and stronger responses to EWS procedures. Conversely, older residents and those with limited literacy skills prefer direct, non-digital communication channels such as community briefings, loudspeakers, or sirens, over electronic messaging, and leaflets (Perera et al., 2020). Signal differentiation problems reduced beacon visibility during adverse weather, and misaligned evacuation expectations (e.g., underestimating flood arrival speed) highlighted weaknesses in system design. Effective EWS require more than technology: they depend on community engagement, culturally tailored communication, and regular training drills to foster resilience (Ghazali et al., 2018).

Despite their life-saving potential, EWS remain inconsistently implemented and too often reactive rather than proactive (Perera et al., 2020; Silva & Eleutério, 2023). Advanced economies increasingly deploy automated, multi-channel systems, yet many flood-prone and developing regions lack even basic warning infrastructure. The consequences of these gaps are evident in several recent disasters. During Brazil's Brumadinho tailings dam failure in 2019, sirens failed to activate, amplifying fatalities (Carmo et al., 2017; United Nations Environment Programme (UNEP) et al., 2020). In the Kedarnath flood in India (2013), communities downstream received little to no actionable warning (Rana et al., 2013). Similarly, investigations into the Oroville Dam crisis in the United States (2017) revealed major deficiencies in communication and coordination, despite a large-scale evacuation being executed (Independent Forensic Team, 2018).

Local participation is increasingly recognized as essential for EWS effectiveness, particularly in contexts where centralized systems are slow or unreliable. Following the Bertam Valley flood in Malaysia (2013), which caused fatalities and major property damage, Ghazali et al (2018) developed a community based EWS (CBEWS). The system integrated remote terminal units, GSM communications, backup power, and strobe lighting, supported by both centralized control rooms and local manual activation. Community testing demonstrated strong responsiveness, with residents promptly detecting signals and initiating timely evacuation. However, weaknesses in network coverage caused delays in siren activation, emphasizing the need for continuous technical upgrades. Importantly, sustaining preparedness requires annual evacuation exercises, community engagement, and collaboration with law enforcement and emergency services (Weerasinghe et al., 2022). These findings reinforce that CBEWS can strengthen resilience by positioning local communities as first responders, complementing centralized monitoring with localized response capacity.

The evidence shows that the success of EWS lies not merely in the presence of monitoring technologies but in their integration with governance, social trust, and community capacity (Wang et al., 2025). Research consistently points to three critical success factors: (1) robust early hazard detection and reliable multi-channel dissemination, (2) clear evacuation planning supported by traffic and shelter management, and (3) sustained public education through awareness programs and drills (Perera et al., 2020; Wang et al., 2024a). Failures in any of these elements increase fatalities, as delays, unclear instructions, or poorly planned evacuation routes can trap residents within flood zones. Furthermore, treating EWS as technical systems alone underutilizes their potential. They must be approached as socio-technical infrastructures that embed scientific monitoring within participatory governance and localized practices (Alvi & Alvi, 2023; Mehta et al., 2020). With climate change increasing the frequency of extreme hydrological events and aging dam infrastructure heightening risks, addressing gaps in community centered, operational EWS is both urgent and essential (Mauney, 2025; Weerasinghe et al., 2022).

2.5.2 Policies, Regulations and Frameworks

Passey et al. (2014) introduced a conceptual framework for risk-informed decision-making in dam safety, developed collaboratively by the Ontario Ministry of Natural Resources and Forestry (MNRF), Ontario Power Generation (OPG), the Grand River Conservation Authority (GRCA), and Hatch Ltd. This framework requires dam owners to develop Dam Safety Management Plans (DSMPs) that integrate risk assessment principles and minimum safety criteria. The DSMP approach manages risks through structured engineering, operational, and maintenance practices, aligning with the Canadian Dam Association (CDA) Dam Safety Guidelines and international best practices. Unlike traditional deterministic methods, this model adopts a risk-based approach, emphasizing ongoing evaluation, peer review, and regulatory oversight. Responsibilities are clearly assigned to dam owners, engineers, independent reviewers, and regulators, ensuring continuous monitoring and quality control. The proposed adoption marked the first official risk-based decision framework for dam safety enforcement in Canada, enhancing public protection, environmental safeguards, and regulatory accountability.

Complementing such frameworks, Xie et al. (2022) proposed the Remote Sensing-Based Dam Hazard Investigation (RSDHI) framework, which employs multi-sensor technologies, including Synthetic Aperture Radar (SAR), optical imaging, and LiDAR, combined with numerical modeling to monitor dam stability. The system detected annual subsidence of approximately 6.3 cm and differential settlement of 4.7 cm in breach-prone sections, identifying secondary consolidation, rather than hydrological factors, as the primary trigger of instability. Finite element modeling revealed that water impoundment increased pore pressure and shear stress, thereby reducing slope stability at the downstream face. Moreover, the framework monitored reservoir storage changes, showing a 76% capacity loss following collapse. RSDHI thus serves as a cost-efficient, scalable, and non-structural hazard reduction tool, particularly valuable for regions lacking on-site monitoring systems, by enabling early detection of instability and facilitating proactive disaster response.

Tingey-Holyoak et al (2013) examined international benchmarks for private dam safety oversight within the context of catchment policy infrastructure. The study highlighted how on-farm private dam failures present cumulative risks to both communities and the environment, particularly where policy frameworks are weak. While Tasmania exemplifies best practice through robust regulation and mandatory dam registration, South Australia continues to rely on voluntary oversight, which has proven ineffective and raised persistent safety concerns since 2005. The authors recommend adopting international standards in water resource and land-use policies, introducing mandatory risk assessments, safety compliance requirements, and enforcement tools to prevent dam-related disasters. They also emphasized the cost-effectiveness of proactive monitoring and damage prevention systems in strengthening resilience at the catchment scale. The same study further assessed small dam safety assurance policies in developing countries, using Vietnam as a case study. Weak regulatory frameworks, insufficient compliance, and poor maintenance practices were found to be widespread across small dams. Vietnam's dam safety system falls significantly below international standards, hindered by persistent issues such as inadequate dam registration, poor accountability structures, limited community preparedness, and ineffective enforcement mechanisms. Field investigations of 22 small dams revealed both structural and managerial deficiencies, underscoring the urgent need for comprehensive safety reforms. The authors recommend a staged approach, beginning with essential requirements, such as dam registration, risk classification, and community education, before advancing to international best practices and World Bank protocols. This methodology provides developing nations with a practical pathway to progressively strengthen dam safety policies, reduce risks, and protect vulnerable communities from catastrophic dam failures.

2.5.3 Evacuation procedures during floods

Another essential non-structural measure that significantly contributes to reducing the consequences of dam failures is the establishment of a well-defined and effectively coordinated evacuation procedure during flood events (Sun et al., 2022). Borowska-Stefańska et al (2019), for example, propose a comprehensive evacuation optimization framework for flood-prone regions that integrates policy mechanisms, infrastructure development, technological solutions, and community-based participation. This holistic approach demonstrates how evacuation planning can be strengthened through the combined influence of governance, physical systems, and local engagement. The framework delivers essential guidelines to flood-risk authorities based on spatial requirements that help enhance emergency rescue operations and transportation development plans. The study illustrates how intelligent transport systems incorporating variable message signs and automated traffic control systems decrease evacuation times together with improved operational efficiency. This research uses an enhanced two-step floating catchment area (E2SFCA) method which enhances spatial accessibility assessments for an improved and realistic allocation of evacuation facilities. The study demonstrates how road congestion together with emergency vehicle deployment affects evacuation effectiveness which in turn justifies real-time based transport route optimization. The research emphasizes community education programs about appropriate emergency behaviors which must be taught to flood-prone residents as a crucial element of preparedness. Borowska-Stefańska et al. (2019) show that monitoring technologies supplemented by optimized routes and involved community education led to advanced flood evacuation planning which rolls back flood hazards effectively.

Apart from that, experimental research done by Dias et al. (2021) highlights the significant influence of water depth on human walking behavior during flood evacuations, demonstrating that greater depths can reduce walking speed by up to 41% between ankle- and waist-deep conditions. The study also found that deeper water forces people to extend their body movements laterally, increasing the space required for safe passage, while men walked faster than women under deeper floodwater conditions. These findings reinforce the importance of considering pedestrian mobility constraints, especially in narrow urban pathways where congestion and physical obstacles can impede evacuation. Complementing this, hydraulic modelling plays a crucial role in flood evacuation planning by generating spatiotemporal inundation maps and estimating flood depths and velocities that inform safe evacuation routes (Monte et al., 2016). By coupling 1D/2D unsteady hydraulic models (e.g., HEC-RAS, MIKE FLOOD) with high-resolution terrain data, planners can simulate the propagation of floodwaters across diverse landscapes and determine critical thresholds at which routes become unsafe (Lee et al., 2017). Together, empirical insights into human movement and advanced hydraulic simulations enhance the accuracy and reliability of evacuation planning, enabling the design of more effective strategies that account for both hydrodynamic forces and human behavioral responses (Bharath et al., 2021).

2.5.3.1 Hydrodynamic Modelling

Numerous earlier research has attempted to evaluate the socioeconomic effects of dam failure events by identifying locations that are inundated or by developing methods for mapping inundation using hydrodynamic, GIS-based, or numerical models (Samsuddin et al., 2024). Most common hydraulic models that have been used for dam break study and flood inundation mapping would be, DAMBRK model which predicts dam breach wave formation and its progression in downstream (Lee et al., 2017). FLO-2D employs a grid approach to identify the floodplain based on elevation and roughness coefficient, and it is effective at predicting flow course and area, forecasting flood hazard, mudflow, and debris flow over alluvial rivers (Pilotti et al., 2014). FLDWAV model is intended to use real forecasting technology to anticipate flow across a single stream or network of streams, model quick flood events from big precipitation events or dam break occurrences, consider terrain and material attributes at various time intervals, and modify flow patterns (Sreekumar et al., 2024). Hydraulic Engineering Centre's River Analysis System (HEC-RAS) models downstream effects based on the findings of dam breach studies and simulates the ensuing flood wave produced by the aftermath of an upstream incident. In the study carried out by (Salajegheh et al., 2009), a quantitative analysis of flood plains of the Polasjan River Basin at Iran's central plateau using HEC-RAS and GIS was done. This study showed that the incorporation of HEC-RAS with ArcGIS is an efficient method for floodplain mapping considering the advantages like the ease of use of integrated programs with user-friendly interfaces, digital products and conservation of time and resources. Additionally, geospatial analysis complements these developments by visualizing flood scenarios and assessing their effects on infrastructural settings, populations, and ecosystems (Pfändler et al., 2024). Table 2.3 identifies the gaps of past studies that have used hydrodynamic modelling and geospatial analysis as separate tools.

Table 2.3

Summarization of used framework and models in past studies for assessing dam failure scenarios

No	Title	Framework/ Model	Gaps	References
1	Two-dimensional dam-break flooding simulation: a GIS-embedded approach	Hydrodynamic modeling and GIS	Basic simulation that ignores any further social, economic, or environmental ramifications.	(Cannata & Marzocchi, 2012)
2	Scenario based flood risk assessment for urbanizing deltas using future land-use simulation (FLUS): Guangzhou Metropolitan Area as a case study	FLUS model Markov chain model ArcGIS	There was no in-depth discussion of the economic impact.	(Lin et al., 2020)
3	A thematic mapping method to assess and analyze potential urban hazards and risks caused by flooding	GIS Quantitative cartographic	Social vulnerability index is unable to pinpoint the exact degree of vulnerability of specific economic or minority variables.	(Hossain & Meng, 2020)
4	Economic impacts of natural disasters in megacities: The case of floods in Sao Paulo, Brazil	Spatial Computable General Equilibrium Model (SCGE)	To comprehend how flooding affects the business without taking social standing and financial impact into account	(Haddad & Teixeira, 2015)
5	Social, economic and environmental assessment of urban sub-catchment flood risks using a multi-criteria approach: A case study in Mumbai City, India	Non-heuristic multi-criteria decision-making (MCDA) approach combining hydrological and hydraulic models with GIS	The relationship between the flood risk categories is poor; social-economic factors are poorly considered; high data demands and a high demand for spatial differentiation.	(Pathak et al., 2020)
6	Hydrodynamic Modelling of Floods and Estimating	2D HEC-RAS Hydrodynamic Model	Site-specific data, low spatial density, assumed relationships of damage,	(Mubialiwo et al., 2022)

No	Title	Framework/ Model	Gaps	References
	Socio-economic Impacts of Floods in Ugandan River Malaba Sub-catchment		lack of validated crop damage functions, insufficient hybrid damage modeling to emphasize that major socio-economic risks require targeted approaches and data	
7	Assessing and visualizing hazard impacts to enhance the resilience of Critical Infrastructures to Urban Flooding	Climate Risk Management Risk and Resilience Modelling	Determine only the extent of the infrastructure damage.	(Vamvakeridou-Lyroudia et al., 2020)

Among different hydraulic modelling tools, the most widely used model is the Hydrologic Engineering Centre's - River Analysis System (HEC-RAS) model developed by the Hydrologic Engineering Centre of the U.S. Army Corps of Engineers in 1981 (Karim et al., 2021). In the recently launched version (release 6.6), the HEC-RAS model has been enriched with novel modules. Based on one- and two-dimensional modeling of the water surface profile of open channels, it has been developed for various computations of steady and unsteady flow. 1D Saint Venant Equations are used to calculate unsteady flow at the channel cross-sections in one-dimensional models. In contrast, the 2D HEC-RAS model investigates the flood inundation map in a 2D flow area (over the floodplain and the river channel) by building a computational Finite Element mesh that solves the 2D Diffusion Wave Equations or the 2D Sallow Water Equations (Saint Venant Equations).

2.5.4 Community Education and Awareness

Even the best warning siren is useless if people do not know how to react. Thus, community education and awareness programs are a critical non-structural strategy to mitigate dam-related disasters (Frankenberg et al., 2013). These initiatives aim to inform and prepare the populations living in a dam's shadow about the risks and the proper actions to take in an emergency (Tsai et al., 2020). Key approaches include:

2.5.4.1 Public awareness campaigns

Many countries host annual events, and publicity drives to keep dam safety on the public radar. For example, the United States observes *National Dam Safety Awareness Day* every May 31 (in remembrance of the 1889 Johnstown Flood tragedy) to educate communities about downstream flood risk and preparedness (Association of State Dam Safety Officials (ASDSO), 2017). Government agencies (like FEMA and state dam safety offices) circulate brochures, infographics, and online maps showing dam inundation zones, encouraging residents to "know your risk" and be ready to evacuate (Federal Emergency Management Agency (FEMA), 2013).

In India, after a major dam-related flood in Kerala (2018), authorities launched awareness drives in villages downstream of major reservoirs, including distributing pamphlets on recognizing siren signals and evacuation routes.

2.5.4.2 School and community drills

Regular drills and exercises greatly enhance preparedness. Some communities organize evacuation drills simulating a dam break scenario (Demiray et al., 2025). For instance, in Washington State (USA), one school district downstream of a dam conducts an annual evacuation drill for students and residents, teaching them to quickly move to high ground when hearing the dam sirens (Ronan et al., 2001). Such drills familiarize the public with warning sounds and routes, reducing confusion during a real event. Table-top exercises involving community leaders, as held for Pomme de Terre Dam in Missouri in 2024, also help identify gaps in local readiness and improve coordination

2.5.4.3 Education and outreach programs

Dam safety agencies and dam owners frequently organize public meetings, workshops, and site tours to inform residents about dam risks and emergency procedures (Association of State Dam Safety Officials (ASDSO), 2017; Gomes et al., 2024). In Australia, guidelines encourage dam owners to act as "good neighbors" by engaging the community, sharing safety information, and involving residents in planning discussions (Victoria Department of Environment, 2015). In Japan and China, some dams feature visitor centers or warning signboards explaining what to do if an alarm sounds. Elsewhere, outreach takes more creative forms: for example, Italy's Vajont Dam memorial, built at the site of a tragic 1963 flood, now serves as an educational hub for visitors and schools, highlighting the consequences of poor risk management (Paronuzzi et al., 2021).

Community education and awareness are life-saving measures because they foster a culture of preparedness (Mossoux et al., 2016). People who understand the risks are more likely to evacuate quickly and calmly. Historical examples show that a lack of awareness can make disasters far worse. In the 1928 failure of the St. Francis Dam in California, no emergency plan existed, and the public had no idea what to do when the dam collapsed at midnight, resulting in 432 deaths (Begnudelli & Sanders, 2007). In contrast, modern communities with strong awareness programs tend to carry out faster, safer evacuations. During recent near failures in the UK and US, the readiness of downstream residents, through education and awareness, was critical to ensuring effective response (Mehta et al., 2020). Awareness campaigns also encourage personal responsibility: households may prepare emergency bags, establish family meeting points, and remain vigilant during storms (Daud et al., 2021). Over the long term, informed communities often advocate for greater investment in safety measures, such as dam repairs or better warning systems. These campaigns bring added benefits too, as they often strengthen preparedness for other hazards like floods or earthquakes. As (Federal Emergency Management Agency (FEMA), 2013) emphasizes, "the most important step you can take is to know your risk… and evacuate when directed", a message that only works if people are informed in advance.

Maintaining public awareness, however, is not without challenges. Over time, communities may become complacent if no incident occurs, while newcomers may be unaware of the risks (Gomes et al., 2024). Outreach must therefore be consistent and recurring. Communicating low-probability risks is also difficult, residents may dismiss drills or information campaigns as irrelevant. Language barriers can limit the reach of materials in rural or diverse regions, and too much emphasis on catastrophic scenarios may generate fear or even depress property values, making some officials hesitant to share full details (Kaman et al., 2024). Measuring effectiveness is also problematic, since success is only proven during a real emergency. Further even then, stress can still cause unpredictable reactions. For this reason, education must be combined with clear warning systems and practiced emergency plans to maximize safety (Daud et al., 2021).

2.6 Chapter Summary

This chapter provides a comprehensive synthesis of existing knowledge on dam failures, their socio-economic consequences, and the non-structural measures used to mitigate associated risks. It begins by outlining the functional importance of dams in supporting hydropower generation, irrigation, flood control, and water supply systems, establishing their critical role in societal and economic development. The chapter then evaluates global evidence on dam failure events, emphasizing the profound and often cascading impacts on communities, infrastructure, and regional economies. A substantial portion of the review is devoted to assessing non-structural strategies, such as hazard mapping, early warning systems, emergency action planning, and community education, highlighting their growing significance in contemporary dam safety management. Importantly, the review identifies a notable research gap in the systematic application of these measures to mitigate socio-economic impacts, thereby reinforcing the relevance of the study's research question. Therefore, the literature review establishes the conceptual foundation for the study by synthesizing key insights, exposing contradictions and gaps in current knowledge, and framing the need for integrated, community-focused approaches to dam failure risk reduction.

3 CHAPTER 03: RESEARCH METHODOLOGY

3.1 Chapter introduction

This chapter discusses the research philosophy, research approach, strategies, procedures, and tools that were utilized to address the aim and the objectives of the study. This chapter plays a major role in establishing the reliability and the credibility of the research findings, providing precision to readers, and ensuring the study's reproducibility. Furthermore, the research process employed throughout the study has been outlined comprehensively.

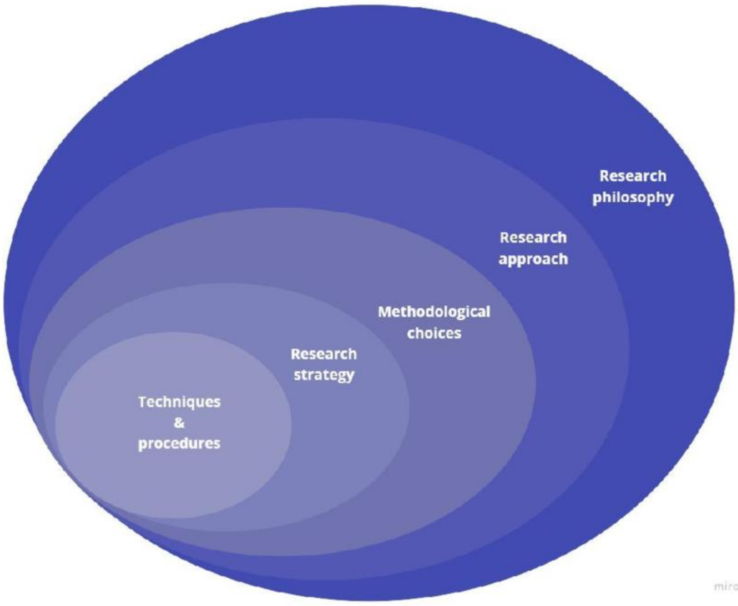
3.2 Research design

According to Mukherjee (2017), structuring the research plan, commonly referred to as the 'research design' is the next step once the research problem is identified. A research design can be defined according to Sekaran & Bougie (2016) as a plan that outlines how to gather additional data, analyze, and interpret it, and ultimately provide an answer to the research question. The main goal of a research design is to ensure that the information collected effectively addresses the original research question (Schoonenboom & Johnson, 2017). The research design incorporated an exploration of the context, a thorough examination of existing literature, the approach to gathering data, and the subsequent analysis of the collected data (Mukherjee, 2017; Rahi, 2017).

In built environment research, methodological design is commonly structured using either the nested approach (Kagioglou et al., 1998) or the research onion framework (Saunders et al., 2019). The selection between these two largely depends on the specific aims and nature of the study (Omotayo & Kulatunga, 2015). While both frameworks promote a systematic and transparent decision-making process, the research onion, comprising more layers than the nested model, offers a more comprehensive structure for guiding methodological choices (Kulatunga et al., 2014). For this reason, the present study adopts the research onion as its methodological design framework. Figure 3.1 illustrates the relevance and application of the research onion within this study.

Figure 3.1

Saunder's research onion



Saunders et al. (2019) emphasize that the central concern of the researcher, data collection and analysis, sits at the core of the onion. However, the systematic nature of the framework requires the researcher to progress through several outer layers before reaching this core. As Al Zefeiti and Mohamad (2015) note, this sequential "peeling" highlights the methodological considerations that precede decisions about data collection and analysis. These layers, beginning from the outermost, include the research philosophy, theoretical approach, methodological choice, research strategy, time horizon, and finally, the techniques and procedures. Each of these layers is summarized in the sections that follow.

3.2.1 Research philosophy

The set of beliefs concerning the nature of the reality being investigated can be defined as the research philosophy (Khatri, 2020). Depending on the research problem being examined, the form of research philosophy utilized in an area of research study will be decided (Scotland, 2012). Research philosophy can be discussed in terms of ontology and epistemology (Abu-Alhaija, 2019). Ontological assumptions focus on the nature of reality, outlining the distinction between reality itself, our perception of it, and how this perception shapes our understanding of phenomena (Chege & Otieno, 2020). Epistemology, on the other hand, concerns the study of knowledge, examining what can be known and the criteria that justify it as knowledge (Petty et al., 2012).

Three major stances of research philosophy are commonly distinguished in the literature: positivism, interpretivism, and pragmatism (Saliya, 2023; Žukauskas et al., 2018). Positivists argue that reality is stable and can be observed objectively without influencing the phenomenon under study (Park et al., 2020). Interpretivists emphasize that reality can only be understood through subjective interpretation and contextual engagement (Junjie & Yingxin, 2022).

Pragmatists, however, recognize the multiplicity of realities and perspectives, acknowledging that no single worldview or methodology can capture the entire picture (Kaushik & Walsh, 2019).

In this study, pragmatism is adopted as the most appropriate research philosophy. Pragmatism supports the integration of both qualitative and quantitative approaches, enabling a comprehensive exploration of complex and multifaceted realities. It emphasizes the pursuit of practical solutions that align with real-world conditions, allowing the study to draw upon both objective measurements and subjective insights to generate richer and more actionable findings. This flexibility ensures that methodological choices are guided by the research problem itself, rather than being constrained by a single philosophical stance.

3.2.2 Research approach

Research approaches describe the logical relationship between theory and empirical evidence, explaining how knowledge is generated and refined throughout the research process. Three principal approaches are widely recognized in methodological literature: deductive, inductive, and abductive reasoning (Saunders et al., 2019). Each approach reflects a distinct mode of inference and offers different strengths depending on the nature of the research problem and the maturity of existing theory.

The deductive approach begins with established theories or conceptual frameworks, from which hypotheses or propositions are derived and subsequently tested against empirical observations (Mehrad & Zangeneh, 2019). This approach is particularly suitable where prior theoretical foundations are well developed, allowing researchers to assess the applicability or validity of existing knowledge in specific contexts. In this study, deductive reasoning is applied in the early stages through the systematic review of literature and the use of established hydraulic, geospatial, and risk assessment models. Existing theories on dam failure mechanisms, flood propagation, socio-economic vulnerability, and disaster risk management inform the selection of variables, modelling parameters, and analytical criteria used in simulation-based assessments.

In contrast, the inductive approach moves from empirical observations toward the development of patterns, themes, or conceptual insights (Rahi, 2017). Rather than testing predefined hypotheses, inductive reasoning allows theory to emerge from data, making it particularly valuable in exploratory contexts where human behaviour, perceptions, and institutional practices play a central role (Taherdoost, 2022). Within this research, inductive reasoning is employed through expert interviews, stakeholder engagement, and observations derived from community-focused activities. Insights gained from these qualitative engagements contribute to identifying contextual factors influencing preparedness, response behaviour, and the effectiveness of non-structural measures, thereby extending understanding beyond what is captured in existing theoretical models.

Bridging these two modes of reasoning, the abductive approach plays a central role in overall research design. Abduction is characterized by an iterative movement between theory and data, allowing surprising or unexpected empirical findings to prompt theoretical refinement or the development of new explanatory propositions (Taherdoost, 2022). This approach is particularly appropriate for complex, real-world problems, such as dam safety and disaster preparedness, where technical systems, human behaviour, and institutional dynamics interact in non-linear ways (Creswell, 2013). In this study, abductive reasoning enables the continuous refinement of analytical assumptions as insights emerge across multiple phases of the research. For example, discrepancies between simulated flood impacts and stakeholder perceptions prompted further investigation through agent-based modelling and the development of a gamified prototype, allowing theoretical understanding and practical application to co-evolve.

Accordingly, this research adopts a combined abductive–inductive–deductive approach, consistent with its pragmatist philosophical stance. Deductive reasoning provides a structured foundation through established theories and models; inductive reasoning allows new insights to emerge from empirical engagement; and abductive reasoning integrates these processes through iterative reflection and refinement. This pluralistic approach ensures methodological coherence while enabling the study to address both the technical dimensions of dam failure impacts and the socio-economic and behavioural complexities associated with non-structural risk mitigation. By moving flexibly between theory and evidence, the research achieves a comprehensive and context-sensitive understanding of how non-structural measures can effectively reduce the socio-economic impacts of dam-related disasters.

3.2.3 Methodological choice

According to Saunders et al. (2019), the methodological choice represents a critical layer within the research onion, shaping how the researcher integrates philosophical assumptions with practical methods of inquiry. It defines whether the study adopts a single methodological tradition or draws from multiple approaches to generate a comprehensive understanding of the research problem. Accordingly, in this study, the decision is inherently influenced by the researcher's philosophical orientation and overarching worldview regarding how knowledge is constructed and interpreted.

Research paradigms, positivist, interpretivist, critical/transformative, and pragmatic, offer different lenses through which knowledge can be approached and interpreted (Chege & Otieno, 2020). Each paradigm carries distinct ontological, epistemological, and axiological assumptions, which subsequently shape the methodological stance adopted within a study (Rahi, 2017; Saunders et al., 2019). In this research, the paradigm of pragmatism guides these methodological decisions. Pragmatism emphasizes the practical implications of research and recognizes that no single methodological tradition is sufficient to capture the multifaceted nature of complex real-world phenomena. Instead, knowledge is best generated through the integration of diverse perspectives and evidence types, thereby aligning philosophical choice with the demands of the research problem (Saliya, 2023).

A mixed-method methodological choice is adopted in this study because the research objectives require both quantitative evidence and qualitative insight to be addressed comprehensively. Understanding the socio-economic impacts of dam failures demands quantifiable analysis derived from hydraulic modelling, exposure assessments, and scenario simulations, while evaluating the effectiveness and feasibility of non-structural mitigation measures also necessitates expert interpretation and contextual knowledge that cannot be captured numerically. By combining these complementary forms of evidence, the study is able to develop a more complete and nuanced understanding of the problem than would be possible through a single method alone.

This integration of qualitative and quantitative techniques is also consistent with the pragmatic orientation of the research, which values methodological flexibility and the use of approaches that best support real-world problem-solving. Pragmatism therefore provides a philosophical foundation that supports, rather than dictates, the choice of mixed methods, ensuring that methodological design remains responsive to the complexity of dam-failure scenarios and the multifaceted nature of risk-reduction decision-making.

By employing this mixed-method choice, the study ensures methodological coherence with its pragmatic philosophy, supports triangulation of findings, and enhances both the credibility and applicability of the results. This integration of methods strengthens the robustness of the research design and addresses the complexity inherent in the study's objectives.

3.2.4 Research Strategy

Within the research onion framework, the research strategy represents the set of coherent techniques that guide how the study's objectives are operationalized (Saunders et al., 2019). It translates the philosophical stance, research approach, and methodological choice into a concrete plan of action, determining the procedures for generating, organizing, and analyzing data. The chosen strategy must therefore reflect both the nature of the research problem and the pragmatic orientation of this study.

Given the aim of investigating the socio-economic impacts of dam failures and evaluating the role of non-structural mitigation measures, this study adopts a multi-strategy research design, combining elements of case study inquiry with expert-informed qualitative investigation. A multi-strategy design is consistent with the broader mixed-method methodological choice and is well suited to complex, real-world problems where diverse forms of evidence are necessary to develop nuanced and actionable insights.

The case study component allows for in-depth examination of dam-failure scenarios, drawing on hydraulic modelling outputs, literature evidence, and contextual socio-economic data. Case study strategies are particularly valuable for studies addressing "how" and "why" questions within bounded systems of real-world significance, and for generating context-rich findings that can inform practical mitigation planning.

Complementing the case study analysis, the study employs a qualitative survey strategy, which enables the collection of context-specific knowledge from practitioners and researchers experienced in dam engineering, disaster risk management, early warning systems, and hydrological modelling. Purposive sampling was used to identify the most suitable participants based on their expertise and relevance to the research focus. This strategy ensures that insights incorporate practitioner realities and professional judgment, which are essential when examining low-frequency but high-impact hazards such as dam failures.

Together, these strategies create a coherent methodological pathway: the case study provides empirical grounding and scenario-based evidence, while the qualitative survey enriches and validates the interpretation of impacts and mitigation options. This strategically integrated approach aligns with pragmatic philosophy by prioritizing methods that best address the research objectives, while strengthening the reliability and contextual relevance of the findings.

3.2.5 Case study design

According to Gustafsson, (2017), case studies have a double function, where the case studies become studies of their own unit, as well as case studies of a larger group of units. Researchers are studying multiple cases whenever they are available to understand the similarities and the differences between each other cases (Baxter & Jack, 2008). Single case study design is suitable when the study represents a unique case or critical case or an extreme case or a representative/ typical case or a longitudinal case or a revelatory case (Ali, 2024).

The case study design forms a central component of the research strategy, providing a structured approach for examining the real-world implications of dam-failure scenarios within a specific geographical and socio-economic context. As emphasized by Ridder (2017), case studies are particularly effective when the research seeks to answer "how" and "why" questions about complex contemporary events over which the researcher has limited control. Dam failures represent such complex phenomena, characterized by multi-layered interactions among hydrological processes, physical infrastructure conditions, and human communities. Accordingly, the case study design offers the most suitable framework for investigating the socio-economic impacts arising from potential failure events and the role of non-structural mitigation measures in reducing these risks.

This study applies a single embedded case study, focusing on a selected dam site and the surrounding downstream communities. The embedded nature of the design enables the analysis to capture multiple units of interest, such as affected households, critical facilities, agricultural zones, and transportation networks, which interact differently with flood propagation patterns. By combining hydraulic modelling outputs, spatial analysis, and expert knowledge, the case study provides a holistic view of the consequences associated with various breach scenarios. This aligns with the mixed-method methodological choice, as it integrates quantitative measures (e.g., inundation depth, hazard intensity, affected population counts) with qualitative insights from expert interviews.

The case study design also provides methodological flexibility, allowing the researcher to draw from diverse data sources to triangulate findings and strengthen credibility. For example, the hydraulic modelling results offer empirical evidence on flood behaviour, while expert interviews contribute contextual interpretations, validation of assumptions, and practitioner-informed perspectives on socio-economic and community-level impacts. This integration ensures that the analysis is not solely reliant on simulation outputs but is enriched by the lived experience and specialized knowledge of practitioners in dam engineering, disaster risk management, and early warning systems.

Furthermore, adopting a case study design aligns with pragmatic philosophy guiding the study. Pragmatism emphasizes methodological appropriateness and practical relevance, supporting strategies that generate actionable knowledge for real-world problem-solving. Through the case study approach, this research can situate dam-failure impacts within their broader socio-environmental setting, accounting for local vulnerabilities, exposure patterns, and institutional capacities. This contextualized understanding is essential for evaluating the effectiveness and feasibility of non-structural mitigation measures such as early warning systems, public awareness programmes, and land-use planning adjustments.

3.2.6 Time horizons

Within the research onion, the time horizon refers to the temporal framework within which the study is conducted, distinguishing whether the research observes phenomena at a single point in time or across an extended period (Saunders et al., 2019). Time horizons are categorised as either cross-sectional, capturing a snapshot of variables at one moment, or longitudinal, which involves repeated observations to examine changes over time.

Given the nature and objectives of this study, a cross-sectional time horizon is adopted. The investigation focuses on analyzing dam-failure impacts and evaluating the effectiveness of non-structural mitigation measures using data collected and analyzed within a singular defined period. The hydraulic modelling outputs, socio-economic exposure data, and expert interview insights represent conditions and perspectives relevant to the specific temporal context of the study. Although dam-failure risks and mitigation strategies evolve over time, addressing such changes is beyond the scope of this research design, particularly because the modeling and expert insights were interpreted within a fixed analytical timeframe.

A cross-sectional horizon is therefore appropriate because it enables the integration of diverse data sources, hydraulic simulations, geospatial assessments, and expert judgments, without requiring longitudinal tracking. It aligns with the study's pragmatic and mixed-method approach, providing an efficient framework for generating actionable insights that reflect the current state of dam-related risk and mitigation planning. This time horizon also complements the case study design by allowing focused, in-depth exploration of the chosen dam scenario within its present socio-environmental context.

3.2.7 Techniques and procedures

The techniques and procedures layer of the research onion represents the operational core of the research process, detailing how data are collected, generated, processed, and analysed to address the research objectives (Saunders et al., 2019). In this study, the techniques and procedures reflect the mixed-method methodological choice and pragmatic philosophy, integrating quantitative modelling approaches with qualitative expert insights to develop a holistic understanding of dam-failure impacts and non-structural mitigation strategies. A detailed account of the techniques and procedures adopted in this study is presented in Section 3.3, where the full research process is systematically outlined and explained.

3.3 Research process

The research process involves a sequence of steps essential for the successful execution of research, encompassing tasks such as defining the research question, comprehensive literature review, formulating hypotheses, drafting the research design, deciding on the sample design, data collection, data analysis, hypotheses testing (if applicable), universalizing and interpretations, and finally, reporting the results (Singh, 2021). Figure 3.2 demonstrates the research process of the study.

Figure 3.2

Research process adopted for the study

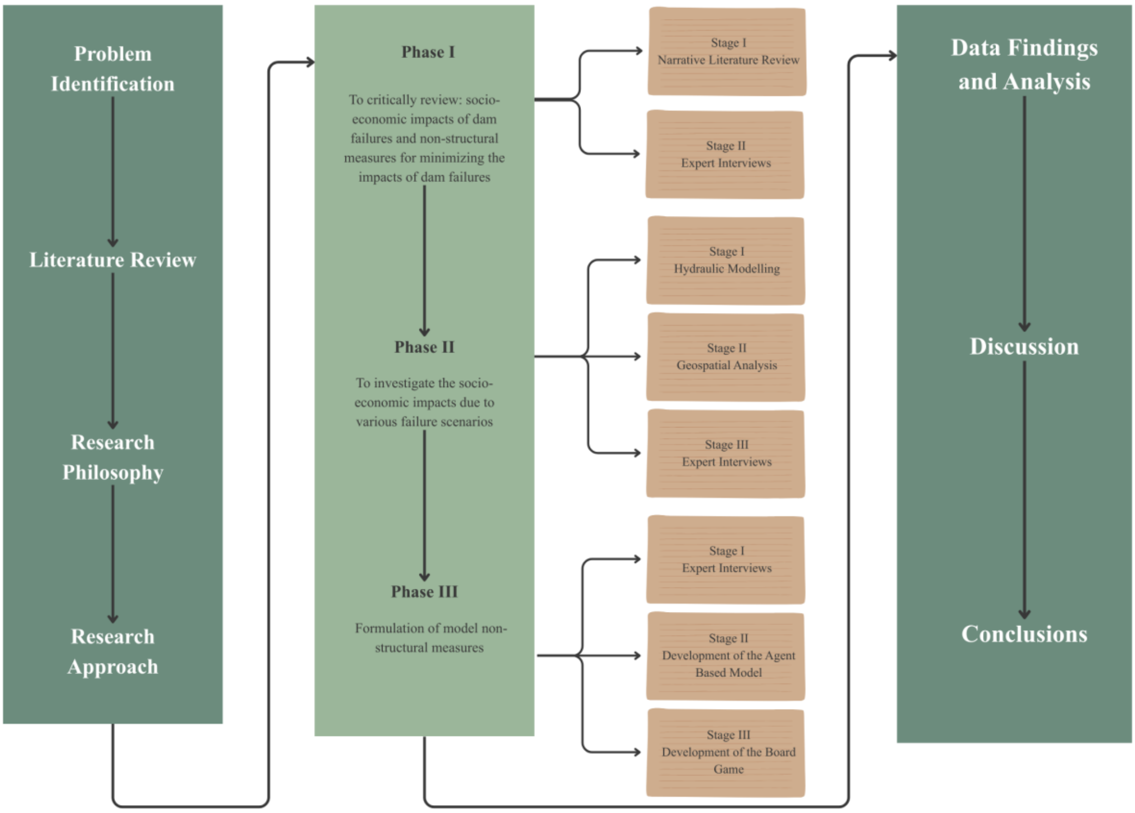


Figure 3.2 illustrates the research process adopted to ensure successful execution and completion of this study. The process was structured into five distinct phases, each of which is discussed in detail below.

3.4 Phase I: To critically review: socio-economic impacts of dam failures and non-structural measures for minimizing the impacts of dam failures

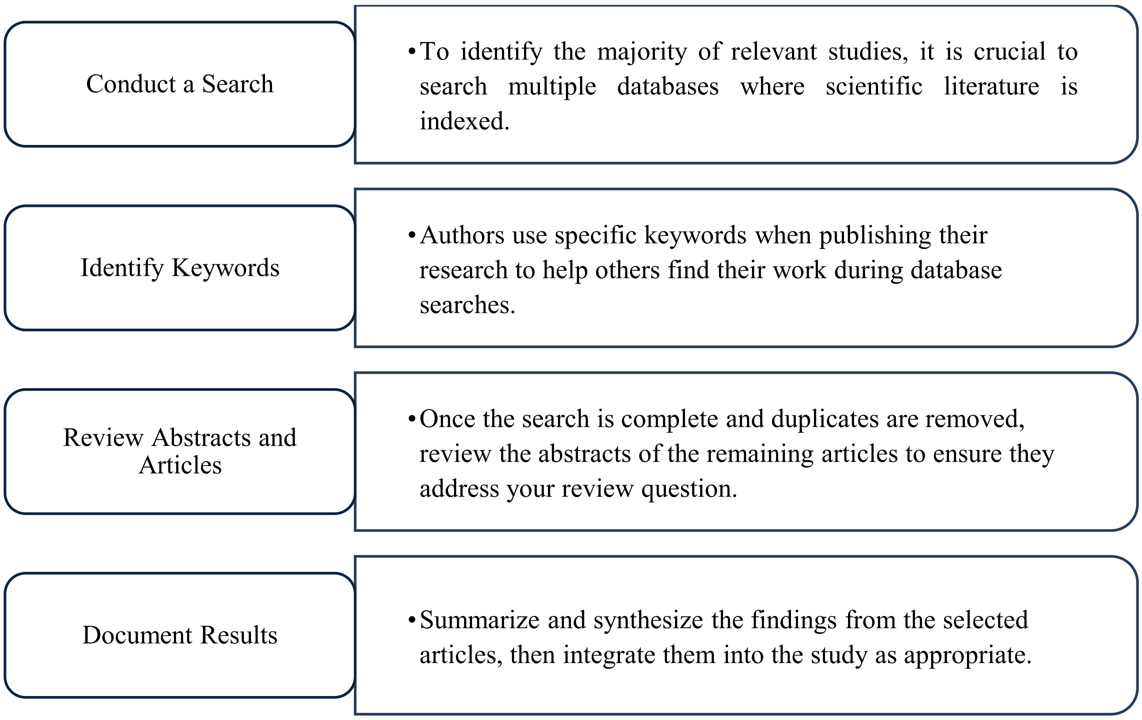
A narrative literature review was conducted to identify the socio-economic impacts of dam failures and non-structural measures for minimizing the impacts of dam failures.

3.4.1 Phase I Stage I (PI.SI): Narrative literature review

A narrative literature review, also called a traditional literature review is a critical, objective, and a comprehensive analysis of the current knowledge on a research area (Palmatier et al., 2018). The process followed to conduct narrative literature is illustrated in Figure 3.3. A narrative literature review was conducted to identify the socio-economic impact arising from dam failures and to evaluate the existing non-structural measures to prevent dam failures.

Figure 3.3

Process followed to carry out the narrative literature review



3.4.2 Phase I Stage II (PI.SII): Expert Interviews

During this phase, semi-structured interviews were conducted (see Appendix A for the interview guideline). The purpose of these interviews was threefold: to evaluate the socio-economic impacts, to validate the results of the hydraulic modelling, and to inform the game development process. The following section provides a detailed discussion of interviews as the data collection method adopted for this study.

3.4.2.1 Data collection method

There are several methods available for primary data collection, including interviews, questionnaire surveys, observations, and focus group discussions (Taherdoost, 2021). Each method has unique strengths: questionnaire surveys enable standardized data collection from large groups (Ricci et al., 2019); observations allow systematic analysis of behaviors and events in natural settings (Ruíz-Roso et al., 2020); and focus group discussions generate diverse perspectives through group interaction.

Among these methods, semi-structured interviews were employed. This approach combines predetermined questions with the flexibility for interviewer-initiated follow-up probes (Ahlin, 2019). Semi-structured interviews were deemed most appropriate because they offer a balance between structure and adaptability: they ensure coverage of key themes while allowing exploration of unexpected insights emerging from participants' responses. This flexibility made them particularly suitable for validating the findings derived from the literature synthesis, while also capturing nuanced perspectives relevant to the study context.

3.4.2.2 Sampling method

The population is the complete set of individuals, objects, or events that demonstrate the behaviors and/or have the characteristics of interest to the researcher in a research study (Berndt, 2020; Rahi, 2017). There are basically two major types of sampling methods.

Probability sampling methods – All elements in the target population have equal opportunities to be chosen in the sample (Elfil & Negida, 2017; Sharma, 2017). Generally, simple random sampling, stratified random sampling, systematic sampling, and clustered random sampling are sampling methods that can be categorized under Probability sampling methods.

Non-Probability sampling methods - Through a non-systematic process the sample population is selected which does not ensure equal opportunities for each subject in the target population (Elfil & Negida, 2017; Sharma, 2017). Convenience sampling, purposive sampling, and snowball sampling methods come under this category.

A purposive sampling strategy was employed to identify the most appropriate interviewees. Participants were selected based on their expertise and experience related to dam-related disasters, their socio-economic and environmental impacts, and the use of hydraulic modeling and spatial analysis. This ensured that the interviews captured informed perspectives directly relevant to the research objectives. Table 3.1 presents the background information of the expert interview participants.

Table 3.1:

Background information of the expert interview participants

Coding for Panel Experts	Selection Criteria											
	Compulsory Qualifications						Additional Qualifications (Satisfy at least 3)					
	5+years of Industry/ Research Experience in the following areas					Professional Experience						
	Satisfy at least 2		Satisfy at least 1									
	Disaster risk management	Dam engineering	Civil Engineering	Sociology	Early warning systems	At least 5+ years of experience in the construction industry	Having built environment related to bachelor's degree	Having built environment related professional qualifications	Having a Post Graduate Degree/ Master's related to build environment/ disaster management	Having 2+ years of experience as a researcher in the built environment/ disaster management	Involvement in dam construction projects	**Accessibility**
E1	✓	✓					✓	✓	✓	✓		✓
E2	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
E3	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
E4	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
E5	✓	✓			✓		✓	✓	✓	✓		✓
E6	✓	✓	✓		✓	✓	✓	✓	✓		✓	✓
E7	✓	✓	✓		✓	✓	✓	✓	✓		✓	✓
E8	✓	✓	✓		✓	✓	✓	✓	✓	✓		✓
E9	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
E10	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

3.4.2.3 Analysis of interview data

The primary objective of data analysis is to interpret and summarize the data (McQuitty, 2018). The initial phase of the analysis involved the transcription and organization of the research data (Stuckey, 2015). The phases of data analysis include organizing data, reducing summarizing, categorizing, identifying, and thereby linking the patterns and themes in the data (Mezmir, 2020).

3.4.2.3.1 Qualitative content analysis

There are various data analysis methods for qualitative studies such as content analysis, narrative analysis, discourse analysis, and thematic analysis. Among them, content analysis was adopted for this study to analyze the data gathered through interviews. The purpose of content analysis is to discover the underlying meaning of text through the quantification of the meaning of spoken or written language (Renz et al., 2018). This type of analysis is more useful to analyse the large amounts of verbal data that are collected through in-depth interviews or focus groups (Gill & Baillie, 2018).

3.5 Phase II: To investigate the socio-economic impacts due to various failure scenarios

This was done through Hydraulic Modelling (Stage I), Geospatial analysis (Stage II) and conducting interviews (Stage III).

3.5.1 Phase II Stage I (PII.SI): Hydraulic modelling

This stage focuses on the implementation approach adopted for hydraulic modelling in this study by considering the Kantale dam. Simulations were carried out using HEC-RAS 2D (refer Section 3.5.1.2) to model the different dam failures and to ascertain their socio-economic impacts.

3.5.1.1 Profile of the case study - Kantale dam

Kantale Dam is an important embankment Dam situated in Kantale, Trincomalee district of Sri Lanka (see Figure 3.4 As the key component of the regional irrigation scheme, the dam impounds the Per Aru River, a relatively small watercourse that ultimately discharges into Koddiyar Bay within the Trincomalee Harbour. Notably, the Kantale Dam is among the longest embankment dams in Sri Lanka, extending approximately 14,000 feet (4,267 meters) in length and exceeding 50 feet (15 meters) in height. The dam exists today even though it was built many centuries ago which proves the high level of engineering knowledge of the ancestors. It was initially designed to harness water from the Per Aru River to help supply water needs for irrigation of the encompassed farmlands. Kantale Reservoir or Kantale Tank formed by the dam has been used as a source for irrigation for thousands of hectares of paddy fields and other crops. Serving the farmers throughout the year, and particularly during the dry season, the water in the reservoir is conveyed through a network of canals.

Figure 3.4

Location of the dam

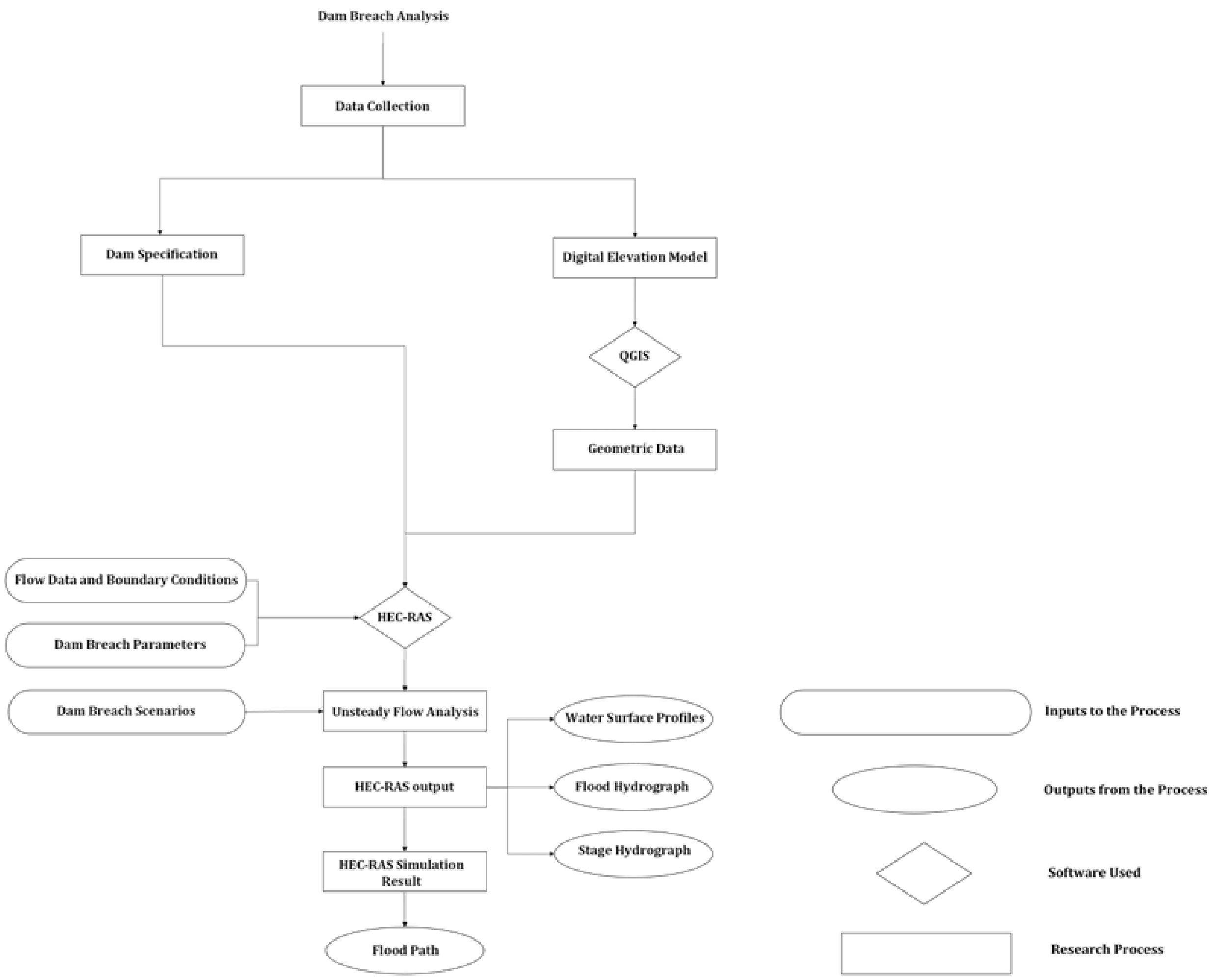
3.5.1.2 HEC RAS Simulation

As discussed in Section 2.5.3.1, the HEC-RAS 2D model provides a reliable framework for simulating dam-break scenarios and analyzing the downstream propagation of flood waves. In this study, the framework was applied to the Kantale Dam case to predict and visualize the consequences of a piping- or seepage-induced failure. Using available hydrological data, the model simulated key flood characteristics, including breach parameters, water surface elevation, flood depth, flow velocity, and flood wave arrival times at vulnerable downstream locations. Consistent with the assumptions of 2D hydrodynamic models, vertical velocities were considered negligible compared to horizontal velocities, since floodwater propagation occurs primarily in the horizontal plane.

The analysis required detailed input data, including dam geometry (type, length, height, and reservoir volume), a Digital Elevation Model (DEM) of the downstream area, Manning's roughness coefficients, and appropriate initial and boundary conditions. The simulation process involved generating the breach outflow hydrograph and flood inundation maps, which are essential for disaster planning and emergency response (Phyo et al., 2023). Key objectives included quantifying breach parameters (e.g., breach width, depth, and formation time) and tracing the propagation of the flood wave along the downstream valley (Peramuna et al., 2024). HEC-RAS, widely recognized in hydraulic studies, integrates channel geometry and bed irregularities to provide accurate estimations of flood dynamics (Bharath et al., 2021; Ferrari et al., 2023). These outputs are critical for evacuation planning, risk assessment, and mitigation strategies in communities exposed to potential dam failures. Figure 3.5 shows the process adopted to do the HEC-RAS simulation.

Figure 3.5

Process adopted to do the HEC-RAS simulation

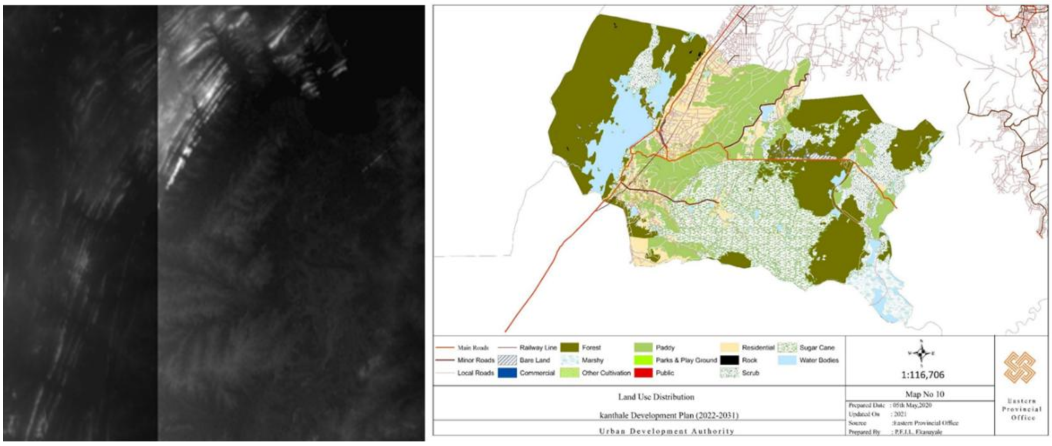


3.5.1.3 Digital Elevation Model

The Digital Elevation Model (DEM) used in the study was sourced from the USGS Earth Explorer (see figure 3.6), processed in QGIS (TIF format), and uploaded to HEC-RAS via RAS Mapper, with a uniform 50 m grid resolution and break lines to capture key flow paths, balancing hydraulic detail with computational efficiency. Although the vertical datum was not explicitly stated, USGS DEMs typically reference EGM96 geoid heights. Hydrologic inputs, including reservoir elevation–storage data and water volume, were obtained from the national dam authority, with inflows represented through the storage area boundary condition. Breach parameterization in HEC-RAS included bottom width, elevation, side slopes, formation time, and initial reservoir level, with ranges informed by literature, the historical 1986 Kantale failure, and expert judgment; three breach locations (center, left, right flanks) were tested, with the eastern flank scenario proving most severe. Authority-supplied reservoir specifications anchored the model, while breach assumptions were validated through expert interviews and historical consistency.

Figure 3.6

(a) Digital Elevation Model (DEM) and (b) Land use distribution



(a) **(b)**

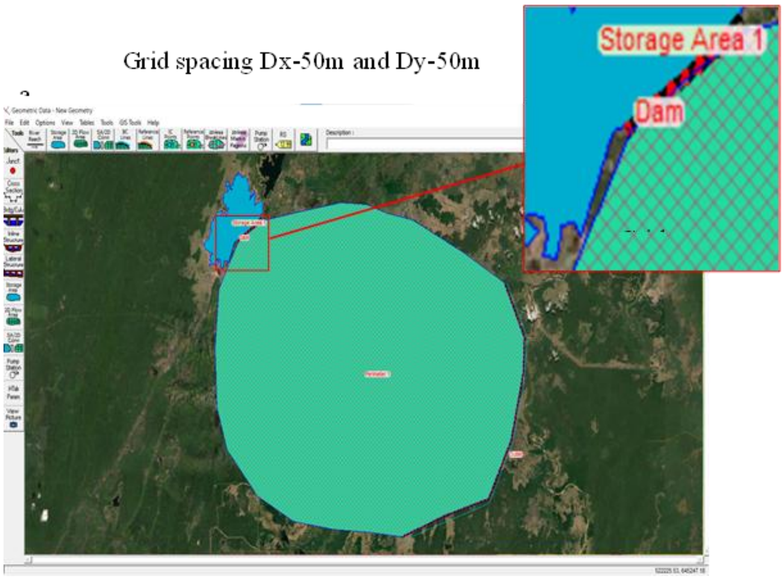
3.5.1.4 Geometric Data

In the HEC-RAS environment, geometric data were specified using the RAS Mapper. Two primary elements were defined: the downstream floodplain and the upstream reservoir. The downstream extent was delineated using the Perimeters option under the geometric data interface, while the upstream storage capacity was characterized through the Storage Area option. A hydraulic connection was then established between these two domains via the View/Edit Geometric Data function, representing the dam structure and its influence on flow dynamics.

Following this, the computational domain for the inundation analysis was developed. A boundary was defined for the floodplain, and a two-dimensional mesh was generated to represent the hydraulic processes. To balance accuracy and computational efficiency, a uniform grid resolution of 50 m was adopted (see figure 3.7), with break lines used to preserve critical flow pathways and structural alignments. This resolution was considered appropriate for the large-scale downstream floodplain, as it enabled the simulation to capture key hydraulic characteristics, including variations in water depth, flow velocity, and flood extent, without creating an excessive number of computational cells. The mesh design thus ensured both sufficient hydraulic detail and a manageable computational cost, allowing for practical runtimes and efficient data handling.

Figure 3.7

Cross-sections of the Kantale reservoir obtained from the HEC-RAS

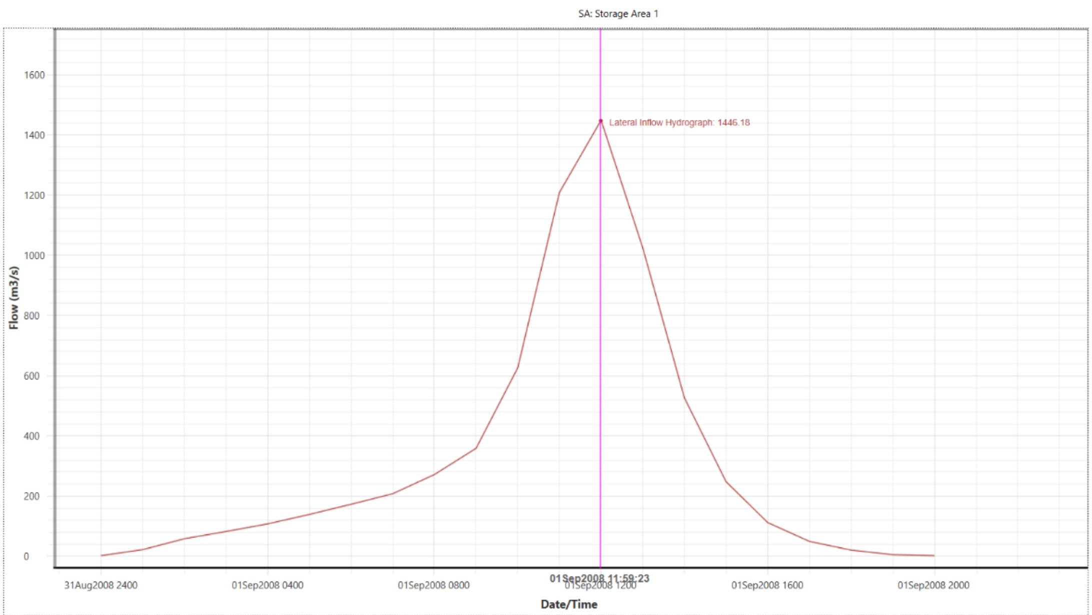


3.5.1.5 Flow data and boundary conditions

Boundary conditions are a crucial input in flood modeling, as they greatly influence the behavior of downstream floodwaters. These conditions must be selected carefully to accurately reflect the actual site conditions. In this analysis, the upstream boundary condition is represented by inflow hydrograph, specifically the probable maximum flood (PMF) hydrograph provided by the dam authority (see figure 3.8). At the inline structure, the boundary condition is defined by the time series of gate operations: the spillway gate is kept open at 0.1 m throughout the simulation period, while the sluice gate remains completely closed.

Figure 3.8

Flow data and boundary conditions

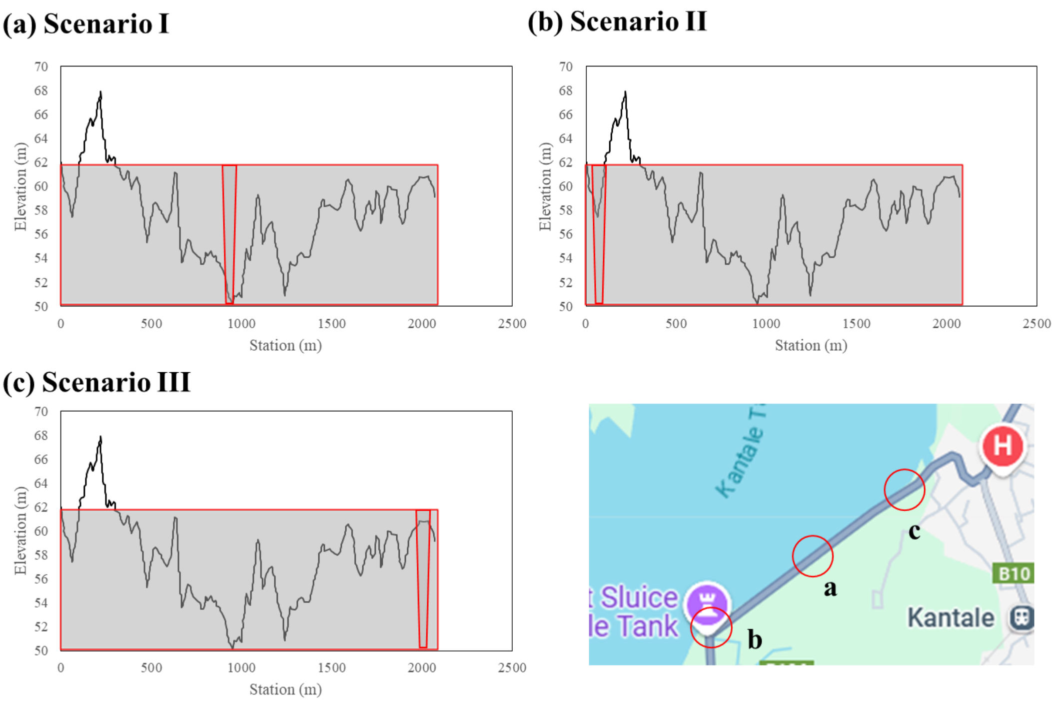


3.5.1.6 Dam Specification and Dam Breach Data

Under the dam specifications, the key parameters required include the reservoir elevation and storage volume, both of which were obtained from the Irrigation Department of Sri Lanka. In addition, several breach-related parameters must be defined for the dam-break modelling process. These include the final breach bottom width, the final breach bottom elevation, the breach side slopes, the breach formation time, and the reservoir elevation at the onset of breach initiation. These data were primarily sourced from the Irrigation Department; however, where specific values were unavailable, supplementary information was derived from comparable dams reported in the literature. Figure 3.9 represents the dam breach plot. The breach locations are taken at stations1000, 100, and 1950m and elevation of 62m.

Figure 3.9

Elevation profile along the specified station distance and the Kantale dam breach plot



3.5.2 Phase II Stage II (PII.SII): Geospatial Analysis

In the geospatial phase, socio-spatial layers were prepared in QGIS using openly available and authority-curated datasets. Building footprints were extracted from QuickOSM and cleaned for duplicates and sliver polygons; land cover came from Google Earth imagery (2022) with manual classification of vegetation, bare ground, and urban fabric; agricultural zones were digitized from Department of Agriculture maps (2021) and cross-checked against satellite imagery; and road networks were derived from OpenStreetMap (2023) and snapped to building footprints and land cover edges to ensure topological consistency (see figures 3.10 and 3.11). All layers were re-projected to a common CRS, topologically validated, and overlaid with flood depth/velocity raster's exported from HEC-RAS. Indicators were defined as: population exposure equals any building centroid intersecting inundation with depth >0.5 m at $t \leq 30$ min;

agricultural impact = crop polygon intersecting flood area with depth >0.3 m for ≥20 min; critical infrastructure (CI) impact = facility polygon (schools, hospitals, roads) located within flood polygons where velocity ≥1 m/s; and transport disruption = road segments inundated at depth >0.2 m regardless of duration. These definitions align with international flood-risk thresholds while reflecting local vulnerability profiles.

Figure 3.10

Composite planning maps illustrating the proposed land use and infrastructure strategies under the Kantale Development Plan (2022–2031). The maps depict environmental conservation zones, proposed road and transport development, existing and proposed healthcare facilities, and educational development zones

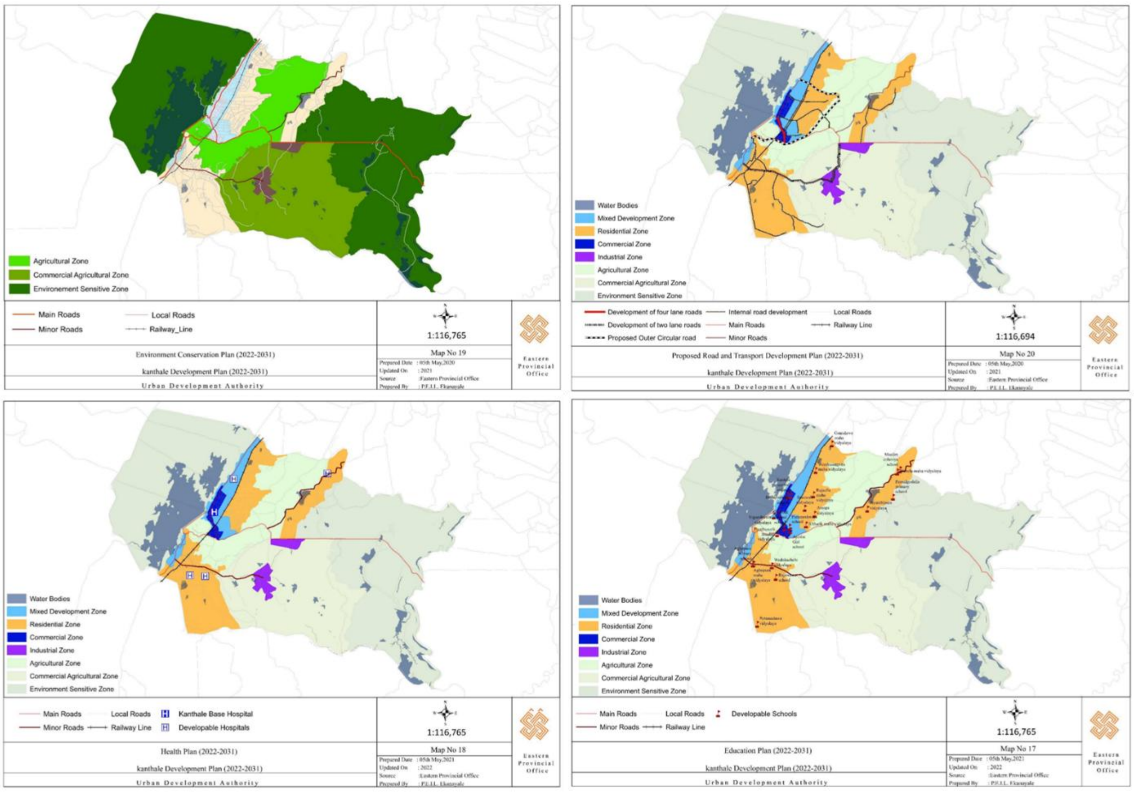
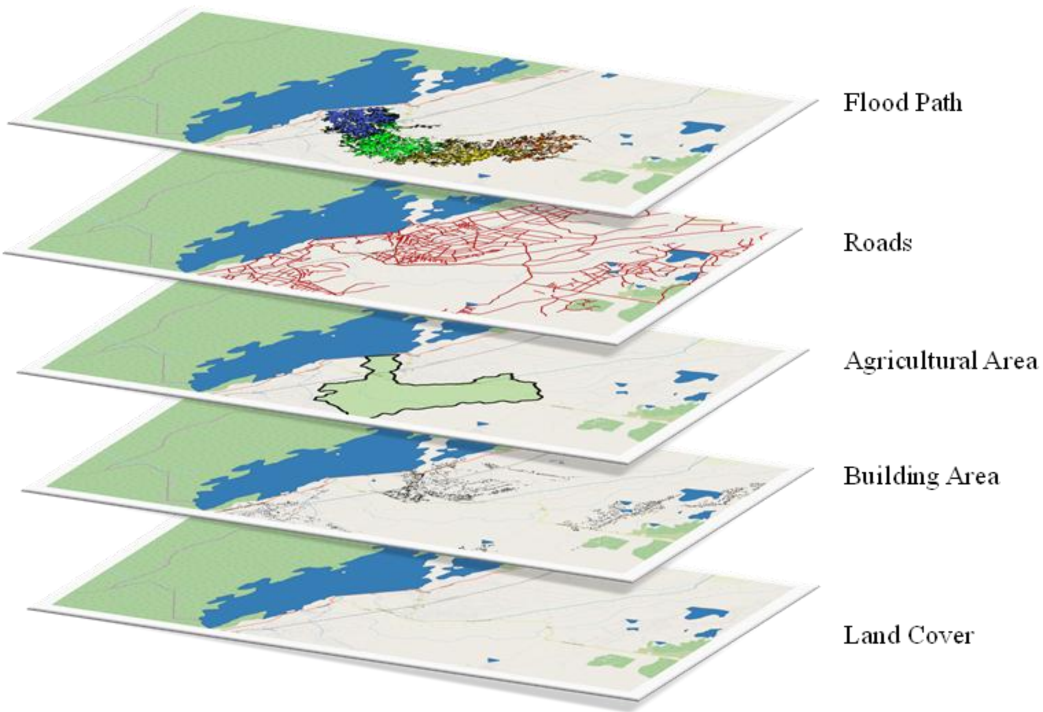


Figure 3.11

Different spatial data used for the analysis



The impact assessment was done by analyzing the intersection of the hazard and exposure layers. In this case, dam break flood maps were used as the hazard layer, and significant indicators such as population and agricultural areas were considered as the exposure layer.

3.6 Phase III: Formulation of Prototype Non-Structural Measures

The development of model non-structural measures in this study was directly informed by the findings of the literature review presented in Chapter 2 (see Section 2.5). The review identified several key approaches for mitigating dam-related disaster risks without altering the physical structure of dams, including early warning systems, evacuation planning, community education and awareness, and gamification as a novel strategy for risk communication (Seddeek, 2023; Wang et al., 2024).

3.6.1 Phase III Stage I (PIII.SI): Conducting interviews

A subset of interviews was conducted to refine the gamification component of the model. These experts were asked to evaluate and rank the decision-making pathways embedded in each player card, thereby ensuring that the board game accurately captured real-world trade-offs and supported meaningful learning outcomes for risk communication. The details regarding the interview design, sample selection, and procedure are provided in PI.SII (Section 3.4.2).

3.6.2 Phase III Stage II (PIII.SII): Development of the Agent Based Model

The Agent-Based Model (ABM) was expected to demonstrate the importance of establishing effective Early Warning Systems (EWS) in dams by simulating evacuation behaviors and outcomes under different warning scenarios.

The ABM approach is a modeling method in which individuals (e.g., people, animals, and cells) and their interaction with each other and their environment are explicitly represented (Wu et al., 2022). It has emerged as a key bottom-up approach for simulating coupled human–natural systems (CHANS) (Crooks & Heppenstall, 2012). It is a process-oriented method that represents real-world systems as open-ended, dynamic networks of interacting agents (Tesfatsion et al., 2017). In ABMs, agents are autonomous, heterogeneous, and spatially explicit, interacting with one another and their environment while being exposed to stochastic influences such as flooding (Zaharaddeen Kado et al., 2014). As active decision-makers, agents operate under decision rules that guide their choice of actions, process new information from environmental events or communication, and adapt behaviors over time (O'Connell & O'Donnell, 2014). By capturing diverse attributes, behaviors, and histories, ABMs allow researchers to explore how individual-level decisions scale up to influence community-wide outcomes (Crooks & Heppenstall, 2012).

The primary value of ABM lies in its ability to simulate emergent system-level dynamics that are difficult to capture with aggregate approaches such as system dynamics models (Bonabeau, 2002). While ABMs are often used to explain rather than predict, they are especially useful where individual decision-making strongly drives collective outcomes. As a result, ABMs have been widely applied across disciplines, including biology (Cogoni et al., 2023), ecology (Crouse et al., 2022), social sciences (Amadae & Watts, 2023), and epidemiology (Sampson et al., 2020). In flood risk management, however, the application of ABM remains relatively nascent. Most peer-reviewed studies have appeared only since 2015 (Anshuka et al., 2022; Zhuo & Han, 2020). A recent systematic review identified just 39 relevant studies, of which 20 addressed emergency management themes such as flood warnings and evacuation, while the remainder focused on long-term risk identification and adaptive strategies (Anshuka et al., 2022). As Anshuka et al. (2022) shows, over the past decade, there have been several agent-based models developed by researchers related to emergency planning for floods (Bernardini et al., 2021; Coates et al., 2019; Dawson et al., 2011; Lumbroso et al., 2023; Taillandier et al., 2021). However, these agent-based models have often been developed for specific sites, one source of flooding (e.g. fluvial, dam failure, tsunami, surface water, or coastal) and have generally only been employed in a limited research context, rather being used to inform emergency plans, strategies or risk assessments for floods or dams (Lumbroso et al., 2023).

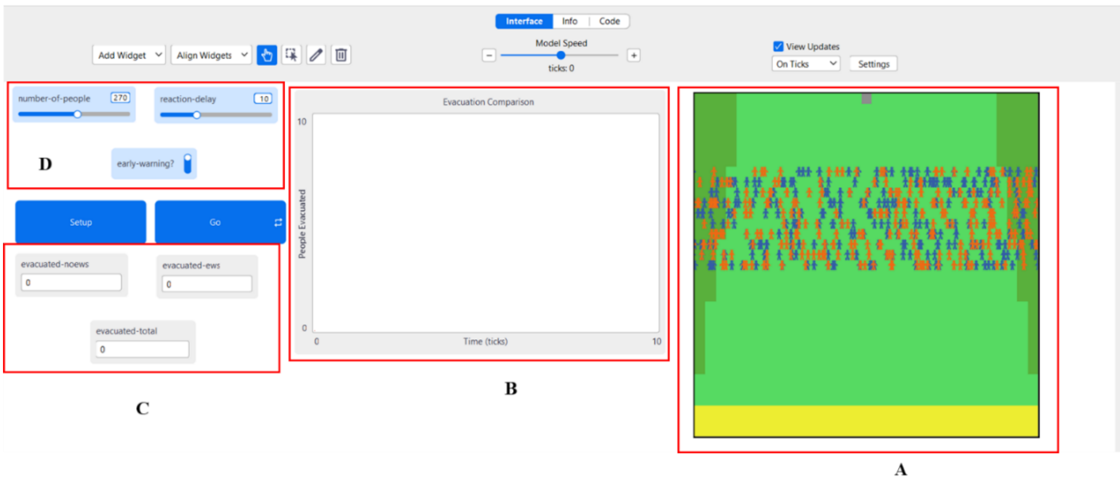
To address this gap, this study develops an agent-based model (ABM) in NetLogo, a free, open-source multi-agent programming environment created in 1999 and maintained by the Center for Connected Learning and Computer-Based Modeling at Northwestern University (Crooks & Heppenstall, 2012). NetLogo is widely used in disaster research to simulate spatially explicit human behavior, making it well suited for integrating hydrodynamic processes with heterogeneous decision-making (Crooks & Heppenstall, 2012). Its flexibility enables the coupling of physical flood dynamics with behavioral responses, advancing ABMs beyond single-case applications. Furthermore, NetLogo has proven effective for complex simulations because its built-in primitives are computationally efficient, and additional programming techniques can further enhance performance (Becher et al., 2014; Railsback & Grimm, 2019). A further advantage of NetLogo is the ease with which models can be shared, adapted, and reused, provided they are well documented. By explicitly linking dam-break inundation dynamics with agent-based evacuation behaviors, this study bridges the divide between academic modeling and practical emergency management, contributing to the development of a more generalized and operational tool for flood and dam safety planning.

3.6.2.1 Simulation Environment

Figure 3.12 shows the interface of the developed agent-based model in NetLogo. Figure 3.12(A) presents the simulation view, which visualizes the dam area, the agents, and the spread of flooding. Figure 3.12(B) displays the plot panel that records the number of people evacuated over time. Figure 3.12(C) demonstrates the evacuation outcomes, showing the number of people evacuated under different conditions. Figure 3.12(D) illustrates the model input controls, including the number of people, reaction delay, and the presence or absence of an early warning system.

Figure 3.12

Interface of the developed agent-based model in NetLogo



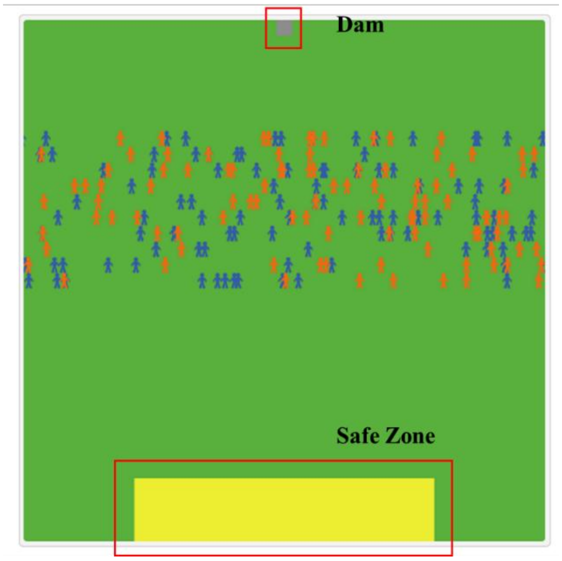
The simulation world was represented as a two-dimensional grid of patches, where each patch corresponded to a 10-meter square of real terrain. Time was discretized such that each tick equaled 0.5 minutes, enabling evacuation times to be represented at a human behavioral scale.

3.6.2.2 Environment Design

The environment was structured to include three main elements: the dam location, the valley channel, and designated safe zones (see figure 3.13). The valley represented the floodplain, where the downstream propagation of floodwater was simulated. Flood dynamics were modeled using a mean downstream velocity of approximately 2 meters per second, with lateral expansion increasing with distance from the dam. This simplified approach is consistent with generalized dam-break hydrological assumptions (Federal Emergency Management Agency (FEMA), 2013), though it does not attempt to replicate detailed hydraulics such as turbulence or wave-front acceleration. Each patch was assigned an arrival time and depth parameter, enabling the model to capture both the timing and severity of flooding across the landscape.

Figure 3.13

Major elements within the work environment



3.6.2.3 Agents and Attributes

Two agent types were defined: people and water overlays. People were the primary agents, each representing an individual at risk. Their attributes included evacuation status, membership in the EWS cohort, risk perception, reaction time, and walking speed. These behavioral characteristics were derived from empirical studies of protective action decision-making and evacuation behavior (Lindell & Prater, 2007). Reaction delays were modeled using a lognormal distribution, reflecting the skew typically observed in human response times (Lindell & Perry, 2012). Walking speed was set with a mean of 1.2 m/s and a standard deviation of 0.3 m/s, reflecting pedestrian movement data (Figueroa-Medina et al., 2023). Water overlays were introduced as secondary agents to represent flooded patches. Rather than recoloring the environment, these agents were stamped onto the map to visually communicate the advancing flood front.

3.6.2.4 Processes and Dynamics

The model incorporated several key processes to capture evacuation behavior under dam-break conditions. First, flood initiation occurred at a specified failure time, after which water spread downstream according to the precomputed arrival times and depths. Second, early warning dissemination was modeled by issuing alerts to a percentage of the population at a defined lead time. Compliance rates were set at 80%, based on observed ranges in hazard communication studies (Vallance & Carlton, 2015). Third, self-detection and social contagion mechanisms allowed non-EWS individuals to initiate evacuation if they observed nearby flooding within a defined perception radius or if a sufficient proportion of their peers began evacuating, reflecting theories of risk perception and social influence (Helbing et al., 2000). Fourth, movement dynamics directed agents toward safe zones, with speeds adjusted downward as local density increased. This rule operates congestion effects described in pedestrian flow research (Helbing et al., 2000; Hoogendoorn & Bovy, 2004). Finally, evacuation outcomes were determined at each tick: individuals who reached safe zones were recorded as evacuated, whereas those overtaken by floodwaters faced depth-dependent mortality risks, with survival assumed at shallow depths below 0.5 m and sharply increasing probabilities of fatality at depths greater than 1m when flows exceeded 2 m/s, consistent with empirical findings on flood mortality (Jonkman & Penning-Rowsell, 2008).

3.6.2.5 Outputs and Visualization

The model tracked evacuation outcomes separately for the EWS and non-EWS cohorts. Key metrics included the number of individuals evacuated and the number of casualties. Visualization was an integral component of the model: agents were animated as they moved toward designated safe zones, while a real-time plot displayed cumulative evacuations under both conditions, enabling direct comparison. This design is consistent with recommendations to combine visual and numerical outputs to enhance transparency in agent-based model reporting (Railsback & Grimm, 2019).

3.6.2.6 Validation and Experimentation

Parameter values were informed by empirical literature. Reaction delays and compliance rates were based on disaster warning and evacuation studies (Lindell & Perry, 2012; Vallance & Carlton, 2015). Flood propagation parameters were cross-checked against hydraulic modeling standards (Federal Emergency Management Agency (FEMA), 2013). Experiments were conducted by systematically varying slider parameters, including population size, flood speed, and EWS coverage, allowing for sensitivity analysis in line with established practices in evacuation modeling (Pel et al., 2012).

3.6.2.7 Sensitivity analysis

A sensitivity analysis was conducted to identify which parameters exert the strongest influence on evacuation and casualty outcomes within the ABM. This step is critical because ABMs, by design, capture nonlinear interactions and emergent behaviors that are not easily understood from first principles alone. By applying Random Forest and Gradient Boosting, the analysis translated complex simulation outputs into interpretable measures of variable importance, providing clearer insights into system behavior. The purpose of this process is therefore twofold: to enhance scientific understanding of the model dynamics and to generate actionable guidance for real-world risk reduction by highlighting where improvements in early warning, infrastructure, or flood management would yield the greatest benefits. In doing so, the sensitivity analysis both validated the robustness of the ABM and identified the most effective levers for improving survival in dam-break scenarios. The Morris Method complemented this by systematically perturbing parameters across the input space to quantify both their overall influence (via the mean of elementary effects) and their nonlinear interactions (via their standard deviation). This integrated analysis strengthens confidence in the ABM's robustness, clarifies the nonlinear mechanisms underpinning evacuation performance, and identifies the most impactful levers

3.6.2.8 Sensitivity analysis methods

3.6.2.8.1 Methodological Process of Random Forest and Gradient Boosting

The machine-learning component of the sensitivity analysis employed Random Forest and Gradient Boosting to quantify the relative importance of model parameters in determining evacuation and casualty outcomes. Both methods operate by fitting ensembles of decision trees but differ in how those trees are constructed. Random Forest uses *bootstrap aggregation*, where multiple trees are trained independently on randomly sampled subsets of the data and predictor variables. Each tree produces its own prediction, and the ensemble output is obtained by averaging these predictions. Parameter importance is then derived from the impurity reduction observed across all splits involving each parameter, providing a stable estimate of its overall contribution to model performance.

By contrast, Gradient Boosting builds trees sequentially, with each new tree trained to correct the residual errors of the previous ensemble. This stage-wise optimization allows the model to capture complex nonlinearities and interaction effects with high fidelity. Feature importance in Gradient Boosting is calculated by aggregating the improvement in model loss attributable to splits on each parameter across all boosting iterations.

In the context of this study, both methods were applied to the full set of ABM simulation outputs, enabling the translation of complex, emergent behaviors into interpretable measures of variable influence. Their combined use ensures a robust assessment, as Random Forest provides variance-reduction and stability, while Gradient Boosting offers sensitivity to subtle but influential nonlinear dynamics.

3.6.2.8.2 The Morris method

The Morris method, also known as the Method of Elementary Effects (MEE), is a global sensitivity analysis technique that provides an efficient screening approach to identify the most influential parameters in a model while requiring relatively few simulations compared to variance-based methods such as Sobol's analysis.

Let $X = (x_1, x_2, \ldots, x_N)$ denote the vector of model parameters, each of which is assigned values from the discrete set:

$$\{0, \frac{1}{p-1}, \frac{2}{p-1}, \ldots, \frac{p-2}{p-1}, 1\}$$

where p represents the number of levels, defining the p-level unit hypercube in the N-dimensional parameter space Ω. After defining the incremental step size $\Delta = \frac{1}{p-1}$, the elementary effect for the i^{th}parameter is computed as:

$$\mathrm{Ri}(\mathrm{X}, \Delta) = \frac{\mathrm{y}(\mathrm{x1}, \ldots \mathrm{xi} - 1, \mathrm{xi} + \Delta, \mathrm{xi} + 1, \ldots \mathrm{xN}) - \mathrm{y}(\mathrm{X})}{\Delta}$$

where $y(X)$is the model output evaluated at point X.

The sampling process in the Morris method involves selecting r trajectories, each composed of $N + 1$points within the parameter space Ω. At each step along a trajectory, only a single parameter is perturbed by the increment Δ, while all others are held constant. This trajectory-based design allows for efficient exploration of the input space by varying parameters one at a time, yet within a global, multidimensional context.

A key feature of this sampling approach is that each parameter, when perturbed, does not revisit previously sampled values, ensuring independence of the elementary effects. Consequently, the total number of model evaluations is limited to $r(N + 1)$, offering a computationally efficient alternative to full factorial designs. Once the sampling is completed, the parameter values are rescaled from the unit hypercube to their original ranges according to their underlying distributions, typically defined by quantiles (Roddam, 2005).

For each parameter x_i, the distribution of elementary effects R_i is obtained from the ensemble of trajectories. Two statistical measures are then derived from this distribution:

- Mean (μ): Represents the overall strength or total-order influence of parameter $x_i$on the model output $y(X)$.
- Standard deviation (σ): Reflects the variability of the elementary effects, identifying parameters that exhibit nonlinear behavior or interactions with other parameters.

In the modified version of the Morris method proposed by (Campolongo et al., 2007), the mean of the absolute values of the elementary effects (μ^*) is used instead of the signed mean μ, providing a more reliable measure of parameter importance when positive and negative effects might otherwise cancel each other out.

Parameters with high μ^*values are considered to exert a strong overall influence on the model output, while those with large σ values are indicative of either nonlinear effects or significant interactions with other variables. Conversely, parameters with low values for both $\mu^*$and σ can often be deemed non-influential within the tested range.

The Morris method thus serves as a computationally efficient screening tool for complex models, making it particularly useful in high-dimensional parameter spaces where exhaustive variance-based analyses (e.g., Sobol's method) may be prohibitively expensive.

Further methodological details are provided in Campolongo et al. (2007) and Morris (1991) which discuss theoretical foundations and performance enhancements of the approach.

3.6.3 Phase III Stage III (PIII.SIII): Development of the game board

The board game was expected to translate technical findings into an accessible format that would enhance community awareness, engagement, and preparedness for dam-break risks. This stage comprises two consecutive phases. Phase 1 involves a systematic literature review to identify existing board games related to dam-failure scenarios, while Phase 2 focuses on the development of the board game designed specifically for this study.

3.6.3.1 Systematic literature review

A literature review provides an effective means of developing a comprehensive understanding of a research domain (He et al., 2017). Among the various approaches, the systematic literature review is widely regarded as the most rigorous and structured method, making it particularly suitable for addressing well-defined research problems (Chigbu et al., 2023). Its growing popularity is attributed to unique features not found in traditional review methods, such as its capacity to minimize bias and enhance reliability (Pahlevan-Sharif et al., 2019). For this study, the systematic review approach was adopted as it enables the synthesis of evidence from diverse sources with a high degree of quality and efficiency (Pollock & Berge, 2018). This method is particularly valuable for examining the body of work on serious games developed in the context of dam failure. The primary aim of the review was to analyze existing serious games in this domain and to assess their potential as a foundation for the development of a new board game designed for dam-related disaster education.

To structure the review process, the PICO framework was employed to derive search terms. The PICO model is a widely used tool for formulating search strategies in systematic reviews (Frandsen et al., 2020). As outlined by Hosseini et al. (2024), there are two variations of this framework: PICO (Population, Intervention, Comparison, Outcome) and PICo (Population, Interest, Context), each tailored to different study characteristics. Given that the research question does not involve a comparison element, the PICo model was deemed more appropriate (see Table 3.2). Accordingly, the research question was framed as: *What serious games are available in the field of disaster management?'*

Table 3.2

Logic grid for PICo analysis of the study

PICo Component	Key terms in Question	Alternative 1	Alternative 2
P-Population	Dam Failure	Dam Break	Dam Disaster
I- Interest	Serious Games	Educational Games	Simulation Games
Co- Context	Disaster Education	Risk Awareness	Emergency Preparedness

Table 3.2 identified the key terms of the research question and contained the keywords chosen from scanning the titles and abstracts of retrieved articles in the initial search. Placing the terms into a logic grid illustrates, how the related concepts or synonyms will combine to construct the final search string (Aromataris & Riitano, 2014).

3.6.3.1.1 Search strategy

The development of the strategy was conducted using the Scopus database, because it has a wider coverage of sources (journals) compared with other databases such as Web of Science (Singh et al., 2021) and it consisted of data that is directly related to this study. The technique adopted used Boolean operators, truncations, and filters. The search string was developed using the terms of the logic grid (Table 3.2) by merging the key terms and their alternatives using "OR" along the row and merging the terms in different rows using "AND". Accordingly, the search string was formulated as.

(TITLE-ABS-KEY ("serious game" OR "educational game" OR "digital game" OR "gamification" OR "game-based learning"))

AND

(TITLE-ABS-KEY ("disaster management" OR "disaster risk reduction" OR "crisis management" OR "disaster preparedness" OR "emergency response" OR "hazard management"))

AND

(TITLE-ABS-KEY ("dam failure" OR "dam break" OR "dam breach" OR "dam safety" OR "dam disaster" OR "flood from dam failure"))

3.6.3.1.2 Eligibility criteria

It is important to have a well-established eligibility criterion when selecting sources to the study to recognize the inclusion and exclusion condition for the study and thereby to ensure the validity, applicability, and comprehensiveness of the study (Salameh et al., 2020). Table 3.3 shows the eligibility criteria prepared for selecting the sources.

Table 3.3

Eligibility criteria for selecting sources for the systematic literature review

Inclusion Criteria	Exclusion Criteria	Rationale
Sources published in English language	Sources published in other languages	English is the most widely used academic language, ensuring accessibility and consistency in analysis
Publication year from 2000 - 2023	Publication year prior to 2000.	Ensures the review captures recent developments in serious games and avoids outdated results

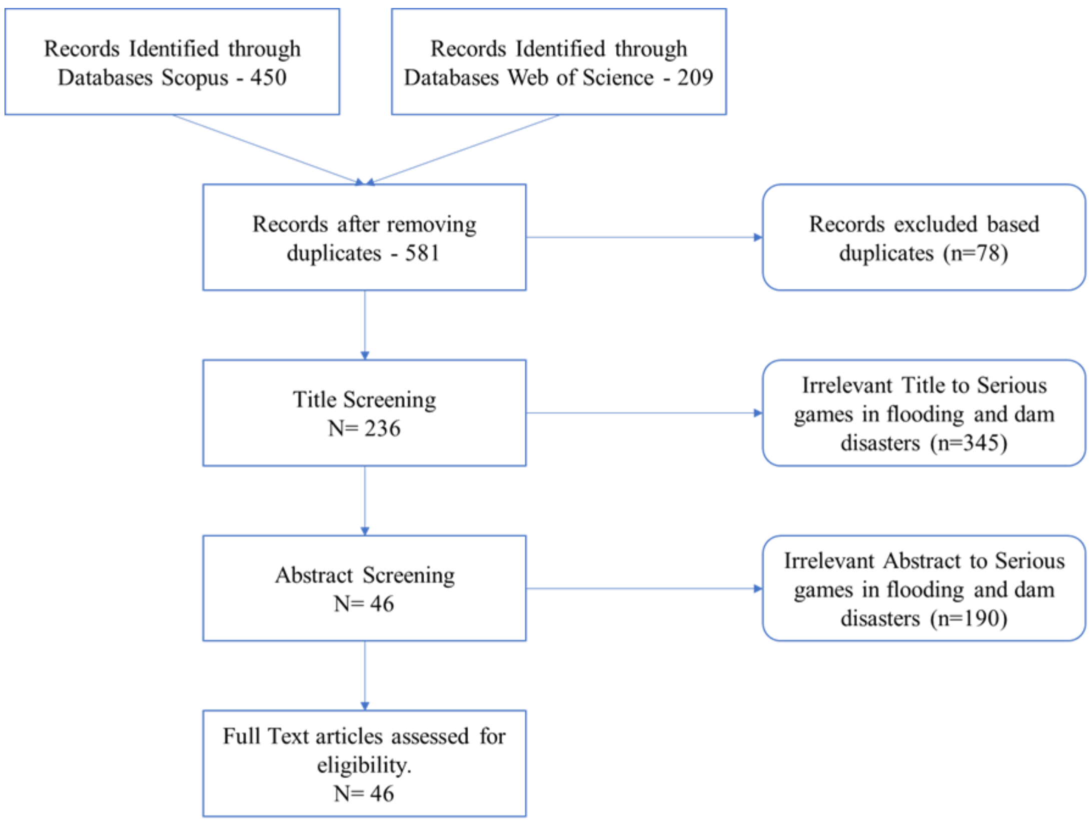
Published and unpublished sources	-	Unpublished studies may contain the latest findings and innovative approaches not yet available in formal publications
Research areas: Serious Games, Dam Failure, Disaster Education, Risk Communication, Emergency Preparedness	Research areas: General Gaming, Non-disaster-related Education, Policy and Regulation, Economic Aspects	Focus is limited to serious games directly related to dam failure and disaster education
Document type: Articles, Conference Papers, Book Chapters, Reviews, Books	-	Allows comprehensive coverage of academic and practical knowledge on the topic-

3.6.3.1.3 Study selection and data extraction

The title, abstract, keywords, authors' names and affiliations, journal name, and year of publication, access type, and source name of the identified records were exported to a MS Excel spreadsheet (CSV format). The selection procedure of the articles is illustrated in Figure 3.14.

Figure 3.14

Study selection flow diagram



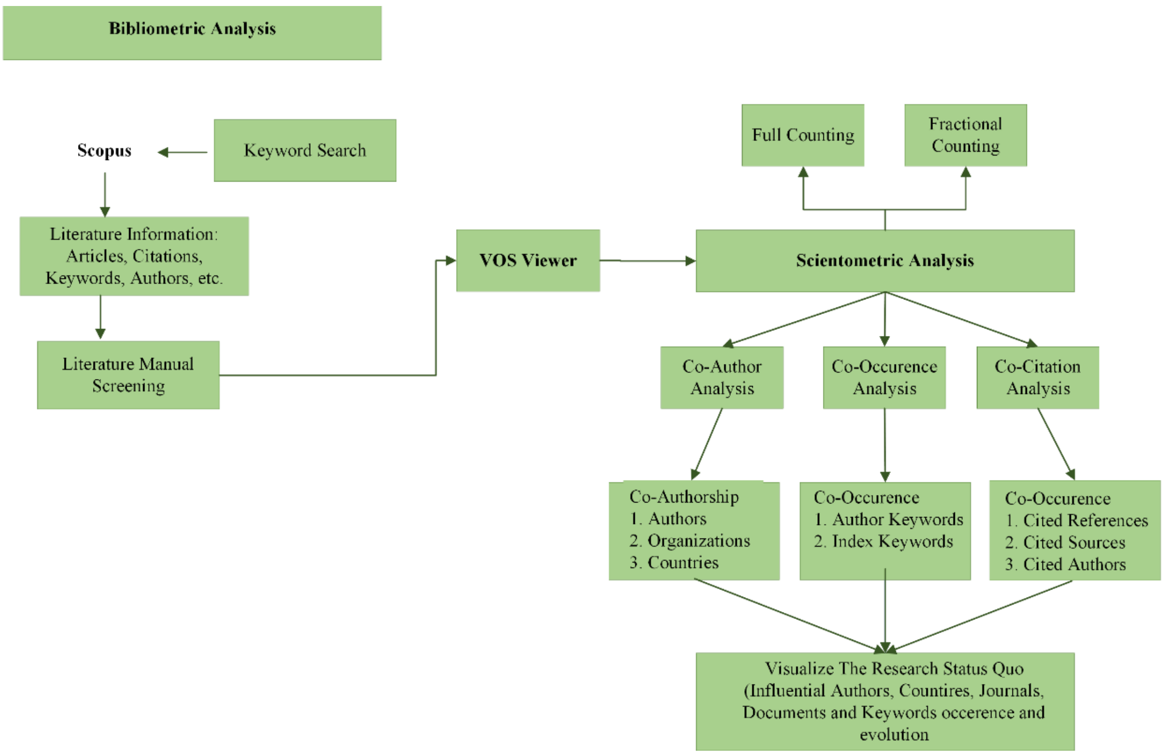
As per Figure 3.14, the initial database search identified 659 records from Scopus. After the removal of duplicates, 78 records were excluded. During the title screening stage, 345 records were excluded due to their lack of relevance to the study. Subsequently, 190 records were excluded following abstract screening. Ultimately, 46 articles were retained for in-depth analysis.

3.6.3.1.4 Scientometric analysis

Scientometric analysis is a method where it includes measuring the research impact, mapping the knowledge structure, understanding the citation process, and evolutions in a domain based on the comprehensive academic dataset (Zhong et al., 2019). Figure 3.15 illustrates the process of Scientometric analysis that was adopted for the study.

Figure 3.15

Process of Scientometric analysis that was adopted for the study



In this study, VOSviewer was employed as a scientific mapping tool. VOSviewer facilitates distance-based bibliometric network visualization, allowing for the identification of relationships between research concepts. Figures 4.11 illustrate the mainstream research keywords and their interconnections. The keyword co-occurrence networks represent statistical associations between terms, visualized as interconnected clusters (Farooq, 2022). These clusters highlight research focus based on the strength of keyword correlations, thereby providing insights into the progression of knowledge within the subject area (Oladinrin et al., 2023). For the analysis, the study applied the settings of “all keywords” with “full counting,” establishing a minimum keyword occurrence threshold of five. As shown in Figure 4.11, 61 out of 1,545 terms met this criterion.”

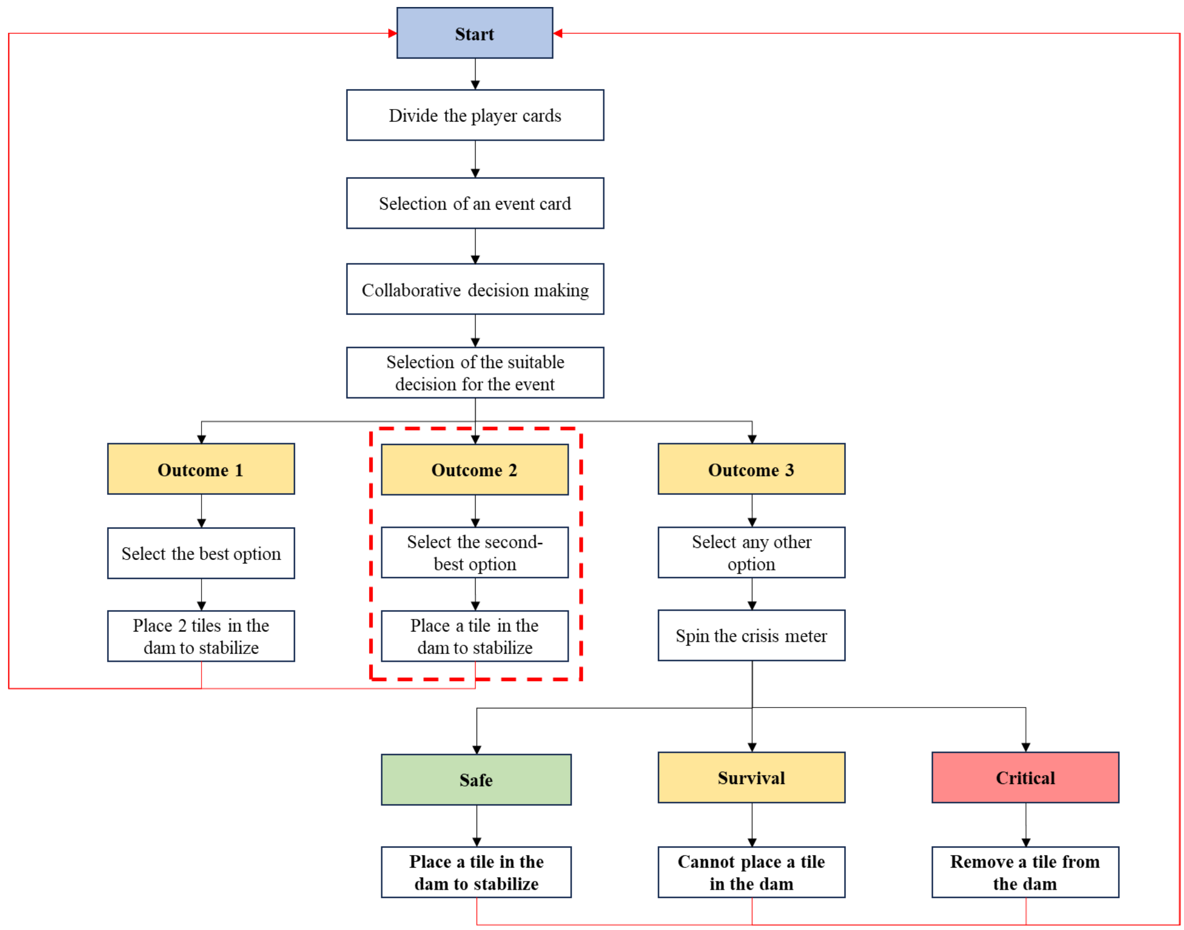
Bellotti et al. (2010) emphasize that the design of effective serious games must follow a set of guiding principles to ensure both engagement and the successful achievement of educational goals. The first step is to clearly define the learning objectives and align them with the game mechanics, meaning that designers must identify the specific knowledge, skills, or behaviors the game intends to develop and embed these within gameplay. For example, a game aimed at building emergency management competencies should present realistic scenarios that require players to apply and practice those skills in simulated conditions. Second, the game must be inclusive, accessible, and user-friendly for a wide range of players, considering variations in cultural background, physical ability, and cognitive capacity so that it is genuinely adaptable to diverse user needs. Third, the design should be immersive and appealing to the target audience, incorporating engaging narratives, compelling visual and audio features, and interactive mechanics that sustain attention and motivation. Finally, effectiveness must be ensured through the integration of assessment and evaluation components that measure whether the intended learning outcomes are achieved.

3.6.3.2 Development of the board game mechanism

The first step of developing the board game was to outline the game mechanism. Figure 3.16 shows the initial mechanism developed for the board game.

Figure 3.16

Game board mechanism



This flowchart illustrates the mechanism of the board game, where players begin at the Start and progress through a series of decisions or challenges that determine their path. Each choice or event leads toward one of three Outcomes (Outcome 1, Outcome 2, or Outcome 3), which then maps into the game's final states of Safe, Survival, or Critical. These states reflect the player's condition or status in the game, Safe indicating stability, Survival representing a risky but manageable situation, and Critical signaling severe danger or near loss. The red feedback loop shows that after reaching an outcome, players re-enter the cycle, making the game iterative and dynamic, where every round reevaluates the player's standing based on new decisions.

3.6.3.3 Development of board game designs

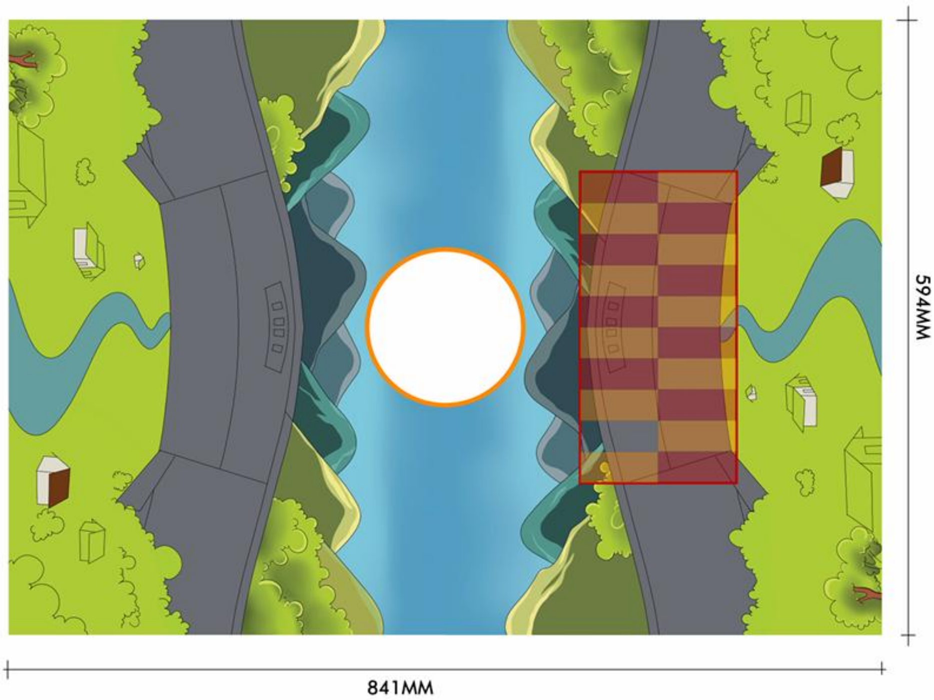
The second step, following the development of the game mechanism, was the design of the board itself. The board design was developed through an iterative process, during which multiple design versions were created, tested, and refined based on feedback from supervisors and peers.

3.6.3.3.1 Conceptual Foundation

Figure 3.17 shows the initial sketch of the board design.

Figure 3.17

Conceptual design of the board game



3.6.3.3.2 Development of Conceptual Design

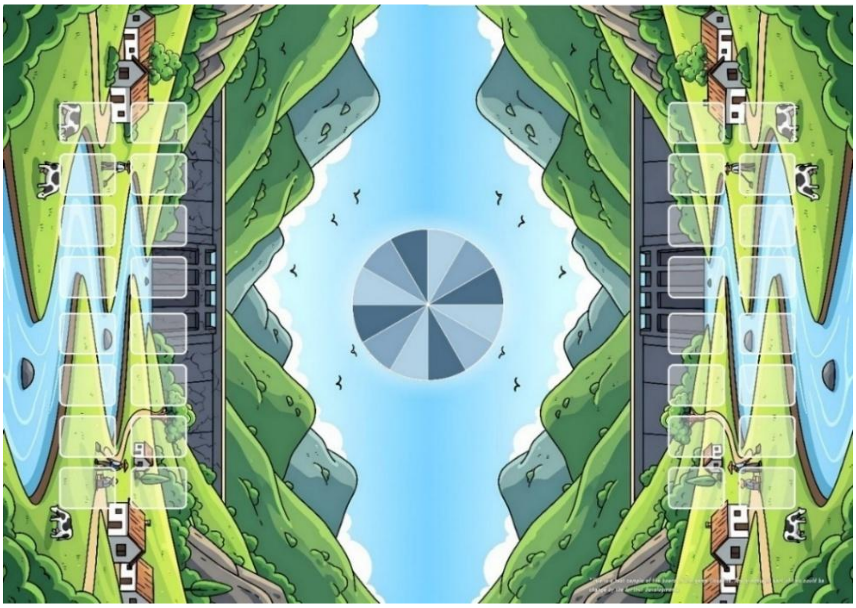
The conceptual design of the board began with establishing the core narrative and spatial framework. The village of Riverbend and its dam served as the central motif, symbolizing both security and vulnerability. In this phase, the emphasis was on constructing a visual metaphor that captured the tension between human settlement, engineered infrastructure, and the natural environment. The dam was positioned as the dominant structural element, bisecting the composition and anchoring the unfolding narrative of risk and resilience. Surrounding it, the river and village landscapes were sketched in exaggerated proportions to ensure immediate recognition of the stakes involved. The conceptual design also established the idea of the board as a storytelling surface, rather than a neutral background, embedding narrative cues, such as rising waters and clustered houses, into the spatial arrangement. This phase prioritized clarity of theme and symbolism, creating a foundation where function and story could converge.

3.6.3.3.3 Development of Detailed Design

In the detailed design stage, the abstract spatial layout evolved into a more refined system of zones, overlays, and illustrative elements (see figure 3.18). Iterative prototypes tested how functional clarity could coexist with thematic immersion. At this stage, environmental and human-scale details were added, houses, farmland, and livestock, to personalize the stakes and reinforce the narrative of a community at risk. The cartoon-like aesthetic was deliberately chosen and refined during this phase, balancing the seriousness of dam failure with a style that was approachable for diverse audiences, including children. The exaggerated curves of the river, the stark geometry of the dam, and the vibrant palettes were all decisions aimed at ensuring readability, emotional accessibility, and visual engagement. The detailed design stage thus translated conceptual themes into a playable, legible system of visual storytelling.

Figure 3.18

Detailed design of the game board

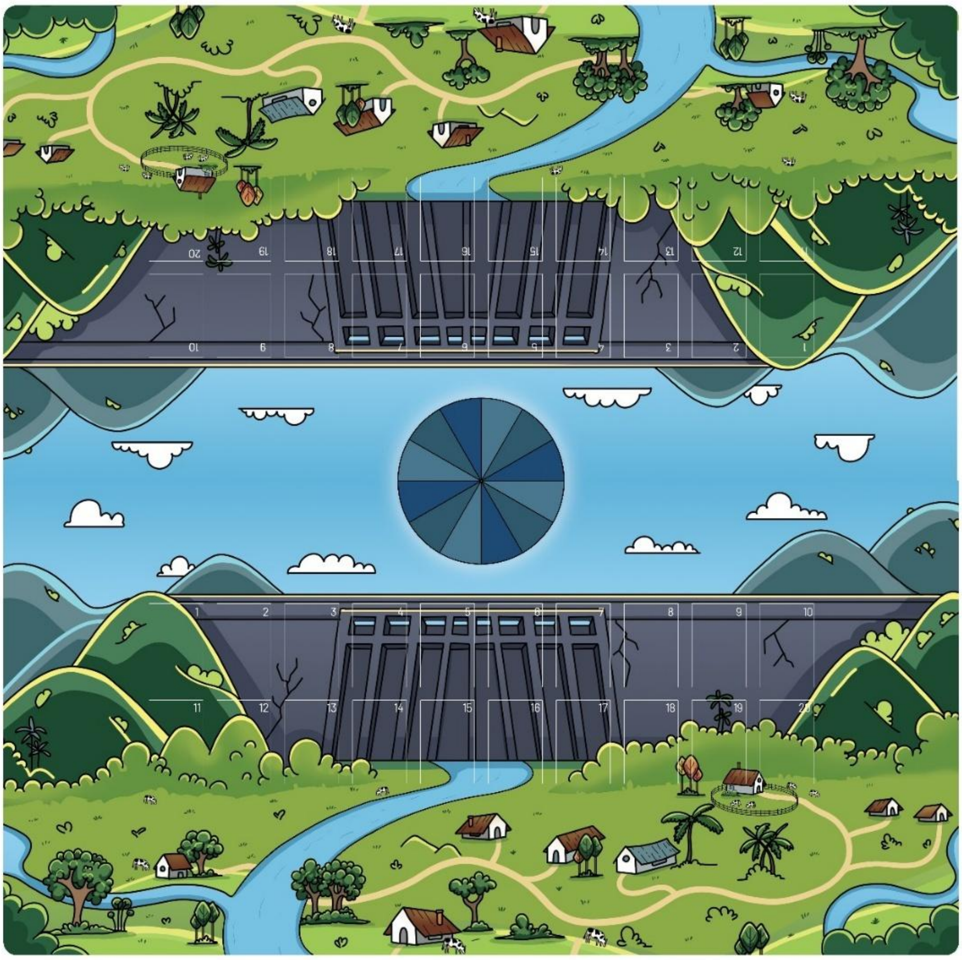


3.6.3.3.4 Development of Final Design

The final design synthesized narrative immersion and mechanical clarity into a cohesive board. Numbered overlays were integrated directly into the dam structure, enabling them to function both as a dramatic focal point and a mechanic for tracking cracks and breaches. The central circular hub was developed as a spinner to evaluate the criticality of the decisions made by each team. The villages and farmlands, now richly illustrated, provided both aesthetic grounding and functional zones for evacuation and resource placement. Importantly, the exaggerated, playful style remained intact, reducing the emotional load of the disaster theme while maintaining urgency through symbolic cues. The final design achieved a balance where every visual element carried dual meaning, narrative and functional, ensuring that the board operated as an active participant in gameplay rather than a static background. Through iterative refinement, the board emerged as a powerful example of how visual design can embody story, mechanics, and pedagogy within a single artifact. Figure 3.19 demonstrates the final design of the board game.

Figure 3.19

Final board design



3.6.3.4 Development of the player cards

Four main player cards were developed with four characters, dam engineer, evacuation specialist, government official and city planner (see figure 3.20).

Figure 3.20

Front view and rear view of the player cards

Each player was provided with six possible decisions to consider in response to a specific event. These decisions were systematically derived from two sources: a review of existing literature on dam safety, risk management, and emergency response, as well as a series of expert interviews with practitioners in civil engineering, urban planning, and disaster management. The integration of scholarly evidence and professional expertise ensured that the decision options reflected both theoretical validity and practical applicability.

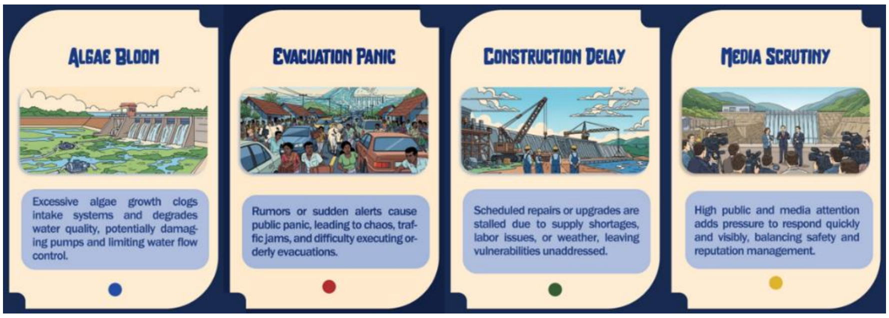
Following data collection, the identified decisions for each event were subjected to a ranking process. Experts evaluated the options according to their effectiveness, feasibility, and potential consequences. This resulted in a structured hierarchy of responses for each event card, ranging from the most effective decision to those with the least impact (see Appendix B for the events and the decision ranking for each player card). By embedding this ranking into the game design, players were challenged not only to act quickly but also to critically evaluate the trade-offs between different courses of action. This method grounded the gameplay in real-world decision-making dynamics while preserving accessibility and engagement through simplified choices.

3.6.3.5 Development of the event cards

The event cards were developed as a critical extension of the board, providing narrative variability and unpredictability to simulate the escalating pressures faced during a dam emergency. A total of twenty cards were created, each representing a unique scenario that challenged the players to act within their designated roles (see figure 3.21).

Figure 3.21

Event cards



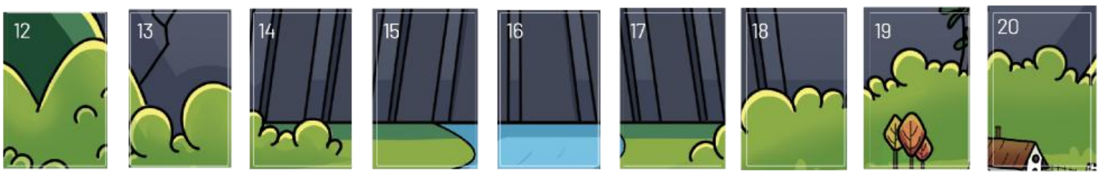
During the detailed design phase, scenarios were categorized across thematic domains such as structural failure, environmental stressors, political interventions, and community disruptions. For instance, one card might describe sudden vibrations shaking the dam wall, requiring the Dam Engineer to mobilize resources, while another could present a political directive that forces the Government Official into difficult trade-offs. The inclusion of both technical and socio-political challenges underscored the multi-layered nature of disaster management, reflecting real-world complexity while still being accessible through a simplified, playable format.

3.6.3.6 Development of the dam tiles

Furthermore, twenty structural tiles were developed as an additional design component to reinforce the board's interactive dimension (see figure 3.22). When a team successfully wins a round, they are granted the opportunity to place a tile into their section of the dam. Conceptually, the tiles operate as a metaphor for repair and reinforcement, visually and physically indicating the stabilization of the dam through collective action. Designed in the form of interlocking puzzle pieces, the tiles can be fitted directly into designated slots on the board. This mechanic not only provides a tangible sense of progress but also symbolizes the incremental nature of disaster mitigation and resilience building.

Figure 3.22

Tiles that will be placed after winning a round to indicate stabilizing the dam



From a production standpoint, the tiles were fabricated through laser cutting, ensuring precision, durability, and aesthetic consistency with the board. The choice of laser cutting allowed the pieces to be both functional, as snugly fitting components that lock into the dam, and visually appealing, with clean edges that harmonize with the cartoon-like style of the overall game. The tactile act of placing tiles served as an embodied representation of stabilization, reinforcing the link between strategic decision-making and visible outcomes within the game space. This design choice strengthened immersion by making the abstract notion of "securing the dam" a physically enacted achievement.

3.6.3.7 Conducting piloting programs

Following the development of the board game, a series of pilot studies were conducted to identify potential errors in the game's mechanisms and components, as well as to evaluate its educational effectiveness. These pilot programs were designed as iterative testing phases, enabling refinement of the game through feedback and structured evaluation.

3.6.3.7.1 Pilot Study 1

The first pilot study was carried out with a group of researchers at the University of Moratuwa. Two separate sessions were conducted with two distinct groups of participants. At the conclusion of each session, participants were provided with a structured questionnaire designed to capture their perceptions and recommendations for improving the game. The feedback obtained during this stage was primarily used to identify and rectify errors in the mechanics, rules, and overall design of the board game.

3.6.3.7.2 Pilot Study 2

Building on the findings of Pilot Study 1, a second pilot study was conducted with a larger sample of undergraduate students. A total of three sessions were held with 30 participants. The objective of this phase was not only to test improved game design but also to compare the effectiveness of game-based learning against traditional lecture-based education. In each session, students first attended a lecture on dam failure and appropriate response measures, followed by an opportunity to engage with the board game as an experiential learning tool.

After the gameplay sessions, participants completed a detailed questionnaire assessing their learning experience and the perceived impact of game-based education compared to lecture-based instruction (see appendix C and D for questionnaires used for each pilot study). The data collected from these questionnaires were analyzed using SPSS statistical software to identify trends, measure effectiveness, and provide insights into the pedagogical value of the board game.

3.7 Chapter Summary

This chapter outlined the study's methodological framework, beginning with the research design and the rationale for a pragmatist, mixed-methods approach. It summarized the narrative and systematic literature reviews; the Kantale Dam case study using hydraulic modelling and geospatial analysis; the development of an agent-based model (ABM) to simulate community behaviors during dam-breach scenarios; and the use of semi-structured interviews to validate outputs, assess socio-economic impacts, and inform the board game's development. The chapter concluded with the iterative design and testing of the board game, demonstrating the integration of quantitative and qualitative methods to examine dam failures, their impacts, and community preparedness strategies.

4 CHAPTER 04: RESEARCH FINDINGS AND ANALYSIS

4.1 Chapter introduction

This chapter presents and analyzes the findings of the study in relation to the research objectives. It covers results from the systematic literature review, hydraulic modelling and geospatial analysis of the Kantale Dam, expert interviews on socio-economic impacts and non-structural measures, Agent based model, and the piloting of the board game. Together, these findings provide a comprehensive understanding of dam failures and evaluate the effectiveness of innovative approaches for enhancing community preparedness.

4.2 Phase I: To critically review: socio-economic impacts of dam failures and non-structural measures for minimizing the impacts of dam failures

4.2.1 Findings of PI.SI: Narrative literature review

Please refer to section 2, for the findings of the narrative literature review.

4.2.2 Findings of PI.SII: Expert interviews

Expert interviews were conducted to identify the critical role of non-structural measures in risk reduction failure and as a basis for developing the agent base model and the board game.

4.2.2.1 The Critical Role of Non-Structural Measures in Dam Failure Risk Reduction

Dam failures, while rare, pose catastrophic risks to human life, critical infrastructure, and ecosystems. As structural reinforcements alone cannot eliminate failure risks, especially in aging dams, high rainfall areas, or zones vulnerable to seismic activity, non-structural measures have emerged as essential pillars of dam safety and disaster resilience. Drawing upon insights from ten domain experts, this analysis synthesizes the most crucial non-structural strategies to prevent, mitigate, and respond effectively to dam-related disasters.

Accordingly, E1 stated that accurate flood hazard maps and dam breach inundation simulations form the scientific foundation for non-structural preparedness. By delineating high-risk zones, these maps inform urban planning decisions, zoning regulations, and emergency response planning. In developing countries where rapid urbanization encroaches into floodplains, such spatial intelligence is critical to prevent future vulnerabilities. Similarly, E3 stated that:

"In my experience working with reservoirs in the Mahaweli Basin, lack of localized and regularly updated flood maps leads to misinformed development in vulnerable areas. Therefore, hazard mapping is not just a planning tool, it is a life-saving instrument."

Furthermore, E2 stated that Early Warning Systems represent the frontline of defense in dam safety. A well-integrated EWS involves the deployment of sensors on dams to detect abnormal reservoir behavior, such as rapid drawdown, unusual seepage, or seismic activity. E2 further explained:

"In the Columbia River Basin, our trials showed that unless warning messages are understood and trusted, evacuation rates remain low."

Therefore, a robust EWS includes technical instrumentation, decision-making protocols, public interface tools, and redundancy layers to prevent single-point failure.

Emergency Action Plans are formal documents that outline step-by-step procedures to follow during a dam emergency. E1 and E4 stated that These plans identify at-risk zones, command structures, roles of response teams, and communication channels. Each EAP must be site-specific. Further explaining E5 stated that:

"At Victoria and Rantembe dams, we conduct annual reviews and mock drills to ensure preparedness. A common issue in Sri Lanka is that EAPs are treated as documentation rather than living instruments of safety."

Moreover, E6 stated that evacuation route planning is more critical when it comes to preventing life loss in dam failure incidents. E2 stated that:

"Evacuation is where life is either saved or lost."

For dams, time is critical, flood waves can travel tens of kilometers in hours or even minutes. Therefore, evacuation routes must be optimized for both time and capacity. Elaborating further E7 stated that at Oroville Dam, gaps in route planning led to chaos. Planners must simulate worst-case scenarios, identify road obstructions, and designate alternate paths. Evacuation drills involving real communities are essential to reveal and fix practical flaws.

Furthermore, all the experts unanimously emphasized that public awareness and education concerning dam failures must be regarded as a top priority. They highlighted that empowering communities with knowledge, preparedness strategies, and clear communication channels significantly enhances resilience and reduces the potential loss of life during dam-related emergencies. E9 specified that one of the most effective non-structural tools has been participatory community engagement through localized awareness programs. In addition to that, E8 specified that education is most impactful when it's repeated, contextualized, and emotionally resonant. For example, using local flood survivors as storytellers created strong engagement. E2 and E5 stated that children are powerful change agents. Integrating dam safety, flood response, and evacuation knowledge into school curricula builds generational awareness.

4.3 Phase II: Investigate the socio-economic impacts due to various failure scenarios

Phase II demonstrates the results of hydraulic modelling and expert interviews for assessing the impacts of various dam failure scenarios.

4.3.1 Findings of PII.SI: Hydraulic modeling

This section presents the results of hydraulic modelling, specifically focusing on the flood hydrograph and stage hydrograph, which outline the flood water's path and its impact on surrounding areas. The simulations illustrate multiple breach scenarios, including failures from the center and corners of the dam. These scenarios highlight the areas affected by floodwater, with significant implications for Kantale town.

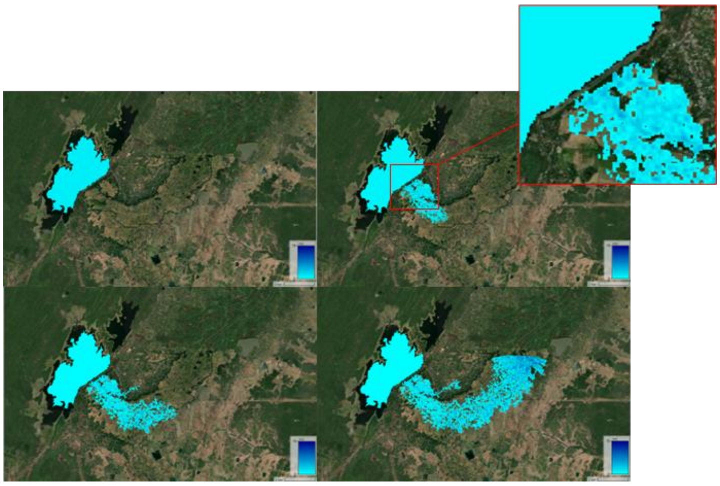
The results are presented to visually and analytically assess the flood path and to determine which areas would be impacted by using hydraulic modeling and simulation techniques. This approach aids in assessing the potential socio-economic impacts of dam failures, with a focus on enhancing disaster preparedness and planning. By identifying the regions vulnerable to floodwaters, these simulations provide valuable insights into minimizing socio-economic risks and preventing future developments in high-risk zones, directly supporting the study's goal of promoting sustainable disaster management practices.

4.3.1.1 Scenario I

Figure 4.1 illustrates the path of the flood water if the dam fails from the center of the dam. It clearly shows the area that is affected by the flood. These simulation techniques offer a novel approach for preplanning to mitigate such disasters from occurring. Especially to identify the affected areas and to prevent any development around those areas.

Figure 4.1

Flood inundation map arises from a dam breach at center point

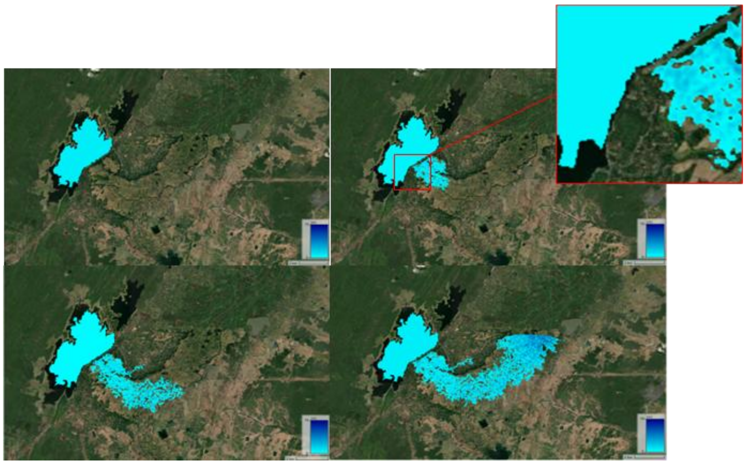


4.3.1.2 Scenario II

Figure 4.2 demonstrates the path of the flood water if the dam fails from the left flank of the dam. The resulting flood propagation follows a pattern broadly like that of Scenario I, but with an important distinction: only a limited volume of water reaches Kantale town, producing comparatively lower levels of inundation and impact within the urban area.

Figure 4.2

Flood inundation map arises from a dam breach in left flank

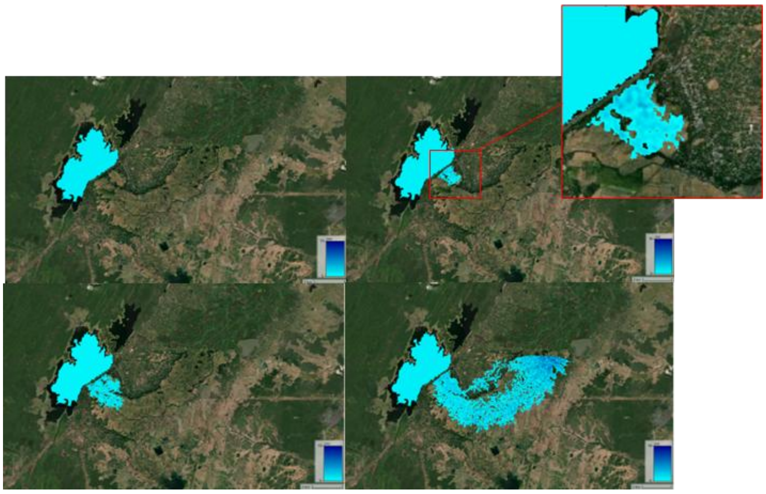


4.3.1.3 Scenario III

Figure 4.3 illustrates the path of the flood water if the dam fails from the right flank of the dam. In the previous two cases there was a small water flow impacting Kantale town whereas, now it can be seen that there is significant impact on Kantale town as there is a water path going through the town.

Figure 4.3

Flood inundation map arises from a dam breach from the right flank



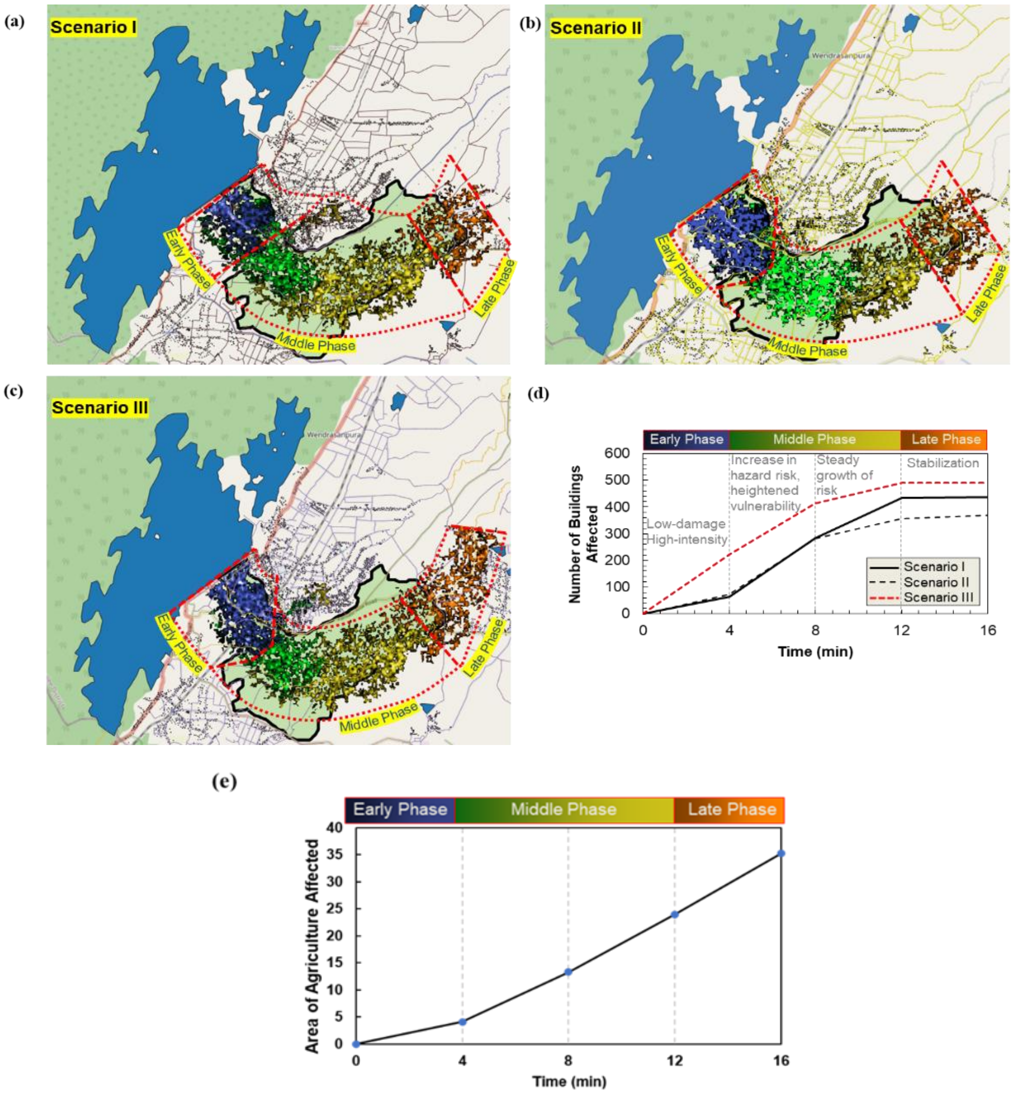
4.3.2 Findings of PII.SII: Geospatial analysis

The geospatial analysis revealed distinct inundation patterns across the three dam breach scenarios (Figure 4.4). When the breach occurs at the center (Scenario I), the flood stabilizes relatively early and produces lower risk, whereas a left-flank breach (Scenario II) results in moderate progression. In contrast, the right-flank breach (Scenario III) generates the most severe and widespread impacts, mirroring historical flood behavior. The cumulative hazard curve (Figure 4.4d) illustrates these dynamics clearly, showing how damage evolves more rapidly and extensively under Scenario III. Beyond immediate structural losses, all scenarios channel floodwaters through Kantale's agricultural zone (Figure 4.4e), inundating 35.22 km² of farmland. This extensive damage to paddy fields not only threatens food security but also disrupts the region's microeconomy, with compounding impacts on local livelihoods. Building exposure along the flood path further underscores the dual risk to both households and agriculture, reinforcing the importance of integrating hazard mapping with socio-economic planning.

The spatial dissemination is relatively low in the first condition, intermediate in the second condition, and high in the third condition. The concentrated impacts early on, outward spread in the middle phase, and peak hazard extent in the late phase, with Scenario III showing the broadest coverage, indicate that while Scenario III has a steep hazard curve, it is spatial, delaying stability and requiring early intervention. Scenarios with low hazard curves show that effective hazard management measures are adopted. Moderate intervention is needed for scenario II, most of which may be required in the middle phase.

Figure 4.4

Geospatial and temporal analysis of the hazard: (a) (b) and (c) Spatial extent of hazard (d); Cumulative hazard curve (e); Agricultural impact



4.3.2.1 Scenario I

As shown in figure 4.4 (d), the hazard curve goes through a gradual, not-very-steep rise in the initial period (from 0 to 4 minutes - early phase). This can be regarded as the initial development of flooding wherein the advance is slow, and the flood begins to spread into the area affected. From 4 to 8 minutes, the curve becomes much steeper, rapidly impacting a greater number of buildings. During this phase, the flood probably reaches highly concentrated structures and thus gives a steep upward slope in cumulative damage. It is the most critical phase, as the rate of impact is maximum. During the next 8-12 minutes (middle phase), the rate of rise is upward and is slower compared to the previous phase. Although the inundation is still in progress, the number of newly impacted buildings is smaller in this phase than in the previous phase. In the late phase, the graph flattens out within 12 to 16 minutes, meaning the cumulative number of affected buildings is about 450. At this stage, two plausible events occur: the flood stabilizes, reaching the maximum extent, or fewer buildings remain in its path.

4.3.2.2 Scenario II

In the early phase, the hazard curve has a slight slope and shows an insignificant number of structurally affected buildings, which slowly pass by stage to an average of 100 (Figure 4.4 (b)). This means the floods start moving slowly earlier as the flood continues to get deeper into areas. In the middle phase, the curve moves to swifter slopes, which indicates a sudden steep rise in the number of buildings affected. It indicates where the flood increases speed and moves to areas with more concentrated buildings, leading to elevated cumulative impacts. In the middle phase, the graph goes higher but at a much slower rate than that in the previous phase. This suggests that flooding has slowed, or most buildings have already been affected in such a small area. In the last phase, the curve flattens at about 350 buildings affected, indicating that very few buildings will be impacted once the flood reaches its maximum extent.

4.3.2.3 Scenario III

In the early phase, the curve steadily increased, impacting around 200 buildings (Figure 4.4(c)). The flood initially affects less dense areas or moves at a moderate speed. The graph curves steeply upwards in the middle phase, meaning a rapid increase in affected buildings. This phase matches the flood reaching areas of high building density or quickening in speed to cause substantial damage within the shortest time. In the late phase, the slope begins to flatten, indicating a slackening in the rate at which buildings are being newly affected. This could mean that the flood is losing momentum or has already affected most structures in its path. Moreover, this indicates that the cumulative number of affected buildings reaches the saturation point at around 500. In this stage, the flood has already reached its apex, and there is not much scope to cover more buildings.

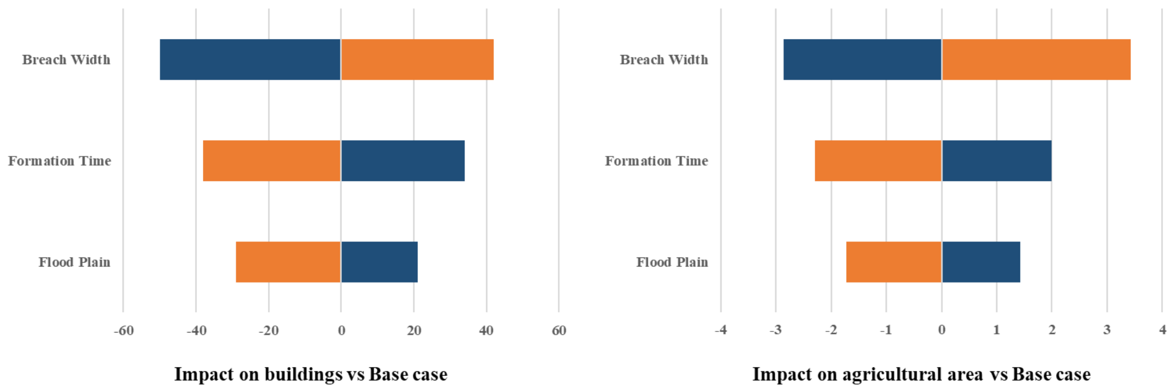
The hazard scenarios show distinct spatial and temporal patterns. In the early phase, hazard risk is low but increases rapidly in Scenarios II and III due to heightened vulnerability. The middle phase sees steady risk growth, with Scenario III showing the steepest rise. By the late phase, Scenario III stabilizes at high intensity, Scenario II follows a moderate trajectory, and Scenario I stabilize earlier at lower risk.

4.3.2.4 Results of the uncertainty analysis

To evaluate model robustness and communicate uncertainty, one-at-a-time sensitivity tests were performed on three influential dam-break parameters: final breach width (80–200 m; base = 120 m), breach formation time (0.25–1.0 h; base = 0.5 h), and effective floodplain roughness (n = 0.035–0.07; base = 0.05). Two impact domains were analyzed: the built environment and agriculture. Tornado plots (see figure 4.5) confirm a consistent ranking of influence, breach width > formation time > roughness, for both buildings and agriculture.

Figure 4.5

Results of the sensitivity analysis



Results demonstrate that breach width is the dominant control across both domains. For the built environment, the number of affected buildings ranged from −12% to +10% relative to the base case. For agriculture, the inundated cropland varied from −10% to +12% relative to the base case. Breach formation time was the second most important parameter: rapid breach development increased impacts, while slower development reduced them. Floodplain roughness exerted a smaller but consistent effect, with smoother surfaces enhancing both building exposure and cropland inundation (+5%) and rougher surfaces reducing them (−6 to −7%). Secondary indicators (peak stage, velocity, depth, and duration) responded with smaller elasticities than the primary exposure metrics.

4.3.2.5 Summary of PII.SI and PII.SII Outcomes: Hydraulic Modeling and Geospatial Analysis

PII.SI and PII.SII employed hydraulic modeling and geospatial analysis to simulate multiple dam breach scenarios and evaluate their socio-economic impacts on Kantale and surrounding areas. Three breach configurations, center, left flank, and right flank, were analyzed to assess flood propagation patterns, inundation extent, and potential damage to building and agricultural environments.

Results indicated that Scenario III (right-flank breach) produced the most severe impacts, with floodwaters directly traversing Kantale town, leading to the highest number of affected buildings (approx. 500) and the greatest agricultural inundation (approx. 35.22 km² of farmland). Scenario I (center flank) caused moderate impacts, while Scenario II (left breach) resulted in the least damage and fastest flood stabilization.

The temporal hazard curves revealed distinct flood progression phases, early, middle, and late, showing that the rate of structural impact was steepest in Scenario III, requiring the earliest and most intensive intervention. Uncertainty analysis confirmed that breach width is the dominant parameter influencing both building and agricultural damage, followed by breach formation time and floodplain roughness.

Overall, Stage 1 demonstrated that integrating hydraulic and geospatial modeling can effectively identify high-risk zones and quantify potential socio-economic losses, providing critical inputs for targeted non-structural mitigation and land-use planning strategies.

4.3.3 Findings of PII.SIII: Expert interviews

Expert interviews were conducted to validate the results of hydraulic modelling and to assess the socio-economic impacts from dam failures.

4.3.3.1 Validation of the results from the simulation and the geospatial analysis

The simulated results identified from the HEC-RAS and the results obtained from geospatial analysis were reviewed and validated through the expert interviews. Accordingly, E1 stated that:

"*The flood propagation showcased in all three figures shows natural alignment with water dispersion after embankment dam breaches at various points.*"

These observations show that flow expansion occurs at the central breach while water moves through more focused paths near the corners in agreement with terrain-induced routing processes. Elaborating further, E2 explained the Kantale area has a natural eastward and southeastward slope, and the flood patterns in Scenarios I, II, and III reflect this. The breach from the center spreads radially, but the terrain channels the flow along lower elevations toward Kantale town, particularly in Scenario III. This is a realistic representation. Similarly, E4 stated that:

"*I'm familiar with the Kantale reservoir and its downstream landscape. The drawing of flow paths shows exactly how floodwaters would move by passing higher terrain to reach Kantale urban settlements particularly through the directed spread from the eastern corner breach in* Scenario III."

In addition to that, E10 elaborated that the flood paths match exactly with the land slopes which surround the Kantale reservoir area. The path in Scenario III precisely traverses the lowest ground elevations to directly endanger the urban center as seen on the original elevation map. The model demonstrates accurate terrain receptiveness through this validation. Explaining further E7 brought a strong argument stating that" *As someone familiar with the ground* *conditions, I confirm the simulation's accuracy."* The Kantale topography is such that any breach on the eastern flank sends water toward the lower elevation town center. This pattern is accurately depicted in Scenario III. Local topographic dips and culverts influence the path as shown. Further E9 said that:

"The terrain in Kantale acts as a natural funnel for water movement."

The breach scenarios show water naturally flowing toward the agricultural basins and built-up areas. The simulation validates the need for location-specific breach modeling due to the strong topographic influence.

Most importantly, E5 said that the scenario III closely aligns with the 1986 event in terms of breach location and downstream impact. It shows a significant flow directly through Kantale town, mimicking the path and destruction recorded historically. In addition to those socio-economic overlays, the GIS analysis supports the types of impacts observed in 1986; agriculture, housing, and road networks are all intersected by the flood extent in Scenario III.

4.3.3.2 Socio-economic Impact from dam failure

The study mainly focused on exploring the socio-economic impacts from dam failures to advance the depth of knowledge. All the experts agreed that the social and economic impact from dam failures will entirely depend on the purpose of the dam, type of dam and the downstream condition. According to E1, dam failures often trigger cascading socio-economic crises. Beyond the immediate loss of life, they result in large-scale displacement, destruction of homes, and collapse of livelihoods. E2 stated that in the case of kantale incident,

"The area surrounding Kantale is highly dependent on irrigated agriculture, particularly paddy cultivation. Therefore, socio-economic effect would not only be the immediate crop loss but also long-term food supply disruption and income loss for farming communities."

E3 stated that the A6 highway and other vital rural access roads run directly through the flood-prone zones identified in the model. A breach could sever Kantale's road connectivity to Trincomalee and Habarana, disrupting trade, transport of goods, school attendance, and emergency medical access. Explaining further E4 emphasized that the dam also serves as a socio-economic backbone by feeding canals that support farming in several downstream villages. Its failure would cripple not just Kantale but a network of smaller settlements. The impact would ripple through employment, irrigation-dependent income, and water security. Further E6 stated that:

"The 1986 event already showed how quickly a failure can impact Kantale. If history repeats itself under current population densities, the number of displaced people would be significantly higher. The social fabric of Kantale could face long-term strain, especially among women, children, and elderly."

In addition, experts highlighted that Kantale is not just a functional town but a historical one with deep cultural significance. A flood of this scale could damage or destroy religious sites, community centers, and schools located near the floodplain. The psychological and cultural loss would be profound and long-lasting. Explaining further, many experts have highlighted breach of large dams such as Victoria dam could lead to severe consequences. Victoria Dam, as one of the primary hydropower-generating dams in Sri Lanka, plays a critical role in the nation's energy supply. If such a dam were to breach, the economic impact on the country would be catastrophic. Moreover, it was emphasized that the most difficult part of a dam failure is recovery. E2 stated:

"Recovery isn't just about rebuilding structures; it's about restoring disrupted social systems, from irrigation networks to transport routes and schools."

As per the experts' opinion, dam failures can destroy years of development gains by wiping out housing, roads, and services. In addition, E3 stated that floodwaters bring waterborne diseases, contaminate drinking sources, and destroy health facilities. Furthermore, psychological impacts such as trauma, anxiety, and depression can persist for years after the event. Rebuilding efforts are expensive and often displace low-income families permanently.

4.3.3.3 Strategies for minimizing the socio-economic impacts of dam failures

All the experts were asked for strategies to minimize the socio-economic impact from dam failure. According to E3, well-designed emergency action plans are critical for minimizing public and economic impacts. E3 further elaborated that:

"These plans should include clear evacuation protocols, communication systems, and coordination with local authorities to ensure rapid response during a dam failure."

Similarly, E2 stated that *"emergency planning is key. We need detailed evacuation plans, communication systems, and regular drills to ensure communities are prepared. Quick and effective response can significantly reduce the loss of life and property damage."*

Furthermore, many experts agreed that engaging with local communities is essential. E4 specifically said that it is important to involve local communities in dam safety discussions, educate them about risks, and empower them to participate in preparedness activities. This builds trust and ensures that responses are culturally and socially appropriate.

In addition to that, E5 stated that:

"Educational campaigns, using flyers, videos, or school programs, can reach broader audiences, tailored to local languages and literacy levels."

Empowering communities might involve training residents to form community-led emergency response teams, equipped to assist with evacuations or first aid. Explaining further, the expert's highlighted that technological advancements also play a significant role in mitigating the impact of dam failures. E1 mentioned that:

"We should invest in real-time monitoring systems, early warning technologies, and predictive analytics to detect potential failures before they occur."

Similarly, E7 explained that as the world increasingly adopts artificial intelligence, it can be integrated with sensors embedded in dams. These sensors monitor parameters such as water pressure, structural stress, and seismic activity, transmitting data in real-time. By leveraging AI-powered predictive analytics, this real-time data can be analyzed alongside historical patterns to forecast potential failures, providing weeks or even months of lead time for necessary repairs.

Moreover, E5 and E6 emphasized the importance of having strong regulatory frameworks. E5 stated that:

"Regulations should mandate updated design standards reflecting current technology and climate data (e.g., increased rainfall from global warming)."

E6 elaborated that policies must also address socio-economic fallout, providing compensation funds or recovery grants for displaced residents. Regular updates to standards incorporate lessons from past failures and emerging risks.

Finally, E8, E3, and E10 specified the importance of a tailored insurance scheme covering floods, property damage, or business interruptions, ensuring quick payouts to affected parties. E8 specifically said that:

"Insurers and governments can collaborate to design affordable products, subsidized for low-income areas."

Such securities can accelerate rebuilding, stabilize local economies, and prevent long-term hardship.

4.3.3.4 Summary of PII.SIII Outcomes: Expert Interviews

Stage III involved expert interviews to validate the hydraulic and geospatial modeling results and to explore the socio-economic implications of dam failures. Experts confirmed the accuracy and realism of the simulations, emphasizing that flood propagation patterns in all three breach scenarios align closely with Kantale's natural topography and historical flood behavior. Notably, Scenario III (right-flank breach) was validated as the most severe and realistic case, matching the 1986 Kantale dam failure in both flow direction and impact extent. Experts agreed that the model's output accurately reflects terrain-induced routing, agricultural exposure, and urban vulnerability.

Regarding socio-economic impacts, experts highlighted that dam failures trigger cascading consequences of life, displacement, destruction of homes and farmland, disruption of transport networks, and long-term economic and psychological hardship. For the Kantale area, dependence on irrigated agriculture means that a breach would devastate livelihoods and food security. The experts also noted potential cultural losses, health crises, and the challenge of long-term recovery, particularly for vulnerable groups such as women, children, and the elderly. On the national scale, failures of major dams like Victoria could severely affect energy production and economic stability.

Experts proposed several non-structural strategies to mitigate these impacts. Priority measures include comprehensive emergency action plans, community-based preparedness programs, public education and awareness campaigns, and real-time monitoring and early warning systems supported by AI and predictive analytics. Strengthening regulatory frameworks, ensuring regular dam safety audits, and developing tailored insurance schemes to support recovery were also identified as key strategies. Collectively, these insights reinforce that technological, institutional, and community-based measures are all essential for minimizing the socio-economic fallout of dam failures and enhancing long-term resilience.

4.3.4 Key findings obtained from phase II to reduce the impacts from dam failures

Figure 4.6 shows the key findings obtained from phase II to reduce the impacts from dam failures

Figure 4.6

Key findings obtained from phase II to reduce the impacts from dam failures

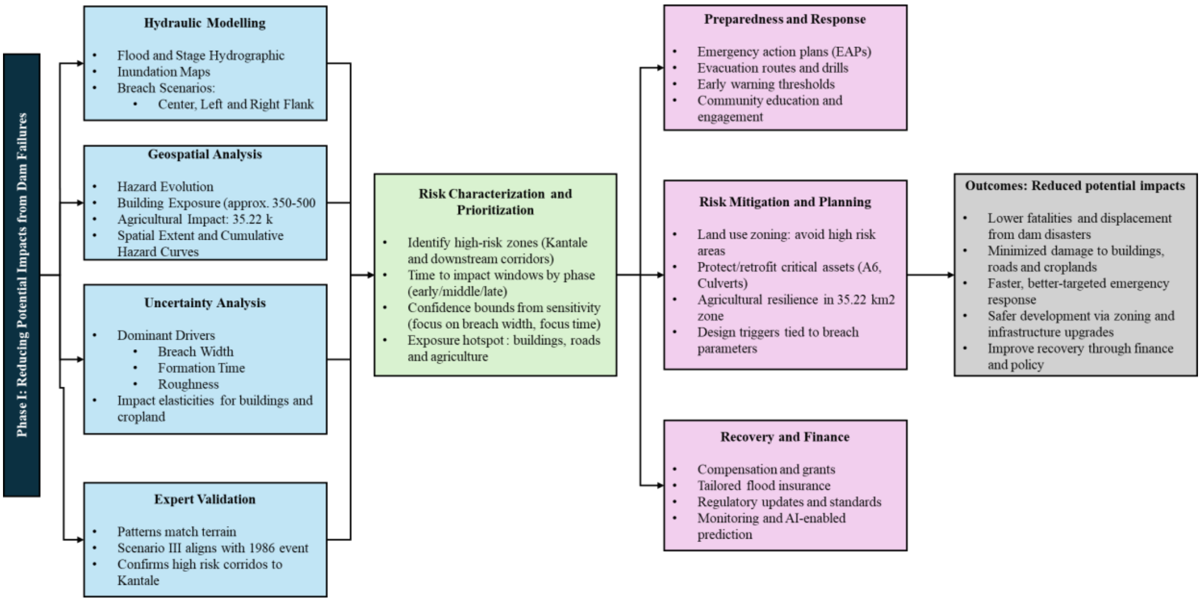


Figure 4.6 demonstrates how scientific approaches such as hydraulic modelling, geospatial analysis, and sensitivity testing provide critical insights into dam-break risks that are relevant anywhere in the world. By simulating multiple breach scenarios, mapping inundation extents, and analyzing hazard curves, this phase identifies which regions are most vulnerable, how impacts evolve over time, and which parameters (such as breach width or formation time) dominate the risk profile. Expert validation confirms the credibility of these models, ensuring that the results reflect real-world topography and flood behavior. Applied globally, such analyses allow governments and engineers to pre-identify danger zones, protect critical infrastructure, regulate land-use development, and design early intervention strategies. In doing so, Phase II results provide a transferable framework for minimizing exposure and guiding preparedness strategies for dam safety worldwide.

4.4 Phase III: Formulation of prototype non-structural measures

4.4.1 Findings of PIII.SI: Expert interviews

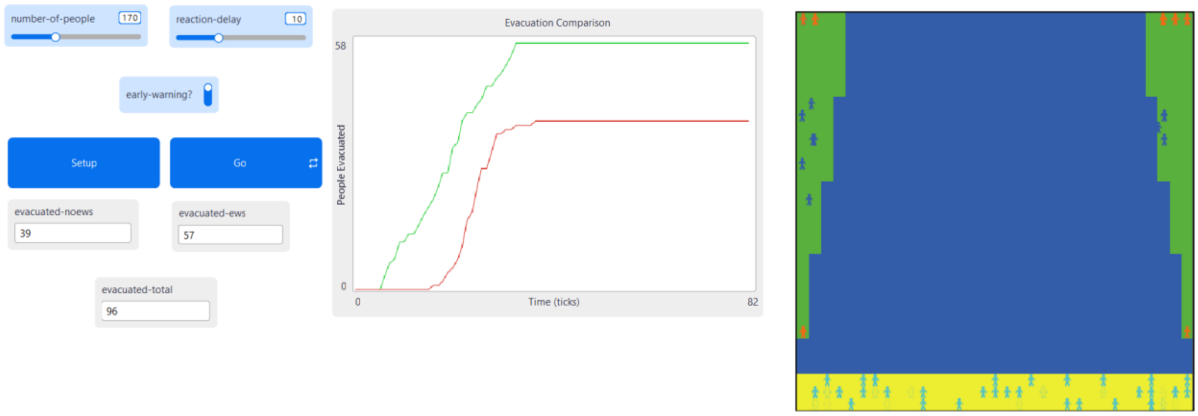
Refer to Appendix B for the decision rankings provided by the experts for the board game.

4.4.2 Findings of PIII.SII: Agent-based model

The developed agent-based model produced distinct outcomes between the Early Warning System (EWS) and non-EWS scenarios. Across multiple simulation runs, the model consistently demonstrated that the presence of an EWS substantially increased the proportion of individuals who successfully evacuated before the flood wave reached their location. Figure 4.7 shows a baseline configuration done using the model.

Figure 4.7

A baseline configuration done using the model



The simulation outputs clearly demonstrate the critical role of Early Warning Systems (EWS) in dam-break evacuation scenarios. When the early-warning switch was activated, the EWS cohort received alerts in advance, enabling faster reactions and resulting in a higher number of successful evacuations (57 individuals) compared to the no-EWS cohort (39 individuals). The evacuation curve for the EWS group rose earlier and more steeply, reflecting timely movement toward safe zones, whereas the no-EWS group exhibited delayed and slower evacuation, leading to greater casualties. Spatial visualizations of the evacuation process provided additional insights: in the EWS scenario, agents began moving toward safe zones shortly after receiving the warning, producing a steady flow that reduced congestion at exits. In contrast, under the non-EWS conditions, many agents delayed their movement until floodwater became visible, resulting in last-minute surges in traffic and localized bottlenecks that increased exposure to flooding. These patterns are consistent with findings from previous evacuation modeling studies, which highlight the importance of timely warnings in distributing evacuation demand more evenly over time (Lindell & Prater, 2007).

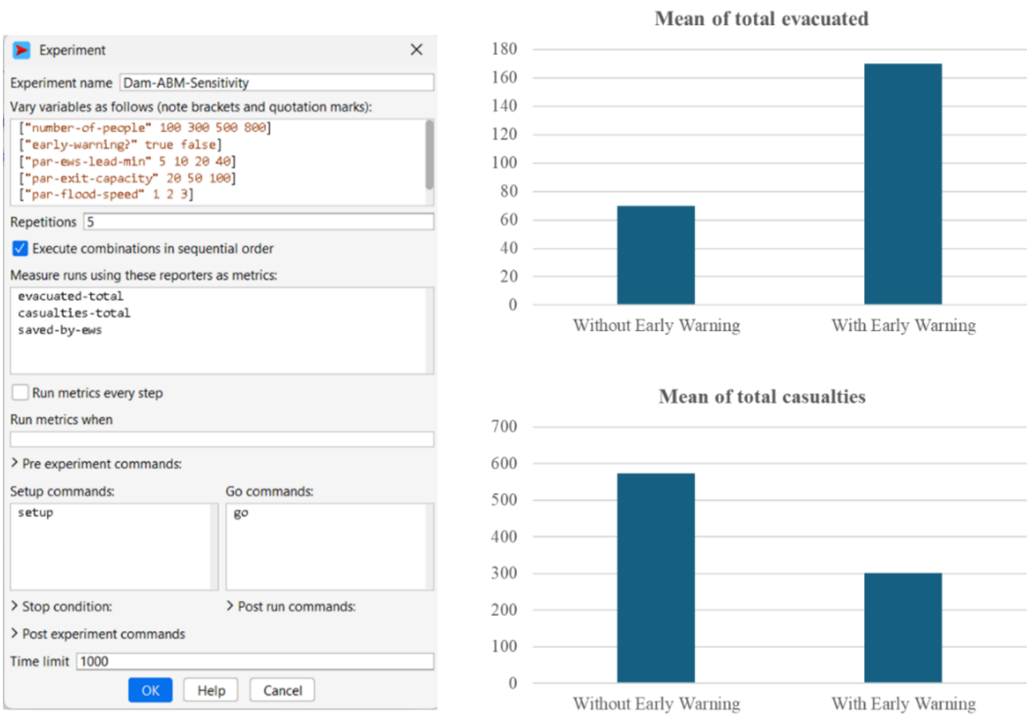
The map visualization reinforces this contrast: although both groups start in the floodplain, those with EWS are more likely to reach the yellow safe zone before the blue floodwaters arrive. Therefore, the results demonstrate that implementing an early warning system substantially increases survival rates by reducing reaction delays and allowing more people to escape before being overtaken by the flood.

4.4.2.1 Results of the sensitivity analysis

To evaluate the relative influence of key parameters on evacuation performance and casualty outcomes, a sensitivity analysis was conducted using results from the agent-based dam-break model (See figure 4.8). Each simulation run varied four input parameters: exit capacity (the number of people that could pass through evacuation routes or shelters per unit time), flood speed (the velocity at which the flood wave propagated through the model environment), congestion factor (a parameter reflecting how crowding and density slowed down evacuation movement), and early warning lead time (the amount of advance notice, in minutes, given before flood arrival). These four parameters represent both hazard intensity and system response capacity, allowing an integrated assessment of how warning systems and infrastructure interact under extreme flood scenarios. For each run, the model recorded two outcomes of interest: evacuated total (the number of agents that successfully reached safety) and casualties total (the number of agents that perished). By analyzing these outputs against the varied inputs, the goal was to determine which factors most strongly shaped evacuation efficiency and survival rates.

Figure 4.8

Sensitivity Analysis using the behavior space in Net logo



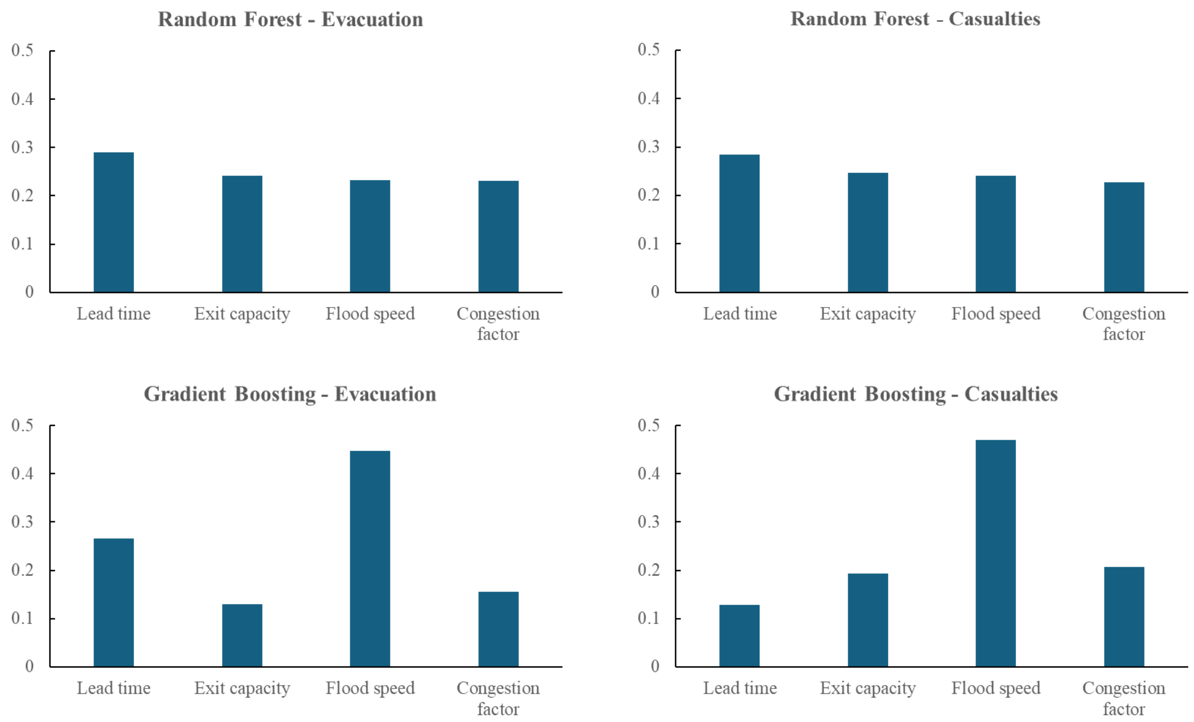
The presence of early warning systems was associated with markedly improved outcomes across all measured indicators. Mean evacuations increased from approximately 70 to 170 individuals, reflecting enhanced population response capacity. Concurrently, mean casualties decreased from over 570 to around 300, with the maximum recorded casualties reduced by nearly half. Furthermore, early warning facilitated measurable life preservation, with an average of nearly 60 lives saved and a maximum of 155. Collectively, these results provide robust evidence that early warning systems substantially increase evacuation efficiency, mitigate mortality, and deliver quantifiable life-saving benefits, underscoring their critical role in disaster risk reduction.

4.4.2.2 Analytical Approach

The analysis proceeded in three stages to capture both linear and nonlinear dynamics. First, a multiple linear regression was fitted using standardized input parameters to test whether outcomes could be explained by simple straight-line relationships. This provided a baseline check of explanatory power, quantified using the R^2 statistic. However, because evacuation processes in agent-based models are typically nonlinear and influenced by interactions between factors, linear regression was unlikely to capture the full complexity. Therefore, two nonlinear machine learning methods were also applied (See figure 4.9). A Random Forest Regressor was used to evaluate feature importance by aggregating the explanatory contribution of each parameter across many decision trees. Random forests are well suited to capturing complex, nonlinear effects and variable interactions. To complement this, a Gradient Boosting Regressor was applied, which builds trees sequentially to emphasize difficult-to-predict cases and often sharpens the ranking of dominant drivers. Comparing the results of these three approaches provided a more robust picture of parameter influence on evacuation outcomes.

Figure 4.9

Results of the random forest and gradient boost analysis



4.4.2.2.1 Random Forest Analysis

The linear regression explained almost none of the variance in either outcome ($R^2 = 0$ for both evacuations and casualties), and standardized coefficients were very close to zero. This indicated that the relationships between parameters and outcomes were not well represented by simple linear models. By contrast, the tree-based approaches yielded meaningful insights. The random forest analysis suggested that all four parameters contributed comparably to outcomes, with only slight differences in importance. For evacuations, lead time (0.289) and exit capacity (0.242) were marginally stronger than flood speed (0.238) and congestion factor (0.231). For casualties, lead time (0.285) and exit capacity (0.246) again held slightly higher weights than flood speed (0.241) and congestion (0.227). These results indicate that, in the random forest model, no single parameter dominated; instead, each played a roughly equal role.

4.4.2.2.2 Gradient Boosting Analysis

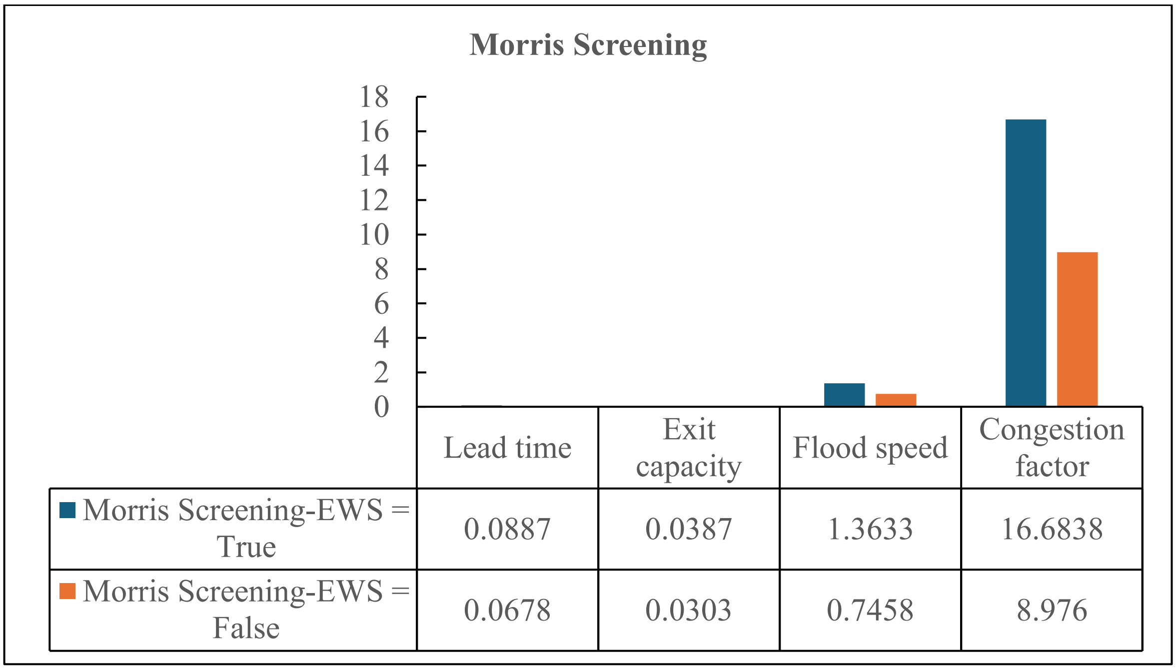
The gradient boosting analysis revealed a clearer hierarchy. For evacuations, flood speed (0.447) was the dominant driver, followed by lead time (0.266), congestion (0.156), and exit capacity (0.130). For casualties, flood speed (0.470) again dominated, with exit capacity (0.194), congestion (0.207), and lead time (0.129) contributing less but still significant shares. These results emphasize that while all four factors matter, flood speed is the single most influential parameter, and its impact far outweighs the others in determining survival.

4.4.2.2.3 Global Sensitivity Analysis with Surrogate Models

While local feature importance measures are valuable, they may miss nonlinearities across the full input space. Therefore, a global sensitivity analysis was conducted using the Morris elementary effects method (μ* for overall influence, σ for nonlinearity/interactions). The results (Figure 4.10) indicate that Congestion factor dominates model behavior, followed by Flood speed, whereas Lead time and Exit capacity exert minimal influence.

Figure 4.10

Results of the Morris Screening



The GSA revealed a different picture of parameter influence. Once early warning system (EWS) presence was fixed, the variance in outcomes attributable to lead time and exit capacity was minimal. Instead, congestion consistently emerged as one of the strongest drivers of casualty outcomes, often exceeding the effect of flood speed. Under EWS conditions, congestion dominated the sensitivity ranking, with flood speed exerting a secondary but still substantial role. Without EWS, flood speed and congestion together explained most of the variance, while exit capacity and lead time contributed very little.

4.4.2.3 Summary of PIII.SII Outcomes: Agent-Based Model

The agent-based model (ABM) demonstrated the critical importance of Early Warning Systems (EWS) in reducing casualties and enhancing evacuation efficiency during dam-break scenarios. Across multiple simulations, the presence of an EWS led to markedly higher evacuation success (57 vs. 39 individuals) and earlier movement toward safe zones, preventing congestion and reducing exposure to floodwater. Spatial analyses confirmed that agents with EWS warnings evacuated more uniformly and reached safety zones faster, aligning with established behavioral evacuation studies (Lindell & Prater, 2007).

Sensitivity analyses identified four key parameters influencing evacuation performance, flood speed, lead time, exit capacity, and congestion factor. Results showed that EWS activation significantly improved survival outcomes, increasing mean evacuations from approximately 70 to 170 and reducing casualties by nearly half. Lead time and exit capacity had the strongest influence in the random forest model, while gradient boosting analysis highlighted flood speed as the dominant factor controlling both evacuation success and mortality.

The global sensitivity analysis refined these insights, revealing that under EWS conditions, congestion became the most influential determinant of casualties, surpassing flood speed. In contrast, in non-EWS scenarios, flood speed and congestion jointly governed outcomes, while lead time and exit capacity played secondary roles.

Thus, the ABM outcomes underscore that effective disaster mitigation depends on both technological systems (EWS, predictive analytics) and infrastructure design (adequate evacuation routes, congestion management). Integrating these factors, slowing flood propagation, extending warning lead times, and improving evacuation throughput, can substantially reduce fatalities and enhance community resilience during dam-related disasters.

4.4.3 Findings of PIII.SIII: Board game

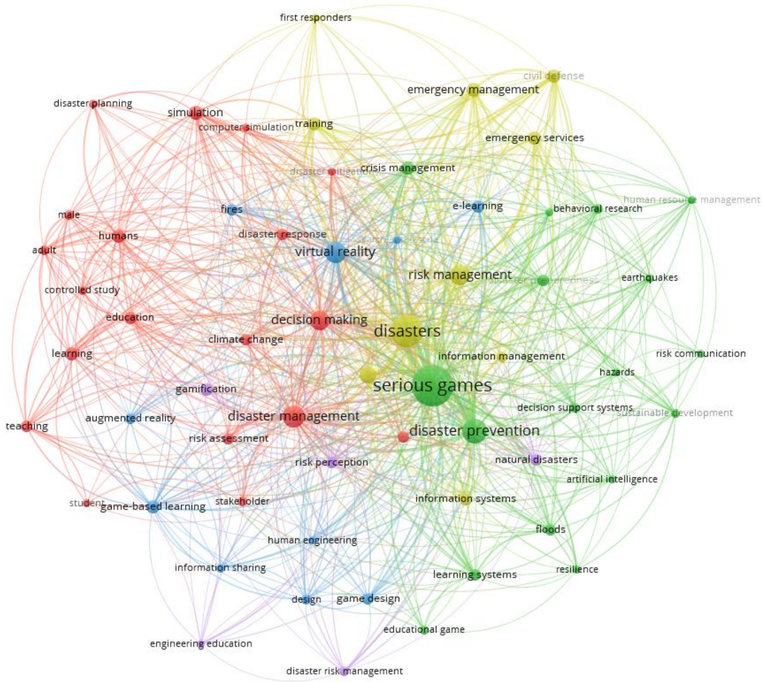
This section demonstrates the findings related to the board game.

4.4.3.1 Results of the bibliometric analysis

Keyword co-occurrence network analysis serves as a valuable method for mapping research landscapes, identifying cross-disciplinary linkages, and detecting gaps in existing knowledge (Kumar et al., 2021). To explore the serious games developed in the field of disaster management, a network was constructed using bibliographic data from 46 carefully selected publications. Figure 4.11, produced with VOS viewer, presents the resulting keyword co-occurrence map, where the most frequently used terms and their associations are displayed.

Figure 4.11

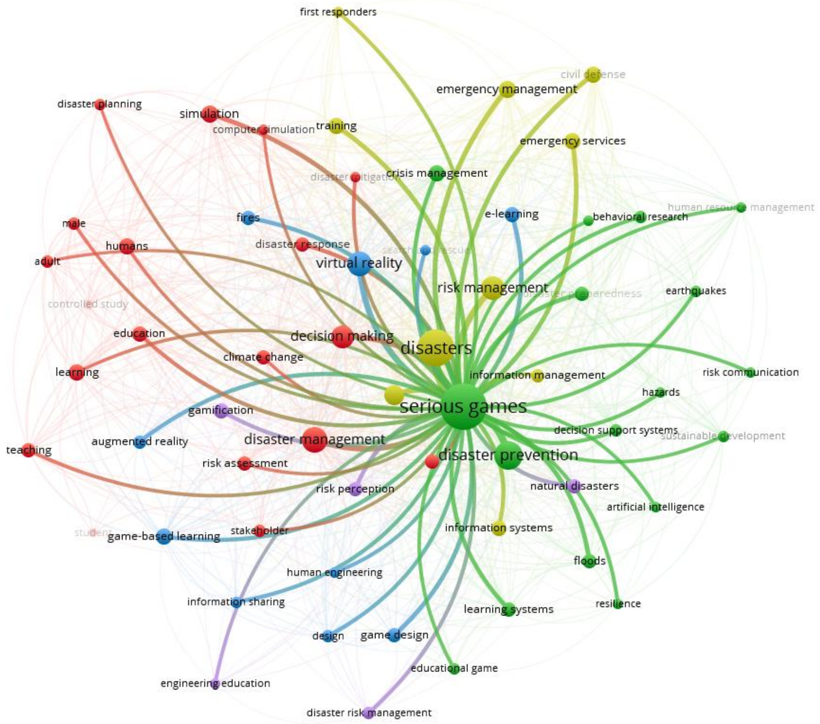
Keyword co-occurrence map



The keyword co-occurrence network reveals that *serious games* (118 occurrences) and *disasters* (74 occurrences) are the most dominant themes, closely linked with *disaster prevention*, *risk management*, and *disaster management*, highlighting their central role in the literature. The clusters show distinct research orientations: one focused on education and training (keywords such as *teaching, learning, students, game-based learning*), another emphasizing risk and preparedness (*resilience, disaster preparedness, floods, earthquakes, decision support systems*), and a third integrating technology-driven approaches (*simulation, virtual reality, augmented reality, e-learning, information sharing*). The strong connections between *serious games*, disaster management, and education suggest an interdisciplinary convergence, where gamification and immersive technologies are increasingly applied to disaster preparedness and response training. At the same time, gaps are evident: social and behavioral aspects like *risk perception* and *risk communication* are less prominent, and sustainability-related terms have weaker connections. This indicates that while technological and educational applications of serious games are advancing, opportunities remain to strengthen research on human behavior, public engagement, and long-term resilience in disaster contexts. Figure 4.12 illustrates the serious games that have been developed across different fields within disaster management.

Figure 4.12

Serious games developed in different fields in disaster management



The keyword co-occurrence network demonstrates that serious games occupy a central position across diverse areas of disaster management. Strong connections to terms such as *disaster prevention, risk management, disaster management,* and *decision-making* show that serious games are increasingly used as tools for preparedness and proactive planning. In prevention, they are linked with *resilience, disaster preparedness, floods, hazards,* and *sustainable development*, reflecting their role in educating communities and enhancing risk awareness. Within operational management, ties to *emergency management, emergency services, crisis management,* and *civil defense* suggest their application in professional training, coordination exercises, and decision-making under pressure.

Technological integration is another defining trend, as indicated by co-occurrence with *virtual reality, augmented reality, gamification,* and *simulation.* These immersive approaches enable realistic, interactive scenarios that improve both professional response capacity and community-level preparedness. Furthermore, the presence of *teaching, learning, game-based learning,* and *engineering education* highlights their value in education, where games function as experiential learning tools to build knowledge and preparedness skills. Emerging associations with *decision support systems, artificial intelligence,* and *information management* suggest a growing use of serious games as platforms for testing policies, evaluating strategies, and analyzing complex system interactions.

Despite this breadth, the analysis also reveals a critical research gap: while serious games are widely applied in fields such as floods, earthquakes, and general crisis management, their use in dam failure scenarios is almost absent. Dam failures pose unique challenges, rapid-onset flooding, cascading infrastructure risks, and the crucial role of early warning systems, yet these characteristics are not well represented in the existing serious games literature. This indicates an underexplored opportunity to design serious games that simulate dam-break conditions, integrate early warning system dynamics, and train both communities and authorities for effective evacuation and risk reduction.

4.4.3.2 Results of the systematic review

4.4.3.2.1 Current disaster education

The growing popularity of hands-on or experiential learning where knowledge is believed to be "created through the transformation of experience" (Kolb, 1984) has introduced a shift from authority- and lecturer-based teaching and learning to more engaging approaches in which a strong emphasis is put on emotional aspects, peer-to-peer relationships, horizontal communication, and active cooperation (Solinska-Nowak et al., 2018). The foundation for using games and simulations as an alternative or supplemental teaching tool to improve skills necessary for a cooperative and flexible response to social-ecological concerns has been established by this participatory educational approach (Solinska-Nowak et al., 2018).

Disaster education is the fundamental process of the disaster prevention workflow (Johnson et al., 2014). A student can learn the fundamentals of disaster avoidance and how to react effectively in the event of a disaster with the help of good disaster education, which also creates a network for information sharing between the community, families, and schools (Frankenberg et al., 2013; Oktari et al., 2015). Increasing students' motivation to learn is crucial in disaster education rather than depending solely on cognitive instruction (Ronan et al., 2001). Enhancing student interest and participation is largely dependent on the instructional strategy employed (Tsai et al., 2020). Current disaster education usually follows the Cognitive, Skill-based, and Affective learning model (Kraiger et al., 1993). Students receive the fundamental conceptual and theoretical knowledge of catastrophe avoidance from their teachers. This information covers things like how disasters occur and the consequences they have (Frankenberg et al., 2013). Teachers anticipate that after imparting this foundational knowledge, students will apply it to develop new talents and improve their perspectives on catastrophe avoidance. Based on the theoretical and conceptual knowledge they have learned in class, students are required to react appropriately in the event of a calamity (Tsai et al., 2020).

Two major challenges persist with this educational approach. The first is finding ways to boost student motivation, moving away from passive, spoon-fed learning. The second is effectively transferring the teacher's or professional experiences to the students (Johnson et al., 2014; Mahamood et al., 2024; Tsai et al., 2020). Studies indicate that conventional teaching methods, such as lecture-based instruction, are less effective in engaging students compared to interactive approaches like experiential learning, especially when it comes to disaster prevention (Becker et al., 2012; Whitney et al., 2004). Since its inception, experiential education has been extensively incorporated into various educational programs. Its purpose is to enhance students' knowledge, skills, and abilities by allowing them to participate in hands-on experiences and personal reflection (Cajanding, 2017; Djonko-Moore et al., 2018).

4.4.3.2.2 Game-based disaster education

Serious games, a subset of experiential learning techniques, have gained popularity recently as the importance of experiential learning in disaster education has increased (Forrest et al., 2022; Schrader, 2022). Games are regarded as an interesting teaching strategy that emphasizes communication, peer relationships, emotional states, and active cooperation (Kolb, 1984; Solinska-Nowak et al., 2018). Over the past 20 years, there has been a noticeable increase in interest in the application of gamification in higher education (Egilmez & Gedik, 2018). Considering that using games to teach instead of lectures has a big impact on learning and raises mastery through real-world experience (Tsai et al., 2020). The creation and application of games for disaster education have been the subject of contemporary research. For example, to teach college students about earthquake preparation, Novak and his group created an interactive escape-room game (Novak et al., 2019). Kaneko et al. (2018) utilized a card game, DMAC, to teach international students in Japan about disaster mitigation.

Serious games are an elegant and visually effective form of discussing real-world problems. Abt, (1979) popularized the idea of serious gaming and demonstrated how simulation games could be utilized for public policymaking, education, and decision-making. Since then, a substantial body of literature has been written about this subject and its several application domains, such as educational, science, education, the military, business, government, healthcare, and water management, to mention a few (Duke, 2011; Mayer, 2009; Rijcken et al., 2012). These are games, which may or may not be computerized, and they serve a variety of entertainment-related functions (Dörner et al., 2016). Although it is ideal for these games to be entertaining, captivating, and hold players' interest, they are also made with education in mind. Accordingly, a serious game is made to fulfill instructional objectives in addition to being visually appealing to a wide range of players, much like commercial games (Bellotti et al., 2013). Table 4.1 illustrates several serious games designed by previous scholars in terms of disaster education.

Table 4.1

Serious games designed by previous scholars in terms of disaster education

Title (Year)	Authors & Venue	Serious Game Description & Mechanics	Target Audience	Intended Outcomes	Geographic Focus
Increasing Flood Awareness Through Dam-Break Serious Games (2024)	*Marcus N. Gomes Jr. et al.* - International Journal of Disaster Risk Reduction. (in press)	Simplified dam-break flood simulation is used as a serious game for dam safety awareness. The framework uses a 1-D hydrodynamic model and GIS data to model downstream flood waves from dam failures, allowing users to visualize flood extent and impacts	Dam safety officials and communities downstream of dams (public and stakeholders at risk)	Improve risk perception and awareness of dam failure consequences (how a dam break can cause catastrophic floods)	Brazil (applied to 20 Brazilian dams; includes the Brumadinho 2019 dam failure case)
Flood Game: 3D Flood Mitigation Game (2025)	*Bekir Z. Demiray et al.* - Env. Modelling & Software (2025)	Web-based 3D simulation game for flood mitigation education. Players select a real-world location and experiment with different flood protection and mitigation strategies (e.g., levees, green infrastructure) in an interactive scenario. The game provides immersive 3D visualizations of flooding based on the chosen measures, allowing players to see the flood impacts of their decisions	K-12 students, college students, and the general public	Raise public awareness of flood risks and teach the benefits/consequences of various mitigation actions. Players learn how different measures affect flood outcomes in their communities	Global (user can simulate flooding in any chosen real location; not tied to one region)

Title (Year)	Authors & Venue	Serious Game Description & Mechanics	Target Audience	Intended Outcomes	Geographic Focus
"Levee Dilemma" Flood Management Game (2023)	*K.-H. Liao et al.* – International Journal of Disaster Risk Reduction 90 (2023)	A scenario-based serious game examining the *levee dilemma* in flood management. Players must decide whether to build levees to protect their community, understanding that levees can protect one area but may worsen flooding downstream or give a false sense of security. The game simulates stakeholders' decisions under climate uncertainty and requires communication between participants to manage shared flood risk.	Policymakers, students, and adult players (study participants acting as community decision-makers in the experiment).	Increase understanding of the trade-offs in levee construction and foster awareness of the *"levee effect."* Playing the game heightened participants' awareness of the levee dilemma (the downstream and long-term risks of levees). (However, the game highlights the social implications and may not completely deter players from choosing levees under pressure.)	No specific location (generic riverine flood scenario; applicable to any region facing levee-building decisions).
Flood Resilience Challenge (FRC) Role-Play Game (2019–2022)	*Evalyna Bogdan & Shaieree Cottar* - IEEE Tech. & Society Mag. (2022)	A multiplayer role-playing board game designed to improve flood resilience and governance. Players assume roles of diverse stakeholders (government, engineers, insurers, developers, residents, media, etc.) and collaborate on flood preparedness plans	Multi-stakeholder groups; used with university students, water management professionals, local officials, residents, and NGO representatives.	Build capacity for collective flood risk decision-making and encourage systems thinking. The game increases flood literacy fosters social learning among participants and	Canada (game context based on Canadian flood governance and policies), but adaptable to other locales.

Title (Year)	Authors & Venue	Serious Game Description & Mechanics	Target Audience	Intended Outcomes	Geographic Focus
		In round 1, players jointly choose flood risk management measures (e.g., building dams/dikes or implementing wetlands conservation, land-use policies) and negotiate trade-offs. In round 2, a flood event is "simulated," after which players reassess their decisions based on damages, update budgets, and vote on policies, followed by a group debrief.		creates a safe environment to practice communication and collaboration in flood scenarios. Players gain empathy for other stakeholders' perspectives and explore sustainable solutions (beyond just "build a dam").	
Dike Dilemmas Under Pressure (Flood Asset Management Game, 2023)	*Frank den Heijer et al.* - Journal. of Flood Risk Management 16(3) (2023)	A serious game focused on flood defense asset management challenges. Participants role-play as different asset managers responsible for a dike (levee) system, facing realistic maintenance and emergency scenarios under time and resource constraints. The game "puts players under pressure" with dilemma scenarios – for example, prioritizing which dike section to reinforce or which maintenance to defer – forcing discussion and cooperation among the various role-players.	Flood management professionals and engineers (the game was played by 67 Dutch dike managers, engineers, and related officials)	Improve collaboration and mutual understanding between stakeholders responsible for flood defenses. Through the game, participants became more aware of each other's priorities and the dilemmas in asset management, recognizing differences in cooperative attitudes. The exercise helped players reflect on their own decision-making style and	The Netherlands (game scenarios based on the Dutch water management context; tested with Dutch regional water authorities)

Title (Year)	Authors & Venue	Serious Game Description & Mechanics	Target Audience	Intended Outcomes	Geographic Focus
		Gameplay emphasizes the technical and social complexity of managing shared flood defenses.		correct misperceptions about colleagues, ultimately enhancing teamwork in flood risk management	
VR Flood Safety Training Simulation (2023)	*A. D'Amico et al.* – International Journal of Disaster Risk Reduction 96 (2023)	A non-immersive VR serious game for urban flood emergency training. Users interact with a 3D virtual city environment on a standard PC (no VR headset required) and are presented with a flooding scenario. The game includes multiple modules and storylines – for example, guiding an avatar to evacuate through flooded streets or choosing safety actions as water rises. The simulation provides real-time feedback (e.g. visual flood levels, consequences of actions) to teach proper emergency responses.	General public and community members (especially those in flood-prone urban areas), for use in disaster preparedness education.	Increase personal preparedness, response skills, and risk awareness for flash floods. After playing, users showed significantly higher flood safety knowledge and self-efficacy (confidence in handling flood emergencies). The realistic scenario also allows researchers to observe evacuation decision-making; player choices in the game mirrored real-world behavior patterns, suggesting the tool can aid	Generic urban scenario (not tied to one city; the VR environment can represent any urban area to illustrate common flood hazards).

Title (Year)	**Authors & Venue**	**Serious Game Description & Mechanics**	**Target Audience**	**Intended Outcomes**	**Geographic Focus**
				in planning and evaluating evacuation strategies.	
Urban–Rural Flood Mitigation Planning Game (2018)	*Mehdi Khoury et al. – Water* 10(12)**:**1885 (2018)	A computational simulation game for participatory flood planning in a mixed rural-urban catchment. Set in Millbrook (a village in Cornwall, UK), the game lets players adjust four key parameters affecting flooding: the level of urban drainage infrastructure investment and the farming systems in three sub-catchments (land use practices). Players run the model to see resulting flood depths, impacted houses, and economic losses on a 3D map of the village. By experimenting with combinations of traditional drainage and natural flood management (NFM) measures, users learn the trade-offs between flood reduction and costs.	Local stakeholders and residents (developed with Millbrook community members and officials; approx. 18 participants in workshops).	Inform and transform local flood risk understanding. **Informative:** players improved their understanding of Millbrook's flood drivers and the effectiveness of various interventions. **Transformative:** the game changed attitudes – over 70% of participants revised their initial assumptions and found new approaches to manage floods. It spurred discussion of implementing natural flood management (like changes in land use) in real council meetings, indicating a shift toward more sustainable flood solutions.	Millbrook, Cornwall, UK (specific to a local catchment, though the approach could be applied to similar communities).

4.4.3.3 Outcomes of the developed board game

This section presents and analyzes the feedback obtained from participants in the pilot studies. The first pilot of the game was conducted at the University of Moratuwa with a group of researchers (see figure 4.13). The primary objective of this pilot study was to identify potential discrepancies and areas for refinement within the game's mechanisms. To achieve this, two separate sessions were organized, each involving a distinct team of participants. Conducting multiple runs allowed for the observation of variations in player interaction, decision-making dynamics, and the overall functionality of the game system, thereby providing valuable feedback for subsequent iterations of design and playtesting.

Figure 4.13

Pilot Study 1

All participants reported that the game was highly engaging and that it significantly motivated them to learn more about dam safety and disaster management. Comparisons of their perceptions before and after gameplay indicated a notable increase in their understanding of dam failure risks and appropriate responses to such scenarios. Participants emphasized that the game not only enhanced their knowledge but also clearly illustrated the importance of collaboration between different stakeholder roles, such as the engineer, emergency responder, government official, and planner.

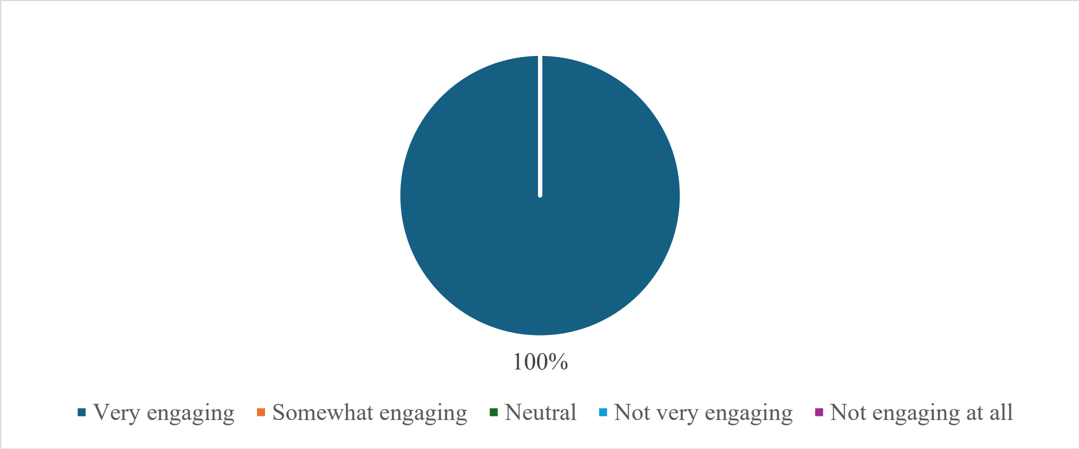
Importantly, respondents highlighted that the learning experience was complemented by enjoyment. They stated that the game fostered a sense of teamwork, requiring them to critically evaluate each event, deliberate with peers, and collectively select the most suitable course of action. The most valued feature, consistently noted across responses, was the collaborative decision-making mechanism. Unlike many competitive board games, this design required at least three aligned decisions (one primary and two supportive) before a round could be played. This structure emphasized interdependence, ensuring that no single player could act in isolation and reinforcing the necessity of cooperation in disaster management contexts.

4.4.3.3.1 General Experience

Figure 4.14 shows the participants feedback on the level of engagement of the board game.

Figure 4.14

Participants' feedback on the level of engagement of the board game



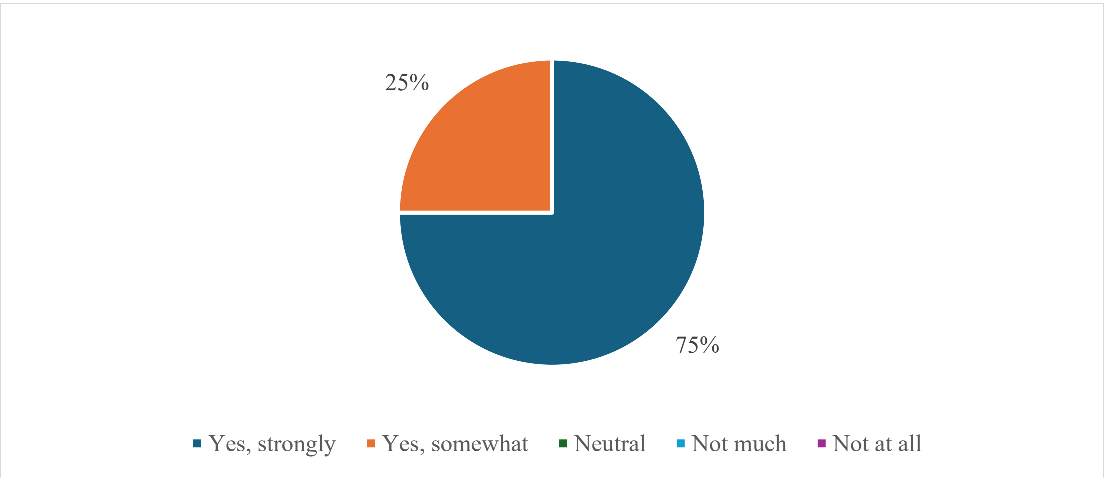
The results indicate that 100% of participants rated the board game as "very engaging." This unanimous response suggests that the game design successfully captured participants' interest and attention. High engagement levels are particularly important for serious games, as they enhance learning effectiveness, knowledge retention, and overall impact. The absence of neutral or negative responses further reinforces the game's potential as a powerful tool for raising awareness in communities vulnerable to dam failures.

4.4.3.3.2 Game motivation for learning about dam safety and disaster management

Figure 4.15 illustrates participants' feedback on the level of motivation they gained from playing the game in relation to learning about dam safety and disaster management.

Figure 4.15

Level of motivation they gained from playing the game in relation to learning about dam safety and disaster management



As shown in Figure 4.15, 75% of participants reported being strongly motivated to learn about dam safety and disaster management through the board game, while the remaining 25% indicated being somewhat motivated. Notably, there were no neutral or negative responses. This demonstrates that the game not only engaged participants but also provided meaningful motivation to explore critical safety and disaster management concepts. Such motivation is essential for fostering preparedness and proactive learning in communities vulnerable to dam failures.

4.4.3.3.3 Knowledge & Awareness

Figure 4.16 demonstrates participants' knowledge and awareness of dam failures before playing the game.

Figure 4.16

Participants' knowledge and awareness of dam failures before playing the game

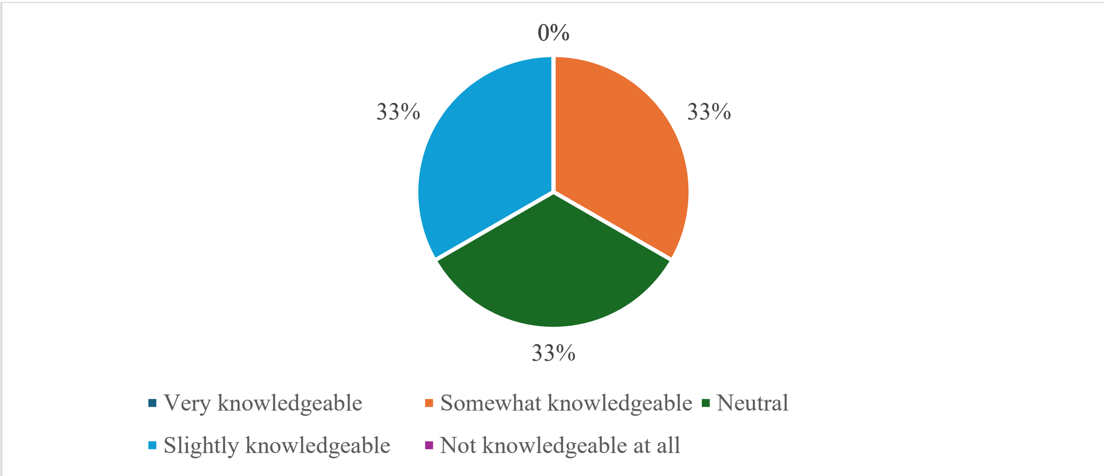
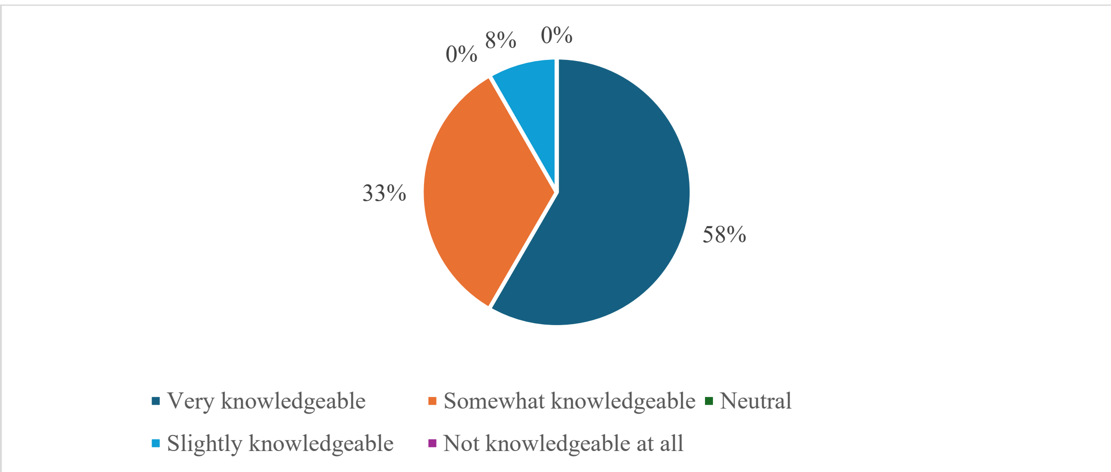


Figure 4.17 demonstrates participants' knowledge and awareness of dam failures after playing the game

Figure 4.17

Participants' knowledge and awareness of dam failures after playing the game



Before playing the game (Figure 4.16), participants' knowledge about dam failures was relatively limited. Responses were distributed across three categories: 33% somewhat knowledgeable, 33% slightly knowledgeable, and 33% neutral. Importantly, none of the participants rated themselves as very knowledgeable, highlighting a clear gap in awareness prior to the intervention.

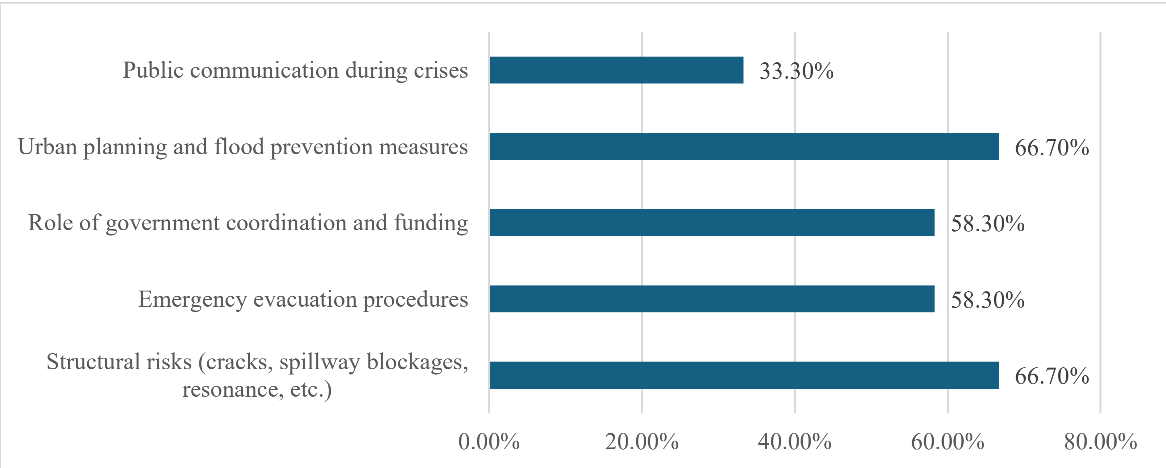
After playing the game (Figure 4.17), there was a marked improvement in self-reported knowledge. A majority of participants (58%) identified as very knowledgeable, with 33% somewhat knowledgeable and 8% slightly knowledgeable. No participants remained neutral or reported being unknowledgeable.

This shift demonstrates that the board game had a positive educational impact, significantly enhancing participants' awareness and understanding of dam failures. The findings suggest that interactive, game-based learning can be an effective tool in building disaster preparedness knowledge among vulnerable communities.

Figure 4.18 illustrates participants' views on dam-related challenges that the game helped them understand better.

Figure 4.18

Participants' views on dam-related challenges that the game helped them understand better



The results indicate that the board game enhanced understanding across multiple dimensions of dam-related challenges. The most frequently cited areas of learning were structural risks (67%) and urban planning/flood prevention measures (67%), suggesting that the game effectively highlighted technical and planning aspects of dam safety. Additionally, 58% of participants reported improved understanding of emergency evacuation procedures and the role of government coordination and funding, both of which are critical for effective disaster management. A smaller proportion (33%) indicated that the game helped them better grasp the importance of public communication during crises, which, while less prominent, still represents an important outcome.

4.4.3.4 Comparing game- and lecture-based learning for dam-failure awareness

The purpose of this stage was to evaluate the effectiveness of the board game in educating participants about dam failure and raising awareness of such incidents, with a particular focus on their potential to be used as an educational tool for communities vulnerable to dam-related risks. Figure 4.19 presents the pilot study conducted with undergraduates from the University of Moratuwa.

Figure 4.19

Pilot Study 2

4.4.3.4.1 Results of descriptive statistics

Descriptive statistics provide the initial overview of how students perceived the effectiveness of game-based learning (GBL) compared to conventional lecture methods. By averaging responses across ten Likert-scale items for each instructional approach, composite scores were generated to represent overall perceived effectiveness. The results reveal that GBL was rated substantially higher (M = 4.49, SD = 0.66) than lecture methods (M = 3.02, SD = 0.95). This indicates that, on average, students strongly favored the interactive and participatory nature of the game compared to traditional teaching. The lower variability (smaller SD) in the GBL condition also suggests greater consensus among participants about its effectiveness, whereas lecture ratings were more dispersed, reflecting varied levels of student engagement. Figures 4.20 and 4.21 visually reinforce these findings by showing clear differences in central tendency and confidence intervals. These statistics provide the foundation for subsequent inferential tests by demonstrating that the two instructional methods differ substantially at the descriptive level.

Figure 4.20

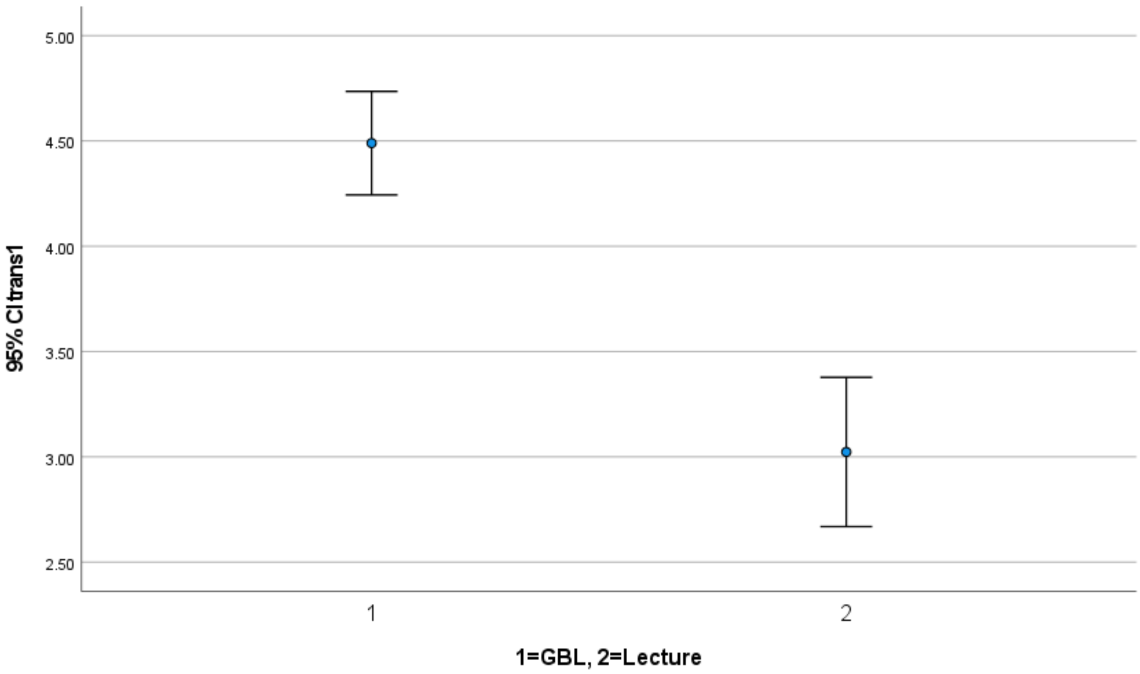
Descriptive statistics for GBL and lecture methods

Descriptive Statistics

	N	Minimum	Maximum	Mean	Std. Deviation
GBL_Total	30	2.60	5.00	4.4900	.65829
Lecture_Total	30	1.40	5.00	3.0233	.94893
Valid N (listwise)	30				

Figure 4.21

Error bar plot comparing mean effectiveness ratings (95% CI) of GBL and lecture methods



4.4.3.4.2 Reliability of Scales

Reliability analysis assesses the internal consistency of the Likert-scale items, ensuring that the composite scores are statistically valid representations of the constructions being measured. Cronbach's alpha values were calculated for both the GBL ($\alpha = 0.83$) and lecture ($\alpha = 0.81$) scales. Both exceed the commonly accepted threshold of 0.70, indicating good internal consistency (Nunnally & Bernstein, 1994). This means that the items within each scale measure the same underlying construct, perceived instructional effectiveness, with a high degree of coherence. The results validate the decision to combine individual items into composite scores, as they reflect reliable and stable measures of perception. Figure 4.22 illustrates these coefficients, providing evidence that the survey instrument used in this study was psychometrically sound. Without such reliability, the observed differences between GBL and lecture methods could not be interpreted with confidence.

Figure 4.22

Cronbach's alpha reliability coefficients for GBL and lecture scales

Reliability

Scale: ALL VARIABLES

Case Processing Summary

		N	%
Cases	Valid	30	20.0
	Excluded[a]	120	80.0
	Total	150	100.0

a. Listwise deletion based on all variables in the procedure.

Reliability Statistics

Cronbach's Alpha	N of Items
.964	10

Reliability

Scale: ALL VARIABLES

Case Processing Summary

		N	%
Cases	Valid	30	20.0
	Excluded[a]	120	80.0
	Total	150	100.0

a. Listwise deletion based on all variables in the procedure.

Reliability Statistics

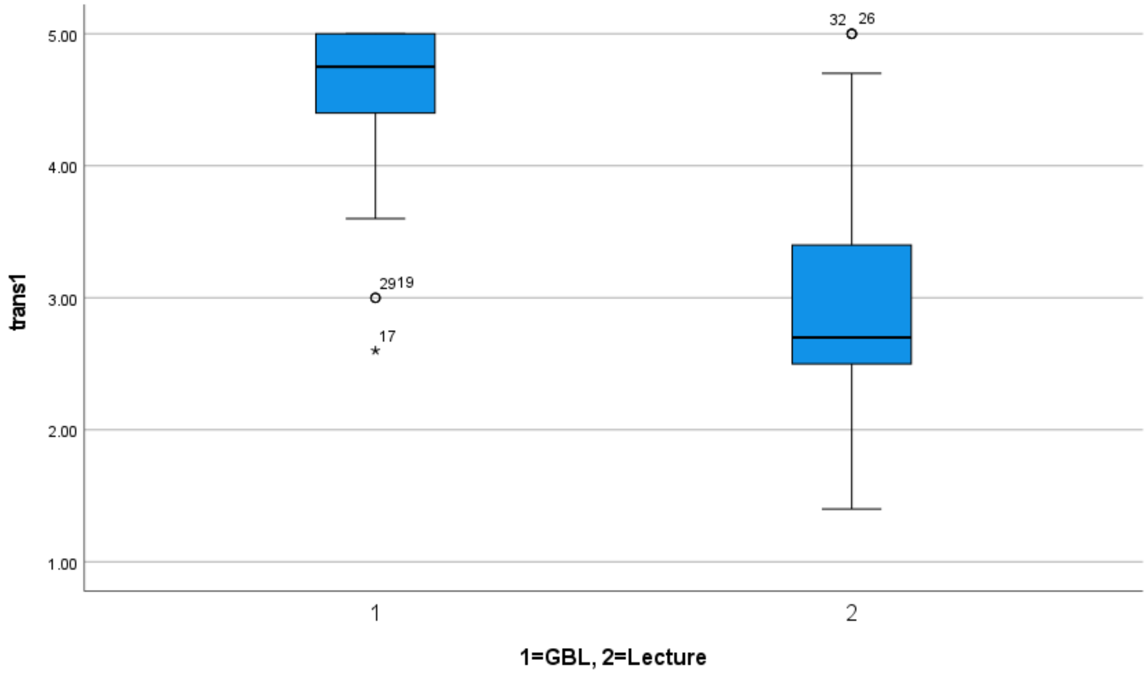
Cronbach's Alpha	N of Items
.966	10

4.4.3.4.3 Hypothesis Testing

To formally test whether the observed descriptive differences in effectiveness ratings were statistically meaningful, a paired samples t-test was conducted. The null hypothesis (H_0) posited no difference in effectiveness ratings between GBL and lecture methods, while the alternative hypothesis (H_1) suggested that students would rate GBL more effective. This choice of test was appropriate because the same group of participants rated both instructional methods, making the design within subjects and controlling for inter-individual variability. Figure 4.23 presents a boxplot of the distributions, showing a visible upward shift in median and interquartile range for GBL ratings compared to lecture ratings. This visualization complements the inferential analysis by highlighting that the differences were consistent across participants, rather than being driven by outliers or small subgroups.

Figure 4.23

Boxplot comparing distributions of GBL vs. lecture ratings



4.4.3.4.4 Results of the T test

The paired samples t-test yielded a highly significant result, $t(29) = 7.49$, $p < .001$, indicating that the probability of observing such a large difference by random chance is exceedingly small. On average, GBL scores were 1.47 points higher than lecture scores, with a 95% confidence interval ranging from 1.07 to 1.87. This demonstrates that GBL outperforms lecture-based instruction by at least one full point on the 5-point Likert scale. Figure 4.24 displays the t-test results in detail. The significance of these findings confirms that the preference for GBL is not anecdotal but systematically robust across the sample. This strong statistical evidence supports the conclusion that the game-based intervention provides a superior educational experience for communicating the risks of dam failure and improving disaster awareness compared to traditional lectures.

Figure 4.24

Results of paired-samples t-test

T-Test

Paired Samples Statistics

		Mean	N	Std. Deviation	Std. Error Mean
Pair 1	GBL_Total	4.4900	30	.65829	.12019
	Lecture_Total	3.0233	30	.94893	.17325

Paired Samples Correlations

		N	Correlation	Sig.
Pair 1	GBL_Total & Lecture_Total	30	.147	.439

Paired Samples Test

		Paired Differences					t	df	Sig. (2-tailed)
					95% Confidence Interval of the Difference				
		Mean	Std. Deviation	Std. Error Mean	Lower	Upper			
Pair 1	GBL_Total - Lecture_Total	1.46667	1.07265	.19584	1.06613	1.86720	7.489	29	<.001

Paired Samples Effect Sizes

			Standardizer[a]	Point Estimate	95% Confidence Interval	
					Lower	Upper
Pair 1	GBL_Total - Lecture_Total	Cohen's d	1.07265	1.367	.860	1.862
		Hedges' correction	1.08677	1.350	.849	1.838

a. The denominator used in estimating the effect sizes.
Cohen's d uses the sample standard deviation of the mean difference.
Hedges' correction uses the sample standard deviation of the mean difference, plus a correction factor.

4.4.3.4.5 Effect Size

While statistical significance establishes the existence of a difference, effect size quantifies its magnitude and practical relevance. Cohen's d was calculated as 1.37, which falls well above the threshold for a "large" effect (0.80) and thus represents an exceptionally strong impact of instructional method on perceived effectiveness. This effect size indicates that the average student's rating of GBL was more than one standard deviation higher than their rating of lectures, a difference that is not only statistically significant but also practically meaningful in educational terms. The application of Hedges' g (1.35), which corrects for small sample bias, confirmed the robustness of this finding. Such a large effect suggests that GBL fosters deeper engagement, motivation, and knowledge application, aligning with educational psychology theories that emphasize the benefits of active, experiential learning. In the context of dam safety awareness, this demonstrates the transformative potential of serious games as tools for risk communication and preparedness training.

4.4.3.5 Summary of PIII.SIII Outcomes: Board Game Development and Evaluation

The pilot testing of the dam safety board game demonstrated its strong potential as an educational and engagement tool for promoting disaster preparedness. Conducted with research participants at the University of Moratuwa, the pilot revealed that the game was highly engaging (100% rating "very engaging"), motivating all players to learn more about dam safety and disaster management. Participants highlighted the collaborative decision-making mechanism, requiring agreement among multiple stakeholders (engineer, planner, emergency responder, and official), as the most valuable feature, reinforcing teamwork and communication in crisis scenarios. The game's structure effectively mirrored real-world coordination challenges in disaster response, fostering critical thinking and cooperation.

Post-game assessments showed a significant improvement in knowledge and awareness of dam failures. Before gameplay, no participants rated themselves as "very knowledgeable," whereas after gameplay, 58% identified as very knowledgeable and 33% as "somewhat knowledgeable." Participants particularly improved their understanding of structural risks (67%), urban planning and flood prevention (67%), emergency evacuation procedures (58%), and institutional coordination (58%), with additional gains in public communication awareness (33%).

The second pilot study compared game-based learning (GBL) with traditional lecture-based instruction among university students. Descriptive statistics showed that GBL was rated substantially higher ($M = 4.49$, $SD = 0.66$) than lectures ($M = 3.02$, $SD = 0.95$), indicating stronger engagement and consistency of perception. Reliability analysis confirmed high internal consistency for both scales (Cronbach's $\alpha = 0.83$ for GBL; 0.81 for lectures), validating the measures. The paired samples t-test further revealed a statistically significant difference ($t(29) = 7.49$, $p < .001$), with GBL outperforming lectures by an average of 1.47 points on a 5-point scale. The effect size was large (Cohen's $d = 1.37$), confirming a practically meaningful advantage of GBL over lectures.

4.4.3.6 Key findings obtained from phase III to reduce the impacts from dam failures

Figure 4.25 shows the key findings obtained from phase III to reduce the impacts from dam failures

Figure 4.25

Key findings obtained from phase I to reduce the impacts from dam failures

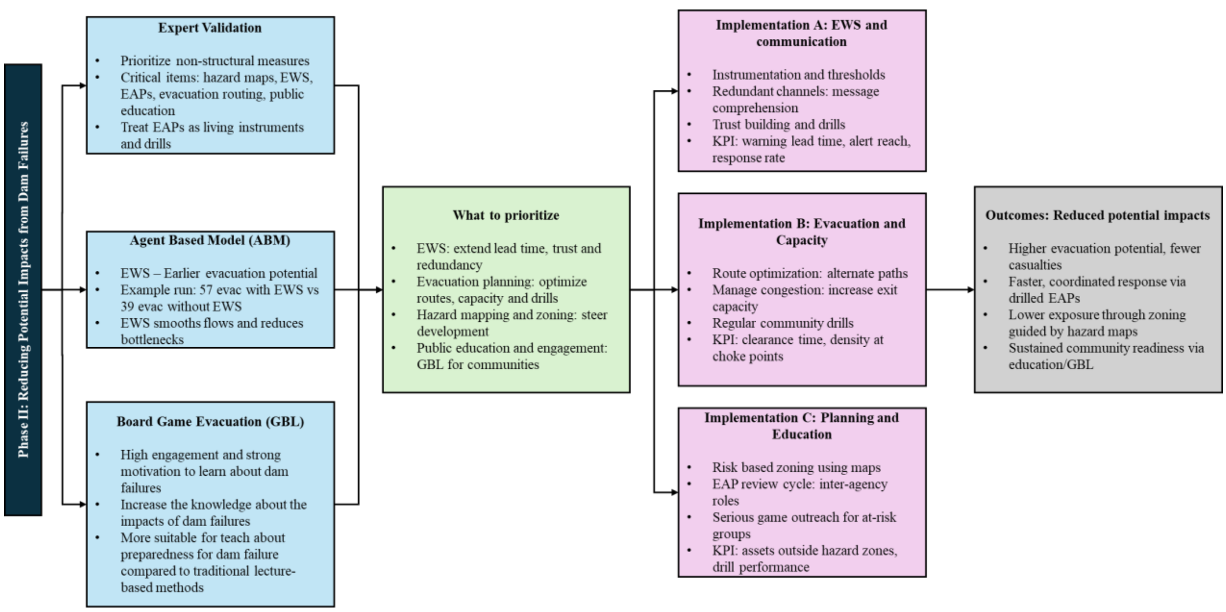


Figure 4.25 highlights how non-structural interventions can universally strengthen dam safety and disaster resilience. Insights from expert interviews, agent-based modelling, sensitivity testing, and educational tools (such as the serious board game) converge to show that early warning systems, optimized evacuation planning, emergency action plans, and public awareness are as critical as structural reinforcements. The modelling results prove that timely warnings and congestion management dramatically improve evacuation outcomes, while global sensitivity analyses emphasize that hazard intensity and bottlenecks shape casualty rates across contexts. The board game and community engagement methods illustrate that education and participation enhance preparedness in diverse cultural and social settings. Taken together, these findings are applicable far beyond a single case study: they demonstrate that investing in early warnings, evacuation capacity, hazard-aware planning, and risk communication can significantly reduce the human and economic costs of dam failures worldwide.

4.5 Chapter Summary

This chapter integrates findings from a systematic review, hydraulic modelling, expert interviews, agent-based simulations, and board game piloting to provide a comprehensive understanding of dam failure risks and community preparedness. The review highlighted the growing role of serious games in disaster education, though gaps remain in human behavior and resilience research. Hydraulic and geospatial analyses of the Kantale Dam quantified physical impacts across multiple breach scenarios, while expert interviews emphasized socio-economic consequences and the critical role of non-structural measures. The agent-based model illustrated how community decision-making shapes risk outcomes, and the piloted board game proved effective in enhancing engagement, knowledge retention, and preparedness compared to traditional methods. Together, these findings demonstrate the value of combining technical modelling with innovative educational strategies to strengthen resilience against dam failures.

5 CHAPTER 05: DISCUSSION

5.1 Chapter Introduction

This chapter synthesizes the study's findings by interpreting the technical, social, and educational dimensions of dam-break risk at the Kantale reservoir. It begins by analyzing the hydrodynamic simulation and geospatial overlays, which revealed terrain-driven flood pathways, rapid escalation of hazard curves, and the disproportionate impacts of a breach on Kantale town and its agricultural hinterland. It then extends the analysis to socio-economic consequences, highlighting vulnerabilities in housing, infrastructure, livelihoods, and cultural heritage. The chapter also explores preparedness and awareness, identifying major gaps in zoning, early warning, and community readiness that intensify disaster risk. Building on this, the agent-based model integrates human behavior into evacuation outcomes, demonstrating how early warnings and response capacity can mitigate losses despite extreme hazard intensity. Finally, the chapter discusses the role of serious games as an educational intervention, comparing their effectiveness with traditional lectures in strengthening disaster awareness. Together, these strands frame a multi-scalar discussion that bridges engineering, socio-economic, and educational insights into dam safety and disaster preparedness.

5.2 Phase I: To critically review: socio-economic impacts of dam failures and non-structural measures for minimizing the impacts of dam failures

The findings of Phase I underscore that the socio-economic consequences of dam failures extend far beyond the immediate physical destruction typically emphasized in engineering-focused risk assessments. As evidenced by expert testimony, the magnitude and nature of socio-economic disruption are shaped not only by the structural characteristics of dams but also by their functional role within wider socio-ecological and economic systems. This aligns with contemporary disaster risk literature, which positions dam failures as complex, cascading events capable of destabilizing both built and social environments.

A central theme emerging from the review is that the purpose and locational context of a dam critically determine the scale of socio-economic disruption. Experts highlighted those failures in irrigation-dependent regions, such as Kantale, can paralyze agricultural production, interrupting livelihoods, food supply chains, and income stability for farming communities. Agriculture is not merely an economic sector in such regions but a cultural and social foundation, meaning disruptions reverberate through multiple layers of community life. The review therefore strengthens the argument that dam risk assessments must incorporate local socio-economic profiles, rather than relying solely on hydrological or engineering parameters.

Another significant insight concerns the vulnerability of critical infrastructure networks, particularly transport and access routes. Expert observations that major roads such as the A6 could be severed by a breach highlight the interconnected nature of socio-economic risk: the obstruction of mobility would impede trade, schooling, and medical response capabilities. This reinforces the notion that dam failures should be conceptualized as system-wide disruptions rather than isolated structural events. Additionally, the potential loss of cultural assets and historical sites emphasizes that socio-economic impacts include intangible dimensions such as psychological trauma, cultural erosion, and long-term community dislocation.

The review also reveals the profound challenges associated with recovery; a phase often underrepresented in risk management discussions. The experts emphasized that rebuilding extends beyond repairing physical structures to restoring disrupted social systems, irrigation networks, schools, healthcare facilities, and the relational fabric of communities. This perspective aligns with broader disaster resilience frameworks that view recovery as a social process requiring coordinated institutional support, sustained funding, and community participation.

With respect to non-structural measures, the review identifies community-centred preparedness as essential for mitigating socio-economic impacts. Emergency action plans (EAPs) featuring clear evacuation protocols, communication systems, and coordinated response procedures were repeatedly highlighted as critical tools for saving lives and reducing losses. Notably, the emphasis placed on regular drills and community engagement reflects the understanding that risk communication must be culturally appropriate, trusted, and continuous. Experts' emphasis on empowering local communities underscores a shift from top-down governance to participatory risk management, where residents are active partners in preparedness rather than passive recipients of warnings.

As a result, Phase I establishes that reducing the socio-economic impacts of dam failures demands a holistic, multi-disciplinary approach. While engineering interventions remain vital, they must be complemented by non-structural measures that strengthen social resilience, enhance institutional coordination, and integrate community knowledge. The review ultimately reaffirms that socio-economic risk is a dynamic function of exposure, vulnerability, and institutional capacity, requiring comprehensive strategies that extend beyond the dam wall itself.

5.3 Phase II: Investigate the socio-economic impacts due to various failure scenarios

5.3.1 Interpretation of simulation and geospatial analysis results

The dam breach simulation results, derived using HEC-RAS 2D, highlight the varied inundation patterns based on the breach location of the Kantale Dam. The simulation results demonstrated a high level of realism in modeling flood propagation from various dam breach scenarios at Kantale. As noted in the literature, dam break modeling tools such as HEC-RAS are instrumental in estimating flood extents, peak discharge, and temporal patterns (Bharath et al., 2021; Ferrari et al., 2023). The model's ability to integrate digital elevation models (DEMs) and simulate terrain-induced flow patterns aligns with the findings of Shahrim & Ros (2020) and Pilotti et al (2020), who demonstrated the model's reliability in generating breach hydrographs and delineating inundated areas. This study effectively validated the simulation outcomes using expert feedback and terrain analysis, reinforcing the claim made by Delaney & Evans (2015) that floodwater movement is often dictated by topographic gradients.

Notably, Scenario III, representing a breach at the eastern end of the dam, produced the most devastating flood path, directly impacting Kantale town and the surrounding agricultural zones. This finding aligns with Ferrari et al (2023), who emphasize the importance of terrain-induced flow paths in determining flood impact zones. The topography of Kantale acts as a natural funnel, channeling floodwaters toward vulnerable urban and agricultural areas. This interpretation was strongly validated by expert responses, which highlighted how a breach along the eastern flank naturally directs water into Kantale's urban basin, thereby confirming the realism and accuracy of the simulation. Moreover, Scenario III closely mirrored the 1986 Kantale dam breach, further emphasizing the terrain's role as a natural conduit for floodwaters. These results underscore the predictive value of hydraulic modeling in identifying high-risk zones and highlight the importance of historical event calibration for ensuring model accuracy.

The hydrograph patterns reveal that the progression of inundation in Scenario III is both temporally intense and spatially extensive. Speaking of slowered to Scenarios I and II, which exhibit slower early-phase impacts and quicker stabilization, Scenario III maintained prolonged growth in cumulative hazard, indicating delayed peak hazard stabilization. Such characteristics necessitate early intervention, as late-phase flooding severely limits evacuation and disaster response times. The cumulative damage curve reaching nearly 400 buildings in less than 20 minutes underscores the rapidity with which urban structures can be overwhelmed, a finding consistent with Phyo et al. (2023) who argue for fine-resolution simulations in emergency planning.

The geospatial analysis added critical depth to the study by quantifying exposure to flood hazards through overlays of land cover, built-up areas, roads, and agricultural zones. This aligns with current research emphasizing the role of GIS in disaster risk mapping (Roulo & Pichuka, 2024; Vamvakeridou-Lyroudia et al., 2020). The analysis clearly revealed that all three breach scenarios threaten key infrastructure and economic assets, but Scenario III presented the highest risk, impacting both dense residential zones and vital agricultural lands. Such findings are consistent with Liang et al (2017), who stress the need for location-specific exposure mapping when assessing economic vulnerabilities from dam failures.

The cumulative hazard curves showed how rapidly the socio-economic impacts can evolve over time. Scenario III, which had the steepest curve, indicated a critical window in the early to middle phase of flooding where emergency response would be most essential. This underscores the time-sensitive nature of flood risk management and the necessity for early warning systems, as advocated by Ellingwood et al (1993) and Al Ruheili et al (2019).

5.3.2 Socio-economic impact from a dam failure

The results from both simulation and expert validation show that the most severe damage arises when the breach occurs on the right flank of the Kantale Dam (Scenario III), sending floodwater through agricultural lands and urban centers. This aligns with Quirogaa et al (2016) and Joshi

& Shahapure (2017), who found piping failures in earthen dams to be particularly destructive due to fast-moving, unconfined flow.

Geospatial analysis and expert interviews further revealed that agricultural disruption, housing damage, transportation system failure, and cultural site degradation are the primary socio-economic consequences of such a flood. Experts emphasized that these impacts extend far beyond the loss of physical infrastructure. Dam failures lead to large-scale displacement, food insecurity due to crop and irrigation losses, and heightened socio-economic inequality. These observations mirror the real-world outcomes of dam failures in Uganda (Mubialiwo et al., 2022) and Brazil (Haddad & Teixeira, 2015).

Kantale's economy is predominantly agriculture-based, relying heavily on a vast network of paddy fields irrigated by the reservoir. The simulations demonstrated that in all three breach scenarios, floodwaters inundate these fields, with Scenario III causing the greatest losses. In total, approximately 35.22 km^2 of agricultural land would be submerged, representing a devastating blow to local food security and rural livelihoods. This supports the findings of Samsuddin et al. (2024), who highlighted the vulnerability of local economies to dam failures through damage to irrigation infrastructure and disruption of agricultural productivity. Moreover, the loss of road connectivity, particularly the A6 highway as noted by several experts, isolates communities, and obstructs access to essential services, complicating post-disaster recovery and emergency healthcare access.

In addition to economic disruptions, the expert interviews illuminated significant social impacts. These include forced displacement, increased public health risks, and enduring psychological trauma, especially among women, children, and the elderly (Lassa et al., 2023; Lorenzoni et al., 2020). As several experts pointed out, the current population density of Kantale far exceeds that of 1986, implying a far greater scale of displacement and social disruption should a similar event occur again.

Cultural and historical losses were also prominently noted by experts. Kantale is home to numerous religious and historical landmarks that are located within the floodplain. A breach of this magnitude could irreversibly damage these sites, resulting in cultural erasure with long-lasting implications for local identity and community cohesion (Carmo et al., 2017).

5.3.3 Preparedness and Community Awareness

Despite the evident risks, the study found preparedness among downstream communities to be alarmingly low. This is consistent with global findings, such as those from Vamvakeridou-Lyroudia (2020), which noted weak disaster resilience in developing nations due to inadequate communication systems and planning. In Kantale, awareness campaigns, flood drills, and local response teams are virtually non-existent, as emphasized by experts. Furthermore, experts stressed that most residents are unaware of their residence within potential inundation zones, and land use planning does not restrict development in these high-risk areas. Without integrating flood modeling outputs into local planning policies, communities remain exposed. Elaborating further experts argued for the establishment of risk-sensitive zoning, supported by hydrodynamic maps, and the creation of designated evacuation routes and shelters.

A critical finding of the study is the evident gap in preparedness among communities living downstream of major dams. Despite the frequency of such catastrophic failures globally, expert interviewees uniformly indicated low levels of public awareness, early warning mechanisms, and structured evacuation plans. This insight corroborates global trends reported by Liang et al (2017), who argues that most developing nations lack proactive dam failure response systems. As several experts elaborated, current urban and rural planning rarely integrate flood risk zones into zoning regulations or development control, allowing critical infrastructure and housing to be built in high-risk areas. This regulatory vacuum is particularly dangerous in rapidly urbanizing areas like Kantale, where population growth is outpacing risk-informed land use planning. Experts also identified that marginalized groups are disproportionately affected by having limited resources to evacuate, rebuild, or recover post-disaster. This vulnerability highlights the intersection of disaster risk and social inequality, emphasizing the need for equitable risk reduction strategies (Vamvakeridou-Lyroudia et al., 2020).

Experts proposed several mitigation strategies, reflecting a shared recognition of the need for multi-pronged approaches to disaster risk reduction. Key recommendations included the implementation of regular drills and educational campaigns, the enforcement of land-use planning informed by hydrodynamic modelling outputs, and the empowerment of local communities through the establishment of community-based disaster risk committees to enhance grassroots-level preparedness and resilience. The interviews further revealed a clear consensus that community preparedness for dam failures remains critically low, a finding consistent with global patterns reported by Roberts et al. (2021) and Lassa et al. (2023). In the case of Kantale, most downstream residents lack access to early warning systems, formal evacuation plans, or even basic awareness of potential flood hazard zones. This highlights a significant gap between the advanced simulation capabilities available to researchers and practitioners and the actual state of readiness at the community level. Such findings validate the argument made by Kalinina et al. (2018) that, despite technological progress, institutional and social preparedness often lag, leaving populations vulnerable in the face of disaster events.

5.4 Phase II: Formulation of Prototype Non-Structural Measures

This phase primarily focuses on the agent-based model to illustrate the importance of installing effective early warning systems (EWS) in dams, as well as on the board game developed as a mechanism for raising awareness of the consequences of dam failures.

5.4.1 Interpretation of the results of the Agent Based Model

5.4.1.1 Integration of Technical and Human Dimensions

The agent-based model (ABM) developed in this study demonstrated that evacuation outcomes during a dam-break event are shaped by the interplay of both technical infrastructure and human decision-making processes. While structural variables such as flood velocity and route capacity define the hazard environment, the model showed that behavioral heterogeneity, differences in reaction time, mobility, and compliance, critically determines survival. Individuals with slower mobility or delayed responses were disproportionately vulnerable to fatalities, which aligns with the protective action decision framework (Lindell & Prater, 2007). However, these vulnerabilities were significantly mitigated when an Early Warning System (EWS) was present, as alerts triggered earlier departures, reducing exposure to floodwaters. This underscores the value of embedding human behavioral dynamics within hazard simulations, highlighting a dual dependency between environmental intensity and social responsiveness often underrepresented in earlier models (Pel et al., 2012).

The qualitative insights obtained from expert interviews reinforced this duality, stressing that technological capacity alone does not guarantee effectiveness. Alerts must be understood, trusted, and rehearsed by communities to translate into meaningful action. Many existing Emergency Action Plans (EAPs) are criticized as static documents rather than dynamic preparedness tools (Rahubadda et al., 2024), and the ABM illustrates the consequences of such shortcomings. Without adequate trust and familiarity, even advanced early-warning technologies risk underutilization. Thus, the model contributes not only a quantification of EWS benefits but also an argument for situating these systems within broader socio-technical frameworks of trust, awareness, and education.

5.4.1.2 Sensitivity of Outcomes to Hazard Intensity and Response Capacity

The results of the sensitivity analysis demonstrate a clear interplay between hazard intensity and system response capacity, aligning closely with established findings in dam-break modelling and evacuation literature. The dominance of flood speed in the gradient boosting analysis reinforces longstanding hydrodynamic research showing that high-velocity flows sharply increase mortality risk and reduce available evacuation time (Jonkman & Penning-Rowsell, 2008). This finding is further supported by global sensitivity screening, which identifies flood speed as a major contributor, particularly in the absence of early warning systems (EWS). At the same time, the model reveals that congestion plays an equally critical role, with the Morris analysis identifying it as the most influential parameter once early warnings are introduced. This aligns with evacuation science literature that situates crowd dynamics, bottlenecking, and density-dependent mobility as dominant constraints on evacuation success, even when individuals comply with alerts (Helbing, Farkas & Vicsek, 2000; Lovreglio et al., 2014). The combined prominence of flood speed and congestion confirms that evacuation performance is an emergent property shaped not only by physical hazard conditions but also by the behavioural and infrastructural characteristics of exposed populations.

The dramatic improvements observed when early warning systems were activated, mean evacuations rising from 70 to 170 and casualties falling from 570 to around 300, are consistent with global evidence showing that timely warnings can reduce disaster mortality by 30–60% (Basher, 2006). Historical events such as the Oroville Dam crisis illustrate the critical value of fast and credible alerts, where early warnings played a decisive role in mass evacuation outcomes (Independent Forensic Team, 2018). The nonlinear gains observed in this model, where even modest increases in lead time substantially raise survival rates, parallel international early warning research demonstrating that additional minutes before hazard arrival provide disproportionately large benefits (Pappenberger et al., 2015). However, once the presence of EWS was fixed, the influence of lead time and exit capacity diminished in the global analysis, suggesting diminishing marginal returns when warnings already stagger evacuation flows. This pattern is consistent with evacuation modelling studies showing that infrastructure improvements matter most when departures are highly synchronized, but less so when warnings distribute evacuees more evenly over time (Pel et al., 2012).

The analytical approach also underscores the strongly nonlinear nature of evacuation systems. The linear regression model explained none of the variance ($R^2 = 0$), confirming that evacuation outcomes cannot be captured by simple additive relationships. This mirrors findings in agent-based evacuation research across floods, tsunamis, and wildfires, where threshold effects, interactions, and feedback loops dominate system behavior (Gwynne et al., 2019; Chen et al., 2021). The divergence between local feature importance (random forest and gradient boosting) and global sensitivity results further supports the assertion that parameter influence is context-dependent, a characteristic often noted in complex systems modelling (Saltelli et al., 2008). While tree-based methods highlighted the importance of all four parameters, with slight preference for lead time and exit capacity, the global Morris analysis exposed deeper nonlinearities, elevating congestion as the primary driver once warning conditions were controlled.

Therefore, the findings of this study reinforce the broader consensus in the literature that dam-break risk is governed by a combination of hydrodynamic hazard characteristics and socio-technical response capacities. Flood speed sets the baseline severity of the event, but congestion, lead time, and exit capacity collectively determine the system's ability to convert available time into successful evacuation. The integration of model outputs with established research provides compelling evidence that targeted investments in early warning systems and crowd-flow efficiency can substantially reduce casualties, even under high-intensity flood scenarios. In doing so, the study contributes to a growing body of research advocating for multi-layered dam safety strategies that combine physical hazard mitigation with behavioral and infrastructural preparedness.

5.4.1.3 Policy and Practical Implications

The results of the ABM hold significant implications for dam safety management and disaster risk reduction. First, expanding the coverage and compliance of early-warning systems should be considered a priority. The model demonstrated that increasing community coverage from 50% to 90% yielded near-linear improvements in evacuation success, reinforcing the critical role of universal access. Second, technological advances must be coupled with participatory education campaigns. Experts emphasized that warnings are ineffective if not trusted or understood, and rehearsals are essential to bridge the awareness gap. Third, integration of ABM outputs into decision-support tools can strengthen training exercises for dam operators and emergency managers by visualizing not only the scale of casualties but also the cascading effects of delays, non-compliance, or inadequate infrastructure.

These findings are particularly relevant for regions where resources for structural dam rehabilitation are limited. In such contexts, EWS represents a cost-effective non-structural intervention that can substantially reduce disaster risk. The implications also extend to tailing dams, where failures remain frequent and catastrophic. Implementing operational EWS alongside strong community engagement could provide an immediate, pragmatic step toward compliance with international standards, such as those promoted by the United Nations Environment Programme (UNEP) et al. (2020).

5.4.2 Interpretation of the results of the Board Game

5.4.2.1 Development process of the game and its mechanism

The development of the board game in this study was not a linear design exercise, but an iterative process grounded in both theoretical insights from serious games literature and practical feedback from participants. At its core, the game mechanism was designed to replicate the complexities and uncertainties of decision-making under disaster conditions, particularly dam failure events. By requiring teams to deliberate over multiple decision options for hypothetical scenarios, the game fostered structured dialogue and collective reasoning. This aligns with Arnab et al. (2015), who emphasize that serious games can act as "pedagogical engines" when they provide space for reflection, debate, and the negotiation of meaning.

A notable design choice was the inclusion of a central circular spinner, which served to evaluate the criticality of decisions made by each team. This element of chance introduced unpredictability, reflecting the stochastic nature of real-world dam failure outcomes, where even well-reasoned interventions may be influenced by uncontrollable external factors. Scholars such as Wouters et al. (2013) and Gee (2007) argue that such stochastic components in games enhance realism, while still allowing learners to critically engage with core concepts. The spinner therefore functioned as both a didactic and symbolic mechanism, underscoring the limits of control in disaster scenarios.

The reward system further evolved through iterative refinement. In the initial mechanism, only teams making the highest-ranked decision were permitted to place tiles on board. While logical in theory, this structure had the unintended consequence of discouraging teams who selected suboptimal yet defensible decisions. Pilot study feedback suggested that this approach risked disengagement among players who, despite strong reasoning, saw no tangible recognition of their efforts. Responding to this critique, the mechanism was updated to allow the team that selected the second-best option to also place a tile. This adjustment not only improved fairness but also encouraged ongoing motivation, reflecting Gee (2007) assertion that effective game-based learning must recognize multiple levels of achievement. The iterative process thus exemplifies the adaptive nature of game design, where responsiveness to user experience ensures alignment between pedagogical objectives and gameplay.

The final output of the board game was therefore a balanced integration of strategy, chance, and collaboration. The visual design of the board itself emphasized dam-related challenges, with zones representing structural issues, socio-economic impacts, and emergency management considerations. The tangible, physical nature of the board game distinguished it from widely available digital serious games, such as Stop Disasters! developed by UN/ISDR. Whereas digital platforms often prioritize resource optimization through computational modeling, the present board game highlighted argumentation, justification, and interpersonal negotiation as central learning outcomes. Flood et al. (2018) note that serious games serve as catalysts for social learning when they encourage group deliberation rather than individual optimization, a principle that was deliberately embedded into this design.

5.4.2.2 Results from the piloting phase

Quantitative and qualitative feedback from the pilots confirmed that the game was both engaging and motivating. Participants consistently reported that the competitive, yet collaborative structure encouraged active participation, while the element of chance-maintained excitement. Importantly, participants also highlighted the game's effectiveness in making them reflect on critical challenges, such as emergency evacuation, the socio-economic ripple effects of dam failure, and the trade-offs involved in structural versus non-structural responses. These findings echo Wouters et al. (2013), who argue that serious games are most impactful when they engage both cognitive and affective dimensions of learning.

One of the most significant outcomes of the pilot studies was the measurable improvement in participants' knowledge and awareness of dam failures. Pre-game assessments indicated that participants had limited or moderate familiarity with the subject. Post-game evaluations, however, revealed a marked increase, with most participants identifying as "very knowledgeable." This finding resonates with Reckien & Eisenack (2013) work, which demonstrates that serious games can significantly enhance disaster risk awareness by contextualizing abstract hazards into relatable scenarios. In this sense, the board game in this study effectively functioned as a non-structural measure for disaster risk reduction, raising awareness in ways that traditional lectures or reports may not achieve.

The results of Pilot Study 2 clearly demonstrate that game-based learning (GBL) was perceived by participants as significantly more effective than conventional lecture-based methods. Students rated GBL substantially higher ($M = 4.49$, $SD = 0.66$) compared to lectures ($M = 3.02$, $SD = 0.95$), with a large and statistically significant difference confirmed by a paired-samples t-test ($t(29) = 7.49$, $p < .001$, Cohen's $d = 1.37$). These findings strongly support the proposition that interactive, experiential approaches provide deeper educational benefits in the context of dam safety awareness.

This aligns with a growing body of literature that has demonstrated the pedagogical advantages of active and participatory learning. For instance, Gee (2003) and Prensky (2007) argued that games promote problem-solving, engagement, and collaboration, qualities often absent in traditional didactic methods. Similarly, Wouters et al. (2013) found that serious games not only enhance motivation but also improve knowledge retention compared to lectures. The results of the current pilot study echo these findings, showing that learners not only preferred the game format but also evaluated it as markedly more effective in conveying complex disaster-related content.

In the field of disaster education, prior studies have also emphasized the need for interactive tools to raise awareness and preparedness. Shahraki et al. (2012) and Xiao et al. (2022) showed that traditional approaches such as awareness campaigns or school-based lectures often struggle to maintain engagement or translate into behavioral readiness. In contrast, gamified interventions have demonstrated stronger impacts on risk perception and preparedness behaviors (van der Meij et al., 2020). The present study's results are consistent with this trend: students responded more positively to the board game, suggesting that active participation, role-play, and scenario-based decision-making create a more memorable and impactful learning experience than passive listening.

The exceptionally large effect size (Cohen's d = 1.37) also reinforces findings by Connolly et al. (2012), who observed that digital and analogue educational games often yield medium-to-large effects on motivation and skill development. In the context of disaster risk reduction, this magnitude of difference is especially meaningful, since engagement is not merely an academic outcome but a prerequisite for effective preparedness and survival during crises. By distributing decision-making across teams and simulating real-time constraints, the board game appears to have successfully reproduced the kinds of pressures and collaborative dynamics that are crucial in actual emergency responses.

At the same time, the results diverge from some earlier work which suggested that lectures, while less engaging, still provide reliable baseline knowledge transfer (Clark et al., 2016). In this study, however, lecture ratings not only averaged lower but also showed greater variability, suggesting that while some students benefitted from lectures, others disengaged entirely. This variability undermines the consistency of lectures as a sole method for disaster awareness education. The finding strengthens arguments by Kolb (1984) and more recently by Boyle et al. (2016), who highlight that experiential learning ensures more uniform participation and deeper internalization of concepts.

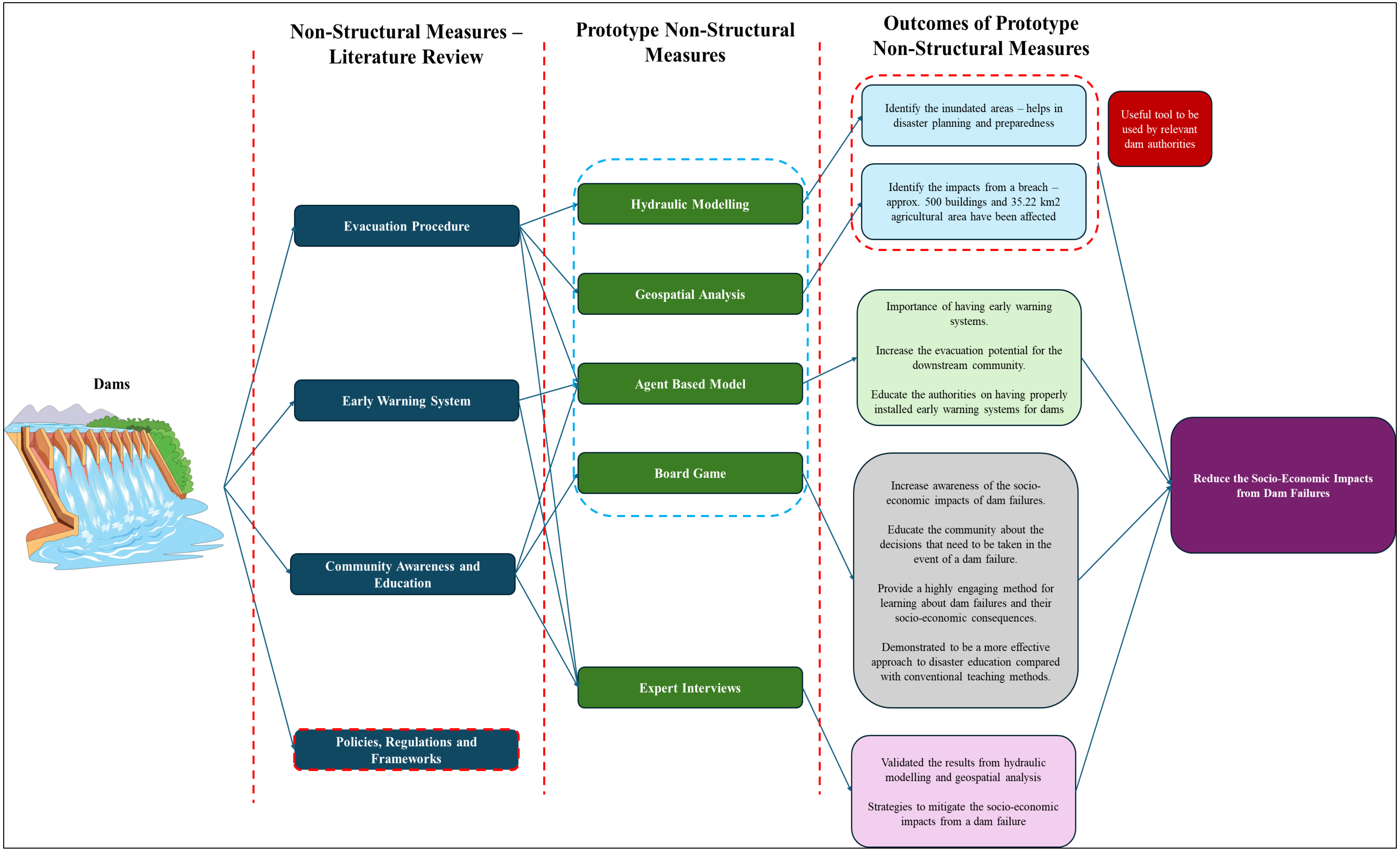
Taking together, the findings of this pilot study contribute to the growing consensus that serious games represent a powerful supplement, and in some contexts an alternative, to traditional lecture-based education. For disaster preparedness, where the goal is not only knowledge transfer but also behavioral readiness, GBL provides unique advantages by embedding learners in interactive, scenario-based environments that encourage both cognitive and affective engagement.

5.5 Final framework on non-structural measures in reducing the socio-economic impacts of dam failures

The framework developed in this research (see Figure 5.1) illustrates how key non-structural measures, evacuation procedures, early warning systems, community awareness and education, and policies and regulatory frameworks, can be systematically evaluated to determine their effectiveness in reducing the socio-economic impacts of dam failures. These measures are linked to a suite of analytical and prototype-based tools, including hydraulic modelling, geospatial analysis, agent-based modelling, board game, and expert interviews, each providing unique insights into preparedness, risk communication, and community resilience. Through hydraulic and geospatial analyses, the framework identifies inundation extents, quantifies impacts such as the number of affected buildings and agricultural land, and supports evidence-based disaster planning. Agent-based modelling further examines human behavior and evacuation dynamics, while the early warning assessment highlights the importance of timely alerts and improved downstream evacuation potential. The board game serves as an innovative educational tool that enhances community understanding of dam failures and required emergency actions, demonstrating greater engagement compared with traditional methods. Expert interviews validate these findings and ensure their relevance to practical dam safety management. Collectively, the framework demonstrates that non-structural measures are most effective when applied in combination, integrating technical, behavioral, and educational approaches to strengthen preparedness and ultimately reduce the socio-economic impacts of dam failures.

Figure 5.1

Final framework on non-structural measures in reducing the socio-economic impacts of dam failures



5.6 Chapter Summary

This chapter demonstrates that dam failure risks at Kantale are shaped by both environmental and human factors. Hydrodynamic and geospatial analyses established that topography channels catastrophic floods into urban and agricultural areas, with Scenario III replicating the devastation of the 1986 breach. The socio-economic analysis emphasized cascading disruptions to livelihoods, infrastructure, and cultural assets, while also highlighting social inequities in recovery. Findings on preparedness exposed a stark gap between advanced modeling capacity and low community readiness, underscoring the urgent need for risk-sensitive planning and early warning. The agent-based model reinforced that while hazard intensity defines baseline risk, human decision-making and timely alerts substantially influence survival outcomes. Finally, the evaluation of serious games confirmed their value as a participatory and engaging supplement to disaster education, outperforming lecture-based approaches in promoting awareness and behavioral readiness. Collectively, the chapter positions dam-break risk as not only a technical challenge but also a socio-technical and educational one, requiring integrated approaches that combine modeling, policy, community resilience, and innovative learning tools.

6 CHAPTER 06: CONLCUSION AND RECOMMENDATIONS

6.1 Chapter introduction

This chapter brings the study to its conclusion by synthesizing the key findings and demonstrating how the research objectives were achieved. It revisits the aims set at the outset, showing how the integration of hydraulic modelling, geospatial analysis, expert interviews, agent-based modelling, and gamified learning contributed to a deeper understanding of the socio-economic impacts of dam failures and the role of non-structural measures in reducing risk. The discussion highlights both theoretical and practical contributions, particularly the value of combining technical analyses with community-based educational strategies to strengthen preparedness. The chapter also presents recommendations for policy and practice, acknowledges limitations, and suggests directions for future research, before closing with a reflection on the broader significance of non-structural measures in enhancing dam safety and community resilience.

6.1.1 Achievement of objective 1: To critically review: socio-economic impacts of dam failures and non-structural measures for minimizing the impacts of dam failures

Objective 1 was achieved through a narrative literature review complemented by insights obtained from expert interviews. The narrative review enabled a critical synthesis of existing scholarship on the socio-economic consequences of dam failures, including direct economic losses, disruptions to livelihoods, long-term community displacement, and broader regional development impacts. This approach allowed for the integration of diverse sources, ranging from peer-reviewed studies to technical reports, thereby providing a comprehensive understanding of both the immediate and cascading effects of dam failure events on affected populations.

To strengthen and contextualize the findings from the literature, expert interviews were conducted with professionals in dam safety, emergency management, and civil infrastructure resilience. These interviews provided nuanced, practice-based perspectives on the effectiveness and limitations of non-structural measures such as early warning systems, community preparedness programmes, risk communication strategies, and emergency action planning. The insights gathered also clarified how institutional capacity, governance frameworks, and stakeholder engagement influence the successful implementation of such measures.

Collectively, the narrative synthesis and expert testimony offered a robust and holistic evaluation of the socio-economic impacts associated with dam failures and the role of non-structural interventions in reducing these impacts. This dual-method approach ensured that Objective 1 was fully met by integrating theoretical knowledge with real-world professional experience, allowing for a well-rounded and critically informed understanding of the topic.

6.1.2 Achievement of objective 2: To investigate the socio-economic impacts due to various failure scenarios using Simulation/ GIS/ Interviews

The second objective was achieved by combining hydraulic modelling, geospatial analysis, and qualitative insights from stakeholder interviews. The 2D HEC-RAS simulations of a piping failure at the Kantale Dam provided detailed outputs on breach parameters, flood depth, velocity, inundation extent, and arrival times in downstream communities. These outputs were integrated with GIS-based spatial mapping to identify vulnerable settlements, infrastructure, and agricultural zones at risk from the modeled flood scenarios. This quantitative analysis established the potential scale and spatial distribution of socio-economic damage under different breach conditions.

To complement these technical findings, semi-structured interviews with local and global stakeholders and experts were conducted. The interviews validated the modelling output while capturing lived experiences, perceptions of risk, and the broader social and economic consequences of dam failure. Respondents emphasized not only immediate threats to life and property but also long-term disruptions to livelihoods, displacement, and economic instability in affected regions.

By integrating simulation results with community-based perspectives, the study produced a holistic understanding of dam-break consequences. The modelling quantified the hazard with precision, while the interviews revealed the human dimension, highlighting issues such as psychological stress, inequities in vulnerability, and the role of local coping strategies. This dual approach ensured that the assessment of socio-economic impacts was both evidence-based and contextually grounded. In doing so, the objective was fully achieved, offering a comprehensive picture of how dam failures can reverberate across physical, social, and economic systems.

6.1.3 Achievement of objective 3: To identify and develop prototypes for non-structural measures.

This objective was achieved by critically examining and testing a range of non-structural measures designed to reduce the consequences of dam failures. The study recognized that while structural interventions remain vital, non-structural measures offer sustainable, adaptive, and community-centered approaches that are often more feasible in resource-limited settings.

Through narrative literature review, early warning systems, evacuation planning, community training, and risk awareness campaigns emerged as proven measures widely recommended in dam safety management. Building on these insights, the study employed hydraulic modelling and GIS mapping to delineate inundation zones, providing the technical basis for preparedness and evacuation planning. These spatial outputs were directly used to inform targeted non-structural interventions for at-risk communities.

A key innovation of the study was the use of an Agent-Based Model (ABM) to simulate human behavior and decision-making during dam-break scenarios. ABM allowed for the exploration of how individuals and households might respond to warnings, evacuation orders, and resource constraints under different failure scenarios. This provided valuable insights into potential bottlenecks, delays, and vulnerabilities in evacuation processes that cannot be captured by hydraulic modelling alone. By modeling social dynamics alongside physical flood hazards, the ABM demonstrated the importance of integrating behavioral factors into preparedness strategies.

Complementing the modelling, semi-structured interviews with stakeholders underscored the necessity of community engagement and knowledge dissemination. Respondents emphasized that socio-economic vulnerabilities could be significantly reduced if communities were provided with timely alerts, accessible risk information, and opportunities for collective learning. The serious board game developed in this study further reinforced this by serving as an experiential learning tool. Participants gained practical understanding of dam-related risks, decision-making under uncertainty, and the trade-offs inherent in disaster management, demonstrating the effectiveness of educational gamification in enhancing preparedness.

Thus, this objective was fulfilled by combining technical tools (hydraulic modelling, GIS, and ABM) with participatory approaches (interviews and board game piloting). Together, they highlighted those non-structural measures, especially when grounded in behavioral modelling and community-based training, can significantly strengthen resilience, empower local populations, and align with the best global practices in disaster risk reduction and governance.

6.1.4 Achievement of objective 4: To evaluate the effectiveness of non-structural measures in minimizing the socio-economic impacts of dam failures through the developed prototypes

Objective 4 was achieved by evaluating the effectiveness of selected non-structural measures using the prototypes developed as part of this research. These prototypes, designed to operationalize key elements of early warning, community preparedness, and risk communication, provided a practical means of assessing how non-structural interventions can contribute to reducing the socio-economic impacts associated with dam failures.

The evaluation process involved testing the prototypes against criteria derived from both the systematic literature review and the insights gained from expert interviews. This included assessing their usability, clarity, functionality, and potential for integration into existing dam safety and emergency management frameworks. By simulating real-world decision-making and information-dissemination contexts, the prototypes allowed the research to move beyond theoretical assessment and into applied validation.

The findings demonstrated that well-designed non-structural measures can significantly enhance preparedness and response capacity among stakeholders, thereby mitigating socio-economic consequences such as loss of life, damage to property, and disruption to livelihoods. The prototype-based evaluation also highlighted practical considerations for implementation, including resource requirements, technological readiness, and user engagement.

Through this applied assessment, the research confirmed the potential of non-structural measures to play a critical role in reducing the socio-economic impacts of dam failures. The prototype evaluation thus fulfilled Objective 4 by providing evidence-based insights into the operational effectiveness and real-world applicability of these interventions.

6.2 Contribution to Knowledge

This study makes several significant contributions to academic discourse and practical understanding of dam safety, socio-economic vulnerability, and innovative non-structural measures for disaster risk reduction.

First, the research advances knowledge by systematically reviewing socio-economic impacts of dam failures and synthesizing global case studies to highlight recurring vulnerabilities, cascading impacts, and existing gaps in preparedness frameworks. Unlike prior studies that often addressed structural and engineering aspects in isolation, this research integrates both technical and social dimensions, thereby offering a more holistic perspective.

Second, the study contributes to methodological innovation through the integration of hydraulic modelling, GIS-based analysis, and agent-based modelling (ABM). By applying the HEC-RAS 2D model to the Kantale Dam case study, the research provides detailed flood propagation insights and visualizations of inundation scenarios. The inclusion of socio-economic data and interviews enriches this technical modelling, ensuring that the human dimensions of dam failure are captured alongside hydrological risks. The use of ABM further strengthens the analysis by simulating community responses and decision-making processes, which have rarely been explored in existing dam safety research.

Third, the research advances non-structural disaster management measures by developing and piloting a gamified board game. This innovative tool bridges the gap between technical knowledge and community-level awareness, offering a replicable model for disaster education. The iterative design process, informed by pilot testing and participant feedback, demonstrates how gamification can effectively translate complex risk information into accessible and engaging learning experiences. In doing so, the study provides an original contribution to the literature on risk communication and community preparedness, particularly in relation to dam safety domain where gamified approaches remain underexplored.

Finally, the study contributes practically by offering a framework for multi-method integration in disaster risk research. The pragmatic combination of systematic literature review, advanced simulation techniques, qualitative interviews, and participatory gamification provides a comprehensive template that can be applied to other infrastructure-related hazards. This integrative methodology not only strengthens the robustness of the findings but also demonstrates the value of combining technical precision with participatory engagement for enhancing disaster resilience.

6.3 Recommendations

Based on the findings of this study, several recommendations are proposed for policymakers, practitioners, and researchers to strengthen dam safety management, mitigate socio-economic impacts, and advance innovative non-structural measures for disaster preparedness. First, dam safety assessments should extend beyond structural evaluations to incorporate socio-economic impact analyses, ensuring that evacuation planning, livelihood disruption, and community vulnerabilities are effectively addressed. Regular socio-economic surveys in downstream communities should be institutionalized to capture evolving risks and update preparedness strategies accordingly. In parallel, greater emphasis should be placed on non-structural measures, including awareness campaigns, community-based early warning systems, and participatory training exercises, with disaster education programs mandated and tailored to local contexts as vital complements to engineering safeguards. Advanced modelling approaches should also be systematically integrated, with hydraulic models such as HEC-RAS used to simulate dam-break scenarios under multiple conditions and linked with GIS-based socio-economic mapping to provide actionable visualizations of flood risks.

Moreover, Agent-Based Modelling (ABM) should be employed to simulate community behavior during disaster events, enabling planners to anticipate response patterns and optimize preparedness. Another key recommendation is the adoption of gamification in disaster education. The board game developed in this study demonstrated strong potential to enhance knowledge, motivation, and preparedness among participants, and future efforts should focus on adapting such tools within disaster management frameworks, including developing digital versions to broaden reach and engage younger demographics. Finally, dam safety management should be embedded within broader institutional and policy frameworks, requiring multi-stakeholder collaboration among water authorities, disaster agencies, local governments, and communities, with clear roles and responsibilities for preparedness and response. Governments should further align dam safety strategies with climate change adaptation and global disaster risk reduction frameworks, recognizing the growing uncertainty and severity of extreme hydrological events.

6.4 Future Research Directions

Future research should focus on evaluating the long-term effectiveness of gamified approaches in shaping behavior and sustaining preparedness within communities vulnerable to dam failures. While this study demonstrated the potential of serious games to enhance awareness and decision-making, longitudinal studies are necessary to determine whether these behavioral changes persist over time. Comparative studies across different cultural and geographic contexts would also provide valuable insights into the scalability and adaptability of gamification as a disaster education tool. In addition, future investigations should explore hybrid methodologies that integrate hydraulic modelling, Agent-Based Modelling (ABM), and participatory approaches to produce more comprehensive and context-specific risk assessments. Such combinations would enable both quantitative simulation of flood dynamics and qualitative insights into human behavior under disaster scenarios, thereby strengthening preparedness strategies. Finally, expanding the research scope beyond dam failures to encompass other critical infrastructure risks, such as levees, reservoirs, and urban drainage systems, would broaden the applicability of the multi-method approach developed in this study and enhance resilience planning across diverse hazard contexts.

6.5 Limitations of the Study

While this study contributes to advancing knowledge on dam safety, socio-economic impacts, and the role of non-structural measures, several limitations should be acknowledged. First, the hydraulic modelling and flood simulations were based on available hydrological data and assumptions regarding breach parameters, boundary conditions, and roughness coefficients. As with any model, simplifications, such as neglecting vertical water velocities, may limit the precision of the results. The outcomes, therefore, represent an approximation rather than exact predictions of real dam-break events. Similarly, the Agent-Based Modelling (ABM) approach, although innovative in simulating community behavior during disaster scenarios, was inherently constrained by the assumptions, decision rules, and parameter settings defined during model construction, which may limit the realism of the behavioral outcomes. Finally, the development and piloting of the board game, despite demonstrating strong potential for enhancing engagement and preparedness, were conducted with relatively small and controlled participant groups. Therefore, the findings may not fully represent how diverse communities with differing literacy levels, cultural backgrounds, and prior exposure to disaster training would interact with the tool. Expanding the game to digital platforms or large-scale community implementations was beyond the scope of this study and remains an area for future exploration.

6.6 Concluding Remark

This study has demonstrated the value of integrating engineering analysis, socio-economic evaluation, and innovative non-structural measures to strengthen community preparedness for dam failures. By combining hydraulic and agent-based modelling with participatory methods and gamification, it advances both theoretical understanding and practical solutions for disaster risk reduction. While the research is bound by certain limitations, the findings underscore the importance of holistic, people-centered approaches that go beyond structural interventions alone. Ultimately, the study not only contributes to academic discourse but also offers actionable insights for policymakers, practitioners, and communities, paving the way for more resilient and adaptive strategies to manage the growing risks associated with dam failures and related hydrological hazards.

REFERENCES

Abdullah, A.-N., & Rahman, S. (2021). Social Impacts of a Mega-Dam Project as Perceived by Local, Resettled and Displaced Communities: A Case Study of Merowe Dam, Sudan. *Economies*, *9*(4), 140. https://doi.org/10.3390/economies9040140

Abt, C. A. (1979). *Serious Games; Viking*.

Abu-Alhaija, A. S. (2019). From epistemology to structural equation modeling: An essential guide in understanding the principles of research philosophy in selecting the appropriate methodology. *Australian Journal of Basic and Applied Sciences*, *13*(9), 122–128. https://doi.org/10.22587/ajbas.2019.13.9.12

Adamo, N., Al-Ansari, N., Sissakian, V., Laue, J., & Knutsson, S. (2020). Dam Safety: Technical Problems of Ageing Concrete Dams. *Journal of Earth Sciences and Geotechnical Engineering*, *10*(6), 241–279.

Ahlin, E. (2019). *Semi-structured interviews with expert practitioners: Their validity and significant contribution to translational research*. SAGE Publications Ltd. https://doi.org/10.4135/9781526466037

Al Ruheili, A., Dahm, R., & Radke, J. (2019). Wadi flood impact assessment of the 2002 cyclonic storm in Dhofar, Oman under present and future sea level conditions. *Journal of Arid Environments*, *165*, 73–80. https://doi.org/10.1016/j.jaridenv.2019.04.002

Ali, M. M. (2024). Case Study: Satya Nadella's Leadership at Microsoft. *Issue 12. Ser*, *26*, 74–79. https://doi.org/10.9790/487X-2612027479

Alvi, I. A., & Alvi, I. S. (2023). Why dams fail: a systems perspective and case study. *Civil Engineering and Environmental Systems*, *40*(3), 150–175. https://doi.org/10.1080/10286608.2023.2283704

Amadae, S. M., & Watts, C. J. (2023). Red Queen and Red King Effects in cultural agent-based modeling: Hawk Dove Binary and Systemic Discrimination. *The Journal of Mathematical Sociology*, *47*(4), 283–310. https://doi.org/10.1080/0022250X.2021.2012668

Anshuka, A., van Ogtrop, F. F., Sanderson, D., & Leao, S. Z. (2022). A systematic review of agent-based model for flood risk management and assessment using the ODD protocol. *Natural Hazards*, *112*(3), 2739–2771. https://doi.org/10.1007/s11069-022-05286-y

Arlikatti, S., Maghelal, P., Agnimitra, N., & Chatterjee, V. (2018). Should I stay or should I go? Mitigation strategies for flash flooding in India. *International Journal of Disaster Risk Reduction*, *27*, 48–56. https://doi.org/10.1016/j.ijdrr.2017.09.019

Arnab, S., Lim, T., Carvalho, M. B., Bellotti, F., de Freitas, S., Louchart, S., Suttie, N., Berta, R., & De Gloria, A. (2015). Mapping learning and game mechanics for serious games analysis. *British Journal of Educational Technology*, *46*(2), 391–411. https://doi.org/10.1111/bjet.12113

Aromataris, E., & Riitano, D. (2014). Systematic reviews. *AJN, American Journal of Nursing*, *114*(5), 49–56. https://doi.org/10.1097/01.NAJ.0000446779.99522.f6

Association of State Dam Safety Officials (ASDSO). (2017). *The Importance of National Dam Safety Awareness Day*. https://damsafety.org/awareness-center#:~:text=National%20Dam%20Safety%20Awareness%20Day,best%20practices%20for%20dam%20safety

Bashar, N. A. M., Zainol, M. R. R. M. A., Aziz, M. S. A., Mazlan, A. Z. A., & Zawawi, M. H. (2023). *Dam Safety: Highlighted Issues and Reliable Assessment for the Sustainable Dam Infrastructure* (pp. 871–880). https://doi.org/10.1007/978-981-99-3708-0_61

Baxter, P., & Jack, S. (2008). Qualitative case study methodology: Study design and implementation for novice researchers. *The Qualitative Report*, *13*(4), 544–559.

Becher, M. A., Grimm, V., Thorbek, P., Horn, J., Kennedy, P. J., & Osborne, J. L. (2014). <scp>BEEHAVE</scp> : a systems model of honeybee colony dynamics and foraging to explore multifactorial causes of colony failure. *Journal of Applied Ecology*, *51*(2), 470–482. https://doi.org/10.1111/1365-2664.12222

Becker, J. S., Paton, D., Johnston, D. M., & Ronan, K. R. (2012). A model of household preparedness for earthquakes: how individuals make meaning of earthquake information and how this influences preparedness. *Natural Hazards*, *64*(1), 107–137. https://doi.org/10.1007/s11069-012-0238-x

Begnudelli, L., & Sanders, B. F. (2007). Simulation of the St. Francis Dam-Break Flood. *Journal of Engineering Mechanics*, *133*(11), 1200–1212. https://doi.org/10.1061/(ASCE)0733-9399(2007)133:11(1200)

Bellotti, F., Berta, R., & De Gloria, A. (2010). Designing Effective Serious Games: Opportunities and Challenges for Research. *International Journal of Emerging Technologies in Learning (IJET)*, *5*(SI3), 22. https://doi.org/10.3991/ijet.v5s3.1500

Bellotti, F., Kapralos, B., Lee, K., Moreno-Ger, P., & Berta, R. (2013). Assessment in and of Serious Games: An Overview. *Advances in Human-Computer Interaction*, *2013*, 1–11. https://doi.org/10.1155/2013/136864

Bernardini, G., Finizio, F., Postacchini, M., & Quagliarini, E. (2021). Assessing the flood risk to evacuees in outdoor built environments and relative risk reduction strategies. *International Journal of Disaster Risk Reduction*, *64*, 102493. https://doi.org/10.1016/j.ijdrr.2021.102493

Berndt, A. E. (2020). Sampling methods. *Journal of Human Lactation*, *36*(2), 224–226. https://doi.org/10.1177/0890334420906850

Bharath, A., Shivapur, A. V, Hiremath, C. G., & Maddamsetty, R. (2021). Dam break analysis using HEC-RAS and HEC-GeoRAS: A case study of Hidkal dam, Karnataka state, India. *Environmental Challenges*, *5*, 100401. https://doi.org/10.1016/j.envc.2021.100401

Bharti, M. K., Sharma, M., & Islam, N. (2020). Study on the Dam & Reservoir, and Analysis of Dam Failures: A Data Base Approach. *International Research Journal of Engineering and Technology (IRJET)*, *7*(5), 1661–1669.

Bonabeau E. (2002). Agent-based modeling: Methods and techniques for simulating human systems. *Proceedings of the National Academy of Sciences*, 7280–7287.

Borowska-Stefańska, M., Kowalski, M., Turoboś, F., & Wiśniewski, S. (2019). Optimisation patterns for the process of a planned evacuation in the event of a flood. *Environmental Hazards*, *18*(4), 335–360. https://doi.org/10.1080/17477891.2019.1593816

Cajanding, R. J. (2017). Effects of a Structured Discharge Planning Program on Perceived Functional Status, Cardiac Self-efficacy, Patient Satisfaction, and Unexpected Hospital Revisits Among Filipino Cardiac Patients. *Journal of Cardiovascular Nursing*, *32*(1), 67–77. https://doi.org/10.1097/JCN.0000000000000303

Campolongo, F., Cariboni, J., & Saltelli, A. (2007). An effective screening design for sensitivity analysis of large models. *Environmental Modelling & Software*, *22*(10), 1509–1518. https://doi.org/10.1016/j.envsoft.2006.10.004

Cannata, M., & Marzocchi, R. (2012). Two-dimensional dam break flooding simulation: a GIS-embedded approach. *Natural Hazards*, *61*(3), 1143–1159. https://doi.org/10.1007/s11069-011-9974-6

Cao, Z., Huang, W., Pender, G., & Liu, X. (2014). Even more destructive: cascade dam break floods. *Journal of Flood Risk Management*, *7*(4), 357–373. https://doi.org/10.1111/jfr3.12051

Carmo, F. F. do, Kamino, L. H. Y., Junior, R. T., Campos, I. C. de, Carmo, F. F. do, Silvino, G., Castro, K. J. da S. X. de, Mauro, M. L., Rodrigues, N. U. A., Miranda, M. P. de S., & Pinto, C. E. F. (2017). Fundão tailings dam failures: the environment tragedy of the largest technological disaster of Brazilian mining in global context. *Perspectives in Ecology and Conservation*, *15*(3), 145–151. https://doi.org/10.1016/j.pecon.2017.06.002

Chan, N. W., Ghani, A. A., Samat, N., Hasan, N. N. N., & Tan, M. L. (2020). *Integrating Structural and Non-structural Flood Management Measures for Greater Effectiveness in Flood Loss Reduction in the Kelantan River Basin, Malaysia* (pp. 1151–1162). https://doi.org/10.1007/978-3-030-32816-0_87

Chege, K., & Otieno, O. (2020). Research philosophy design and methodologies: A systematic review of research paradigms in information technology. *Global Scientific Journels* , *8*(5). www.globalscientificjournal.com

Chigbu, U. E., Atiku, S. O., & Du Plessis, C. C. (2023). The science of literature reviews: Searching, identifying, selecting, and synthesizing. *Publications*, *11*(1), 2. https://doi.org/10.3390/publications11010002

Choi, J.-K., Morrison, D., Hallinan, K. P., & Brecha, R. J. (2014). Economic and environmental impacts of community-based residential building energy efficiency investment. *Energy*, *78*, 877–886. https://doi.org/10.1016/j.energy.2014.10.082

Coates, G., Li, C., Ahilan, S., Wright, N., & Alharbi, M. (2019). Agent-based modeling and simulation to assess flood preparedness and recovery of manufacturing small and medium-sized enterprises. *Engineering Applications of Artificial Intelligence*, *78*, 195–217. https://doi.org/10.1016/j.engappai.2018.11.010

Cogoni, F., Bernard, D., Kazhen, R., Valitutti, S., Lobjois, V., & Cussat-Blanc, S. (2023). *ISiCell: involving biologists in the design process of agent-based models in cell biology*. https://doi.org/10.1101/2023.06.30.547165

Costa, J. E. (1985). *Floods from dam failures (USGS Open-File Report 85-560)*.

Courtnadge, A., Gosden, J., & Brown, A. (2017). *Guide to Drawdown Capacity for Reservoir Safety and Emergency Planning SC130001 Volume 1– Main Guide. Environment Agency*. https://www.gov.uk/flood-and-coastal-erosion-risk-management-research-reports/guide-to-drawdown-capacity-for-reservoir-safety-and-emergency-planning

Creswell, J. W. (2013). *Research design: Qualitative, quantitative, and mixed methods approaches* (4th ed.). SAGE Publications.

Crooks, A. T., & Heppenstall, A. J. (2012). Introduction to Agent-Based Modelling. In *Agent-Based Models of Geographical Systems* (pp. 85–105). Springer Netherlands. https://doi.org/10.1007/978-90-481-8927-4_5

Crouse, K. N., Desai, N. P., Cassidy, K. A., Stahler, E. E., Lehman, C. L., & Wilson, M. L. (2022). Larger territories reduce mortality risk for chimpanzees, wolves, and agents: Multiple lines of evidence in a model validation framework. *Ecological Modelling*, *471*, 110063. https://doi.org/10.1016/j.ecolmodel.2022.110063

Daud, N. M., Madzman, A. U., Hassan, S. H., Bakar, A. A. A., Tutur, N., Noh, M. K. M., Manan, E. A., & Hamzah, A. F. (2021). Downstream Community Awareness of the Failure Risk and Emergency Action Plan of Bukit Merah Dam. *Civil Engineering and Architecture*, *9*(5A), 138–144. https://doi.org/10.13189/cea.2021.091316

Davies, W. E., Bailey, J. F., & Kelly, D. B. (1972). *West Virginia's Buffalo Creek flood: A study of the hydrology and engineering geology (USGS Circular 667)*.

Dawson, R. J., Peppe, R., & Wang, M. (2011). An agent-based model for risk-based flood incident management. *Natural Hazards*, *59*(1), 167–189. https://doi.org/10.1007/s11069-011-9745-4

De Paiva, C. A., Barella, C. F., & Fonseca, A. (2024). Assessing and managing safety risks to downstream communities (in hindsight): What went wrong in the licensing and impact assessment procedures of Brazil's deadliest dam breaks? *Environmental Impact Assessment Review*, *106*, 107536. https://doi.org/10.1016/j.eiar.2024.107536

Delaney, K. B., & Evans, S. G. (2015). The 2000 Yigong landslide (Tibetan Plateau), rockslide-dammed lake and outburst flood: Review, remote sensing analysis, and process modelling. *Geomorphology*, *246*, 377–393. https://doi.org/10.1016/j.geomorph.2015.06.020

Demiray, B. Z., Sermet, Y., Yildirim, E., & Demir, I. (2025). FloodGame: An interactive 3D serious game on flood mitigation for disaster awareness and education. *Environmental Modelling & Software*, *188*, 106418. https://doi.org/10.1016/j.envsoft.2025.106418

Derdous, O., Djemili, L., Bouchehed, H., & Tachi, S. E. (2015). A GIS based approach for the prediction of the dam break flood hazard – A case study of Zardezas reservoir "Skikda, Algeria." *Journal of Water and Land Development*, *27*(1), 15–20. https://doi.org/10.1515/jwld-2015-0020

Di Baldassarre, G., Mazzoleni, M., & Rusca, M. (2021). The legacy of large dams in the United States. *Ambio*, *50*(10), 1798–1808. https://doi.org/10.1007/s13280-021-01533-x

Dias, C., Rahman, N. A., & Zaiter, A. (2021). Evacuation under flooded conditions: Experimental investigation of the influence of water depth on walking behaviors. *International Journal of Disaster Risk Reduction*, *58*. https://doi.org/10.1016/j.ijdrr.2021.102192

Djonko-Moore, C. M., Leonard, J., Holifield, Q., Bailey, E. B., & Almughyirah, S. M. (2018). Using Culturally Relevant Experiential Education to Enhance Urban Children's Knowledge and Engagement in Science. *Journal of Experiential Education*, *41*(2), 137–153. https://doi.org/10.1177/1053825917742164

Dolman, D. I., Brown, I. F., Anderson, L. O., Warner, J. F., Marchezini, V., & Santos, G. L. P. (2018). Re-thinking socio-economic impact assessments of disasters: The 2015 flood in Rio Branco, Brazilian Amazon. *International Journal of Disaster Risk Reduction*, *31*, 212–219. https://doi.org/10.1016/j.ijdrr.2018.04.024

Dong, K., Yang, D., Sheng, J., Zhang, W., & Jing, P. (2024). Dynamic planning method of evacuation route in dam-break flood scenario based on the ACO-GA hybrid algorithm. *International Journal of Disaster Risk Reduction*, *100*, 104219. https://doi.org/10.1016/j.ijdrr.2023.104219

Dörner, R., Göbel, S., Effelsberg, W., & Wiemeyer, J. (2016). *Serious Games* (R. Dörner, S. Göbel, W. Effelsberg, & J. Wiemeyer, Eds.). Springer International Publishing. https://doi.org/10.1007/978-3-319-40612-1

dos Santos Vergilio, C., Lacerda, D., da Silva Souza, T., de Oliveira, B. C. V., Fioresi, V. S., de Souza, V. V., da Rocha Rodrigues, G., de Araujo Moreira Barbosa, M. K., Sartori, E., Rangel, T. P., de Almeida, D. Q. R., de Almeida, M. G., Thompson, F., & de Rezende, C. E. (2021). Immediate and long-term impacts of one of the worst mining tailing dam failure worldwide (Bento Rodrigues, Minas Gerais, Brazil). *Science of The Total Environment*, *756*, 143697. https://doi.org/10.1016/j.scitotenv.2020.143697

Duke, R. D. (2011). Origin and Evolution of Policy Simulation: A Personal Journey. *Simulation & Gaming*, *42*(3), 342–358. https://doi.org/10.1177/1046878110367570

Egilmez, G., & Gedik, R. (2018). *A Gamification Approach for Experiential Education of Inventory A Gamification Approach for Experiential Education of Inventory Control Control*. https://peer.asee.org/29684

Elfil, M., & Negida, A. (2017). Sampling methods in Clinical Research; an Educational Review. *Emergency*, *5*(1), 52. https://doi.org/10.1136/eb-2014

Ellingwood, B., Corotis, R. B., Boland, J., & Jones, N. P. (1993). Assessing Cost of Dam Failure. *Journal of Water Resources Planning and Management*, *119*(1), 64–82. https://doi.org/10.1061/(ASCE)0733-9496(1993)119:1(64)

Farooq, R. (2022). A review of knowledge management research in the past three decades: a bibliometric analysis. *VINE Journal of Information and Knowledge Management Systems*.

Federal Emergency Management Agency (FEMA). (2013). *Federal Guidelines for Dam Safety: Hazard Potential Classification System for Dams*.

Ferrari, A., Vacondio, R., & Mignosa, P. (2023). High-resolution 2D shallow water modelling of dam failure floods for emergency action plans. *Journal of Hydrology*, *618*, 129192. https://doi.org/10.1016/j.jhydrol.2023.129192

Figueroa-Medina, A. M., Valdés-Díaz, D., Colucci-Ríos, B., Cardona-Rodríguez, N., & Chamorro-Parejo, A. (2023). Analysis of walking speeds and success rates on mid-block crossings using virtual reality simulation. *Accident Analysis & Prevention*, *183*, 106987. https://doi.org/10.1016/j.aap.2023.106987

Flood, S., Cradock-Henry, N. A., Blackett, P., & Edwards, P. (2018). Adaptive and interactive climate futures: systematic review of ‘serious games’ for engagement and decision-making. *Environmental Research Letters*, *13*(6), 063005. https://doi.org/10.1088/1748-9326/aac1c6

Forrest, S. A., Kubíková, M., & Macháč, J. (2022). Serious gaming in flood risk management. *WIREs Water*, *9*(4). https://doi.org/10.1002/wat2.1589

Frandsen, T. F., Bruun Nielsen, M. F., Lindhardt, C. L., & Eriksen, M. B. (2020). Using the full PICO model as a search tool for systematic reviews resulted in lower recall for some PICO elements. *Journal of Clinical Epidemiology*, *127*, 69–75. https://doi.org/10.1016/j.jclinepi.2020.07.005

Frankenberg, E., Sikoki, B., Sumantri, C., Suriastini, W., & Thomas, D. (2013). Education, Vulnerability, and Resilience after a Natural Disaster. *Ecology and Society*, *18*(2), art16. https://doi.org/10.5751/ES-05377-180216

Ge, W., Sun, H., Jing, L., Li, Z., Li, Y., Cao, B., Wang, T., Jiao, Y., Zhang, H., Wang, J., & van Gelder, P. (2024). Economic life evaluation of reservoir dams based on comprehensive costs and benefits analysis considering potential dam breach: A case study of the Luhun reservoir in China. *Journal of Hydrology*, *639*, 131613. https://doi.org/10.1016/j.jhydrol.2024.131613

Ge, W., Wang, X., Li, Z., Zhang, H., Guo, X., Wang, T., Gao, W., Lin, C., & van Gelder, P. (2021). Interval Analysis of the Loss of Life Caused by Dam Failure. *Journal of Water Resources Planning and Management*, *147*(1). https://doi.org/10.1061/(asce)wr.1943-5452.0001311

Gee, J. P. (2007). *What video games have to teach us about learning and literacy* (2nd ed.). Palgrave Macmillan.

Ghazali, A., Thiruchelvam, S., Sabri Muda, R., Nasharuddin Mustapha, K., Kamal Kadir, A., Faiqa Norkhairi, F., Yahya, N., Hakimie, H., Aziz Mat Isa, A., Fadhli Mamat, A., Hasini, H., Salleh Mohamed Sahari, K., Che Muda, Z., & Yu Jin, N. (2018). Development of Community-Based Early Warning System (CBEWS) in Enhancing Community Preparedness for Dam-Related Disasters in Malaysia. In *ASM Sci. J* (Vol. 11, Issue 2).

Gill, P., & Baillie, J. (2018). Interviews and focus groups in qualitative research: an update for the digital age. *British Dental Journal*, *225*(7), 668–672. https://doi.org/10.1038/sj.bdj.2018.815

Gomes, M. N., Castro, M. de A. R. A., Silva, P. G. C. da, Giacomoni, M. H., & Mendiondo, E. M. (2024). Increasing flood awareness through dam-break serious games. *International Journal of Disaster Risk Reduction*, *108*, 104543. https://doi.org/10.1016/j.ijdrr.2024.104543

Gopinath, V. (2022). *Components of dam – 12 dam components explained*. Dams, Hydrauilics. https://vincivilworld.com/2022/10/17/components-of-dam-functions/

Gu, H., Fu, X., Zhu, Y., Chen, Y., & Huang, L. (2020). Analysis of Social and Environmental Impact of Earth-Rock Dam Breaks Based on a Fuzzy Comprehensive Evaluation Method. *Sustainability*, *12*(15), 6239. https://doi.org/10.3390/su12156239

Guimarães, R. N., Moreira, V. R., Cruz, J. R. A., Saliba, A. P. M., & Amaral, M. C. S. (2022). History of tailings dam failure: Impacts on access to safe water and influence on the legislative framework. *Science of The Total Environment*, *852*, 158536. https://doi.org/10.1016/j.scitotenv.2022.158536

Gustafsson, J. (2017). *Single case studies vs. multiple case studies: A comparative study*.

Haddad, E. A., & Teixeira, E. (2015). Economic impacts of natural disasters in megacities: The case of floods in São Paulo, Brazil. *Habitat International*, *45*, 106–113. https://doi.org/10.1016/j.habitatint.2014.06.023

He, G., Chai, J., Qin, Y., Xu, Z., & Li, S. (2020). Evaluation of Dam Break Social Impact Assessments Based on an Improved Variable Fuzzy Set Model. *Water*, *12*(4), 970. https://doi.org/10.3390/w12040970

He, Q., Wang, G., Luo, L., Shi, Q., Xie, J., & Meng, X. (2017). Mapping the managerial areas of Building Information Modeling (BIM) using scientometric analysis. *International Journal of Project Management*, *35*(4), 670–685. https://doi.org/10.1016/j.ijproman.2016.08.001

Helbing, D., Farkas, I., & Vicsek, T. (2000). Simulating dynamical features of escape panic. *Nature*, *407*(6803), 487–490. https://doi.org/10.1038/35035023

Hoogendoorn, S. P., & Bovy, P. H. L. (2004). Pedestrian route-choice and activity scheduling theory and models. *Transportation Research Part B: Methodological*, *38*(2), 169–190. https://doi.org/10.1016/S0191-2615(03)00007-9

Hossain, M. K., & Meng, Q. (2020). A thematic mapping method to assess and analyze potential urban hazards and risks caused by flooding. *Computers, Environment and Urban Systems*, *79*, 101417. https://doi.org/10.1016/j.compenvurbsys.2019.101417

Hosseini, M.-S., Jahanshahlou, F., Akbarzadeh, M. A., Zarei, M., & Vaez-Gharamaleki, Y. (2024). Formulating research questions for evidence-based studies. *Journal of Medicine, Surgery, and Public Health*, *2*, 100046. https://doi.org/10.1016/j.glmedi.2023.100046

Independent Forensic Team. (2018). *Independent Forensic Team Report: Oroville Dam Spillway Incident*.

International Commission on Large Dams (ICOLD). (1995). *Dam failures statistical analysis*.

Johnson, V. A., Ronan, K. R., Johnston, D. M., & Peace, R. (2014). Evaluations of disaster education programs for children: A methodological review. *International Journal of Disaster Risk Reduction*, *9*, 107–123. https://doi.org/10.1016/j.ijdrr.2014.04.001

Jonkman, S. N., & Penning-Rowsell, E. (2008). Human Instability in Flood Flows. *JAWRA Journal of the American Water Resources Association*, *44*(5), 1208–1218. https://doi.org/10.1111/j.1752-1688.2008.00217.x

Joshi, M. M., & Shahapure, S. S. (2017). Two Dimensional Dam Break Flow Study Using HEC-RAS for Ujjani Dam. *International Journal of Engineering and Technology*, *9*(4), 2923–2928. https://doi.org/10.21817/ijet/2017/v9i4/170904032

Junjie, M., & Yingxin, M. (2022). The discussions of positivism and interpretivism. *Global Academic Journal of Humanities and Social Sciences*, *4*(1), 10–14. https://doi.org/10.36348/gajhss.2022.v04i01.002

Kagioglou, M., Cooper, R., Aouad, G., Sexton, M., Hinks, J., & Sheath, D. (1998). Cross-industry learning: the development of a generic design and construction process based on stage/gate new product development processes found in the manufacturing industry. *Engineering Design Conference*, 595–602.

Kaman, Z. K., Khanm, T., Mokhtar, S. Bt., Samsuddin, S. A., & Ali, Z. (2024). Factors Influencing Community Participation in Dam Failure Flood Risk Management: Challenges and Recommendations. *International Journal for Disaster and Development Interface*, *4*(2), 140–161. https://doi.org/10.53824/ijddi.v4i2.86

Kaneko, R., Salman Al Farisi, M., Miwa, K., Yamada, S., & Kuri, M. (2018). *Evaluation of the Disaster Mitigation Action Card Game for international students in Japan*. https://www.researchgate.net/publication/325263426

Karim, I. R., Hassan, Z. F., Abdullah, H. H., & Alwan, I. A. (2021). 2D-HEC-RAS Modeling of Flood Wave Propagation in a Semi-Arid Area Due to Dam Overtopping Failure. *Civil Engineering Journal*, *7*(9), 1501–1514. https://doi.org/10.28991/cej-2021-03091739

Kaushik, V., & Walsh, C. A. (2019). Pragmatism as a research paradigm and its implications for social work research. *Social Sciences*, *8*(9), 255. https://doi.org/10.3390/socsci8090255

Khatri, K. K. (2020). Research paradigm: A philosophy of educational research. *International Journal of English Literature and Social Sciences*, *5*(5), 1435–1440. https://doi.org/10.22161/ijels.55.15

Khosravi, K., Rostaminejad, M., Cooper, J. R., Mao, L., & Melesse, A. M. (2019). Dam break analysis and flood inundation mapping: The case study of Sefid-Roud Dam, Iran. In *Extreme Hydrology and Climate Variability* (pp. 395–405). Elsevier. https://doi.org/10.1016/B978-0-12-815998-9.00031-2

Kolb, D. A. (1984). *Experiential Learning: Experience As The Source Of Learning And Development Executive skills of Family Medicine Faculty View project How You Learn Is How You Live View project*. http://www.learningfromexperience.com/images/uploads/process-of-experiential-learning.pdf!

Kraiger, K., Ford, J. K., & Salas, E. (1993). Application of cognitive, skill-based, and affective theories of learning outcomes to new methods of training evaluation. *Journal of Applied Psychology*, *78*(2), 311–328. https://doi.org/10.1037/0021-9010.78.2.311

Kulatunga, K. J., Amaratunga, D., & Haigh, R. (2014). Researching construction client and innovation: methodological perspective. *7th International Postgraduate Conference in the Built and Human Environment*.

Kumar, S., Jaswal, A., Pandey, A., & Sharma, N. (2017). Literature Review of Dam Break Studies and Inundation Mapping Using Hydraulic Models and GIS. *International Research Journal of Engineering and Technology (IRJET)*, *4*(5), 55–61.

Kumar, S., Kar, A. K., & Ilavarasan, P. V. (2021). Applications of text mining in services management: A systematic literature review. *International Journal of Information Management Data Insights*, *1*(1), 100008. https://doi.org/10.1016/j.jjimei.2021.100008

Lassa, J., Petal, M., & Surjan, A. (2023). Understanding the impacts of floods on learning quality, school facilities, and educational recovery in Indonesia. *Disasters*, *47*(2), 412–436. https://doi.org/10.1111/disa.12543

Latrubesse, E. M., Park, E., Sieh, K., Dang, T., Lin, Y. N., & Yun, S.-H. (2020). Dam failure and a catastrophic flood in the Mekong basin (Bolaven Plateau), southern Laos, 2018. *Geomorphology*, *362*, 107221. https://doi.org/10.1016/j.geomorph.2020.107221

Lee, J. Y., Park, D. H., Kim, S.-J., & Kim, T.-W. (2017). Estimation of Break Outflow from the Goeyeon Reservoir Using DAMBRK Model. *Journal of The Korean Society of Civil Engineers*, *37*(2), 459–466. https://doi.org/10.12652/Ksce.2017.37.2.0459

Liang, L., Liu, Q., & Li, M. (2017). *Dam-Break Risk Assessment Model of Tailings Reservoir Based on Variable Weight Synthesis and Analytic Hierarchy Process*. *38*, 1790.

Lin, W., Sun, Y., Nijhuis, S., & Wang, Z. (2020). Scenario-based flood risk assessment for urbanizing deltas using future land-use simulation (FLUS): Guangzhou Metropolitan Area as a case study. *Science of The Total Environment*, *739*, 139899. https://doi.org/10.1016/j.scitotenv.2020.139899

Lindell, M. K., & Perry, R. W. (2012). The Protective Action Decision Model: Theoretical Modifications and Additional Evidence. *Risk Analysis*, *32*(4), 616–632. https://doi.org/10.1111/j.1539-6924.2011.01647.x

Lindell, M. K., & Prater, C. S. (2007). Critical Behavioral Assumptions in Evacuation Time Estimate Analysis for Private Vehicles: Examples from Hurricane Research and Planning. *Journal of Urban Planning and Development*, *133*(1), 18–29. https://doi.org/10.1061/(ASCE)0733-9488(2007)133:1(18)

Lorenzoni, N., Stühlinger, V., Stummer, H., & Raich, M. (2020). Long-Term Impact of Disasters on the Public Health System: A Multi-Case Analysis. *International Journal of Environmental Research and Public Health*, *17*(17), 6251. https://doi.org/10.3390/ijerph17176251

Lumbroso, D., Davison, M., & Wetton, M. (2023). Development of an agent-based model to improve emergency planning for floods and dam failures. *Journal of Hydroinformatics*, *25*(5), 1610–1628. https://doi.org/10.2166/hydro.2023.194

Lyu, Z., Chai, J., Xu, Z., Qin, Y., & Cao, J. (2019). A Comprehensive Review on Reasons for Tailings Dam Failures Based on Case History. *Advances in Civil Engineering*, *2019*(1). https://doi.org/10.1155/2019/4159306

Mahamood, R., Kankanamge, N., Kovida De Silva, C., Ranasinghe, D., & Kangana, N. (2024). *Levelling Up Disaster Education: How Gamified Apps Empower Children and Youth—A Systematic Review*. https://doi.org/10.2139/ssrn.4969758

Manzoor, Z., Ehsan, M., Khan, M. B., Manzoor, A., Akhter, M. M., Sohail, M. T., Hussain, A., Shafi, A., Abu-Alam, T., & Abioui, M. (2022). Floods and flood management and its socio-economic impact on Pakistan: A review of the empirical literature. *Frontiers in Environmental Science*, *10*. https://doi.org/10.3389/fenvs.2022.1021862

Mauney, L. (2025). *Early Warning Systems can provide real-time information on the health of a dam, conditions during incidents, and advanced warning to evacuate ahead of dam failure flooding*. ASDSO Lessons Learned Main Navigation. https://damfailures.org/lessons-learned/early-warning-systems

Mayer, I. S. (2009). The Gaming of Policy and the Politics of Gaming: A Review. *Simulation & Gaming*, *40*(6), 825–862. https://doi.org/10.1177/1046878109346456

McQuitty, S. (2018). The Purposes of multivariate data analysis methods: An applied commentary. *Journal of African Business*, *19*(1), 124–142. https://doi.org/10.1080/15228916.2017.1374816

Mehrad, A., & Zangeneh, M. T. (2019). Comparison between qualitative and quantitative research approaches: Social sciences. *International Journal For Research In Educational Studies*, *5*(7). https://orcid.org/0000-0003-4364-5709

Mehta, A. M., Weeks, C. S., & Tyquin, E. (2020). Towards preparedness for dam failure: An evidence base for risk communication for downstream communities. *International*

Journal of Disaster Risk Reduction, *50*, 101820. https://doi.org/10.1016/j.ijdrr.2020.101820

Mezmir, E. (2020). Qualitative data analysis: An overview of data reduction, data display and interpretation. *Research on Humanities and Social Sciences*. https://doi.org/10.7176/rhss/10-21-02

Monte, B., Costa, D., Chaves, M., Magalhães, L., & Uvo, C. (2016). Hydrological and hydraulic modelling applied to the mapping of flood-prone areas. *Revista Brasileira de Recursos Hídricos*, *21*(1), 152–167. https://doi.org/10.21168/rbrh.v21n1.p152-167

Morris, M. D. (1991). Factorial Sampling Plans for Preliminary Computational Experiments. *Technometrics*, *33*(2), 161–174. https://doi.org/10.1080/00401706.1991.10484804

Mossoux, S., Delcamp, A., Poppe, S., Michellier, C., Canters, F., & Kervyn, M. (2016). Hazagora: Will you survive the next disaster? – A serious game to raise awareness about geohazards and disaster risk reduction. *Natural Hazards and Earth System Sciences*, *16*(1), 135–147. https://doi.org/10.5194/nhess-16-135-2016

Mubialiwo, A., Abebe, A., Kawo, N. S., Ekolu, J., Nadarajah, S., & Onyutha, C. (2022). Hydrodynamic Modelling of Floods and Estimating Socio-economic Impacts of Floods in Ugandan River Malaba Sub-catchment. *Earth Systems and Environment*, *6*(1), 45–67. https://doi.org/10.1007/s41748-021-00283-w

Muda, R. S., Md Amin, M. F., Mohd Khidzir, A. B., Tukiman, I., & Mohd. Hussain, M. R. (2021). Knowledge Transfer in People-Centered Dam-Related Disaster Program in Cameron Highlands. *Journal of Advanced Research in Applied Sciences and Engineering Technology*, *24*(1), 37–46. https://doi.org/10.37934/araset.24.1.3746

Muda, R. S., Tukiman, I., Md Amin, M. F., Mohd. Hussain, Mohd. R., & Mohd Khidzir, A. B. (2020). Dam related disaster framework for emergency preparedness. *PLANNING MALAYSIA*, *18*. https://doi.org/10.21837/pm.v18i14.837

Mukherjee, M. (2017). A review of research design. *INTERNATIONAL JOURNAL OF ADVANCED ENGINEERING AND MANAGEMENT*, *2*(3), 56. https://doi.org/10.24999/IJOAEM/02030016

Nguyen, H. D., Nguyen, Q.-H., Dang, D. K., Van, C. P., Truong, Q. H., Pham, S. D., Bui, Q.-T., & Petrisor, A.-I. (2024). A novel flood risk management approach based on future climate and land use change scenarios. *Science of The Total Environment*, *921*, 171204. https://doi.org/10.1016/j.scitotenv.2024.171204

Nielsen, D., Spiryagin, M., & Cole, C. (2019). Model to estimate infrastructure damage costs for different train types. *Australian Journal of Mechanical Engineering*, *17*(3), 219–231. https://doi.org/10.1080/14484846.2017.1359896

Novak, J., Lozos, J. C., & Spear, S. E. (2019). Development of an Interactive Escape Room Intervention to Educate College Students about Earthquake Preparedness. *Natural Hazards Review*, *20*(1). https://doi.org/10.1061/(ASCE)NH.1527-6996.0000322

O'Connell, P. E., & O'Donnell, G. (2014). Towards modelling flood protection investment as a coupled human and natural system. *Hydrology and Earth System Sciences*, *18*(1), 155–171. https://doi.org/10.5194/hess-18-155-2014

Oktari, R. S., Shiwaku, K., Munadi, K., Syamsidik, & Shaw, R. (2015). A conceptual model of a school–community collaborative network in enhancing coastal community resilience in Banda Aceh, Indonesia. *International Journal of Disaster Risk Reduction*, *12*, 300–310. https://doi.org/10.1016/j.ijdrr.2015.02.006

Oladinrin, O. T., Arif, M., Rana, M. Q., & Gyoh, L. (2023). Interrelations between construction ethics and innovation: a bibliometric analysis using VOSviewer. *Construction Innovation*, *23*(3), 505–523.

Omotayo, T., & Kulatunga, U. (2015). The research methodology for the development of a kaizen costing framework suitable for indigenous construction firms in Lagos, Nigeria. *Proceedings of ARCOM Doctoral Workshop Research Methodology*, 1–12.

Pa, P., & Sin, S. (2020). Modeling Approach for Earthen Dam Breach Analysis in North Yamar Dam, Myanmar. *American Scientific Research Journal for Engineering, Technology, and Sciences (ASRJETS)*, *69*(1), 59–72.

Pahlevan-Sharif, S., Mura, P., & Wijesinghe, S. N. R. (2019). A systematic review of systematic reviews in tourism. *Journal of Hospitality and Tourism Management*, *39*, 158–165. https://doi.org/10.1016/j.jhtm.2019.04.001

Palmatier, R. W., Houston, M. B., & Hulland, J. (2018). Review articles: purpose, process, and structure. *Journal of the Academy of Marketing Science*, *46*(1), 1–5. https://doi.org/10.1007/s11747-017-0563-4

Parente, C. E. T., Lino, A. S., Carvalho, G. O., Pizzochero, A. C., Azevedo-Silva, C. E., Freitas, M. O., Teixeira, C., Moura, R. L., Ferreira Filho, V. J. M., & Malm, O. (2021). First year after the Brumadinho tailings' dam collapse: Spatial and seasonal variation of trace elements in sediments, fishes and macrophytes from the Paraopeba River, Brazil. *Environmental Research*, *193*, 110526. https://doi.org/10.1016/j.envres.2020.110526

Park, Y. S., Konge, L., & Artino, A. R. (2020). The Positivism paradigm of research. *Academic Medicine*, *95*(5), 690–694. https://doi.org/10.1097/ACM.0000000000003093

Paronuzzi, P., Bolla, A., Pinto, D., Lenaz, D., & Soccal, M. (2021). The clays involved in the 1963 Vajont landslide: Genesis and geomechanical implications. *Engineering Geology*, *294*, 106376. https://doi.org/10.1016/j.enggeo.2021.106376

Passey, M., Papm, B., Zielinski, A., & Eng, P. (2014). *DAM SAFETY MANAGEMENT PLANS: A CONCEPTUAL FRAMEWORK FOR RISK-INFORMED DECISION MAKING IN ONTARIO*. https://doi.org/10.13140/2.1.4084.6726

Pathak, S., Liu, M., Jato-Espino, D., & Zevenbergen, C. (2020). Social, economic and environmental assessment of urban sub-catchment flood risks using a multi-criteria approach: A case study in Mumbai City, India. *Journal of Hydrology*, *591*, 125216. https://doi.org/10.1016/j.jhydrol.2020.125216

Pel, A. J., Bliemer, M. C. J., & Hoogendoorn, S. P. (2012). A review on travel behaviour modelling in dynamic traffic simulation models for evacuations. *Transportation*, *39*(1), 97–123. https://doi.org/10.1007/s11116-011-9320-6

Pellicani, R., Parisi, A., Iemmolo, G., & Apollonio, C. (2018). Economic Risk Evaluation in Urban Flooding and Instability-Prone Areas: The Case Study of San Giovanni Rotondo (Southern Italy). *Geosciences*, *8*(4), 112. https://doi.org/10.3390/geosciences8040112

Peramuna, P. D. P. O., Neluwala, N. G. P. B., Wijesundara, K. K., DeSilva, S., Venkatesan, S., & Dissanayake, P. B. R. (2024). Review on model development techniques for dam break flood wave propagation. *WIREs Water*, *11*(2). https://doi.org/10.1002/wat2.1688

Perera, C., Jayasooriya, D., Jayasiri, G., Randil, C., Bandara, C., Siriwardana, C., Dissanayake, R., Hippola, S., Sylva, K., Kamalrathne, T., & Kulatunga, A. (2020). Evaluation of gaps in early warning mechanisms and evacuation procedures for coastal communities in Sri Lanka. *International Journal of Disaster Resilience in the Built Environment*, *11*(3), 415–433. https://doi.org/10.1108/IJDRBE-07-2019-0048

Perera, D., Agnihotri, J., Seidou, O., & Djalante, R. (2020). Identifying societal challenges in flood early warning systems. *International Journal of Disaster Risk Reduction*, *51*, 101794. https://doi.org/10.1016/j.ijdrr.2020.101794

Perera, D., & North, T. (2021). The Socio-Economic Impacts of Aged-Dam Removal: A Review. *Journal of Geoscience and Environment Protection*, *09*(10), 62–78. https://doi.org/10.4236/gep.2021.910005

Pérez-Brito, C. T. (2018). Addressing Social Impacts of Urban Rail Projects. In *The Urban Rail Development Handbook* (pp. 523–558). The World Bank. https://doi.org/10.1596/978-1-4648-1272-9_ch14

Perry, R. W., & Lindell, M. K. (2003). Preparedness for Emergency Response: Guidelines for the Emergency Planning Process. *Disasters*, *27*(4), 336–350. https://doi.org/10.1111/j.0361-3666.2003.00237.x

Persson, E., & Granberg, M. (2021). Implementation through collaborative crisis management and contingency planning: the case of dam failure in Sweden. *Journal of Risk Research*, *24*(10), 1335–1348. https://doi.org/10.1080/13669877.2020.1863845

Petty, N. J., Thomson, O. P., & Stew, G. (2012). Ready for a paradigm shift? Part 1: Introducing the philosophy of qualitative research. *Manual Therapy*, *17*(4), 267–274. https://doi.org/10.1016/j.math.2012.03.006

Pfändler, P., Keßler, S., Huber, M., & Angst, U. (2024). Spatial variability of half-cell potential data from a reinforced concrete structure—a geostatistical analysis. *Structure and Infrastructure Engineering*, *20*(11), 1698–1713. https://doi.org/10.1080/15732479.2022.2158204

Phyo, A. P., Yabar, H., & Richards, D. (2023). Managing dam breach and flood inundation by HEC-RAS modeling and GIS mapping for disaster risk management. *Case Studies in*

Chemical and Environmental Engineering, *8*, 100487. https://doi.org/10.1016/j.cscee.2023.100487

Pilotti, M., Maranzoni, A., Milanesi, L., Tomirotti, M., & Valerio, G. (2014). Dam-break modeling in alpine valleys. *Journal of Mountain Science*, *11*(6), 1429–1441. https://doi.org/10.1007/s11629-014-3042-0

Pilotti, M., Milanesi, L., Bacchi, V., Tomirotti, M., & Maranzoni, A. (2020). Dam-Break Wave Propagation in Alpine Valley with HEC-RAS 2D: Experimental Cancano Test Case. *Journal of Hydraulic Engineering*, *146*(6). https://doi.org/10.1061/(ASCE)HY.1943-7900.0001779

Pollock, A., & Berge, E. (2018). How to do a systematic review. *International Journal of Stroke*, *13*(2), 138–156. https://doi.org/10.1177/1747493017743796

Quirogaa, V. M., Kurea, S., Udoa, K., & Manoa, A. (2016). Application of 2D numerical simulation for the analysis of the February 2014 Bolivian Amazonia flood: Application of the new HEC-RAS version 5. *Ribagua*, *3*(1), 25–33. https://doi.org/10.1016/j.riba.2015.12.001

Rahi, S. (2017). Research design and methods: A systematic review of research paradigms, sampling issues and instruments development. *International Journal of Economics & Management Sciences*, *06*(02). https://doi.org/10.4172/2162-6359.1000403

Rahubadda, R. V. A. D., Dassanayake, S. M., De-silva, M. C. K., Thayaparan, M., & Kulathunga, U. (2024). Simulation of plausible hazard scenarios associated with dam failures: case study on Kantale dam, Sri Lanka. *17th International Research Conference - FARU 2024*, 407–418. https://doi.org/10.31705/FARU.2024.42

Railsback, S. F., & Grimm, V. (2019). *Agent-Based and Individual-Based Modeling: A Practical Introduction* (2nd ed.). Princeton University Press.

Rana, N., Singhal, J., & Gupta, V. (2013). Kedarnath disaster: Facts and plausible causes. *Current Science*, *105*(2), 171–174.

Reckien, D., & Eisenack, K. (2013). Climate Change Gaming on Board and Screen. *Simulation & Gaming*, *44*(2–3), 253–271. https://doi.org/10.1177/1046878113480867

Renz, S. M., Carrington, J. M., & Badger, T. A. (2018). Two strategies for qualitative content analysis: An intra method approach to triangulation. *Qualitative Health Research*, *28*(5), 824–831. https://doi.org/10.1177/1049732317753586

Ricci, L., Lanfranchi, J.-B., Lemetayer, F., Rotonda, C., Guillemin, F., Coste, J., & Spitz, E. (2019). Qualitative methods used to generate questionnaire items: A systematic review. *Qualitative Health Research*, *29*(1), 149–156. https://doi.org/10.1177/1049732318783186

Ridder, H.-G. (2017). The theory contribution of case study research designs. *Business Research*, *10*(2), 281–305. https://doi.org/10.1007/s40685-017-0045-z

Rijcken, T., Stijnen, J., & Slootjes, N. (2012). “SimDelta”—Inquiry into an Internet-Based Interactive Model for Water Infrastructure Development in The Netherlands. *Water*, *4*(2), 295–320. https://doi.org/10.3390/w4020295

Roddam, A. W. (2005). Statistics for the Quality Control Chemistry Laboratory. *Journal of the Royal Statistical Society Series A: Statistics in Society*, *168*(2), 464–464. https://doi.org/10.1111/j.1467-985X.2005.358_13.x

Rogers, J. D. (2006). *Lessons Learned from the St. Francis Dam Failure*. https://scholarsmine.mst.edu/geosci_geo_peteng_facwork

Ronan, K. R., Johnston, D. M., Daly, M., & Fairley, R. (2001). School children’s risk perceptions and preparedness: a hazards education survey. *Australasian Journal of Disaster and Trauma Studies*, *2001*(1). https://www.massey.ac.nz/~trauma/issues/2001-1/ronan.htm

Roulo, D., & Pichuka, S. (2024). Assessing the effects of extreme rainfall patterns and their impact on dam safety: a case study on Indian dam failures. *Natural Hazards*, *120*(14), 12967–12987. https://doi.org/10.1007/s11069-024-06720-z

Ruíz-Roso, M. B., de Carvalho Padilha, P., Matilla-Escalante, D. C., Brun, P., Ulloa, N., Acevedo-Correa, D., Arantes Ferreira Peres, W., Martorell, M., Rangel Bousquet Carrilho, T., de Oliveira Cardoso, L., Carrasco-Marín, F., Paternina-Sierra, K., Lopez de las Hazas, M.-C., Rodriguez-Meza, J. E., Villalba-Montero, L. F., Bernabè, G., Pauletto, A., Taci, X., Cárcamo-Regla, R., … Dávalos, A. (2020). Changes of physical activity and ultra-processed food consumption in adolescents from different countries during COVID-19 Pandemic: An observational study. *Nutrients*, *12*(8), 2289. https://doi.org/10.3390/nu12082289

Salajegheh, A., Bakhshaei, M., Chavoshi, S., Keshtkar, A. R., & Najafi Hajivar, M. (2009). *Floodplain mapping using HEC-RAS and GIS in semi-arid regions of Iran*. http://jdesert.ut.ac.ir

Salameh, J.-P., Bossuyt, P. M., McGrath, T. A., Thombs, B. D., Hyde, C. J., Macaskill, P., Deeks, J. J., Leeflang, M., Korevaar, D. A., Whiting, P., Takwoingi, Y., Reitsma, J. B., Cohen, J. F., Frank, R. A., Hunt, H. A., Hooft, L., Rutjes, A. W. S., Willis, B. H., Gatsonis, C., … McInnes, M. D. F. (2020). Preferred reporting items for systematic review and meta-analysis of diagnostic test accuracy studies (PRISMA-DTA): explanation, elaboration, and checklist. *BMJ*, m2632. https://doi.org/10.1136/bmj.m2632

Saliya, C. A. (2023). Research philosophy. In *Social Research Methodology and Publishing Results: A Guide to Non-Native English Speakers* (pp. 35–51). https://doi.org/10.4018/978-1-6684-6859-3.ch004

Sampson, A., Theresa, A., & Joseph R, O. (2020). Evaluation of the Burden and Intervention Strategies of TB-HIV Co-Infection in West Africa. *Journal of Infectious Diseases and Epidemiology*, *6*(4). https://doi.org/10.23937/2474-3658/1510143

Samsuddin, S. A., Karmilla Kaman, Z., Khanm, T., Ali, Z., & Mat, N. (2024). Assessing socio-economic and environmental losses of dam- failure flood risk: a review on sustainable framework. *JOURNAL OF SUSTAINABILITY SCIENCE AND MANAGEMENT*, *19*(1), 171–195. https://doi.org/10.46754/jssm.2024.01.014

Samsuddin, S., Karmilla kaman, Z., Khanm, T., Ali, Z., & Mat, N. (2024). Assessing socio-economic and environmental losses of dam- failure flood risk: a review on sustainable framework. *Journal of Sustainability Science and Management*, *19*(1), 171–195. https://doi.org/10.46754/jssm.2024.01.014

Saunders, M., Lewis, P., & Thornhill, A. (2019). *Research methods for business students* (8th ed.). Pearson Education.

Schapper, A., & Urban, F. (2021). Large dams, norms and Indigenous Peoples. *Development Policy Review*, *39*(S1). https://doi.org/10.1111/dpr.12467

Schoonenboom, J., & Johnson, R. B. (2017). How to construct a mixed methods research design. *KZfSS Kölner Zeitschrift Für Soziologie Und Sozialpsychologie*, *69*(S2), 107–131. https://doi.org/10.1007/s11577-017-0454-1

Schrader, C. (2022). Serious Games and Game-Based Learning. In *Handbook of Open, Distance and Digital Education* (pp. 1–14). Springer Singapore. https://doi.org/10.1007/978-981-19-0351-9_74-1

Scotland, J. (2012). Exploring the philosophical underpinnings of research: Relating ontology and epistemology to the methodology and methods of the scientific, interpretive, and critical research paradigms. *English Language Teaching*, *5*(9). https://doi.org/10.5539/elt.v5n9p9

Seddeek, M. (2023). Structural and Non-structural Measures Integration through Multi-hazard Risk Approach - Sohag Governorate as an Example. *SVU-International Journal of Engineering Sciences and Applications*, *4*(2), 303–317. https://doi.org/10.21608/svusrc.2023.222761.1138

Shabu, T., & Musa, S. D. (2015). Downstream Socio-Economic Impact of Dam Failure: A Case Study of 2012 River Flooding in Benue State, Nigeria*. *Journal of Environmental Issues and Agriculture in Developing Countries*, *7*(3).

Shahraki, A., Zadbar, A., Motevalli, M., & Aghajani, F. (2012). Modeling of earth dam break with SMPDBK case study: Bidekan earth dam. *World Applied Sciences Journal*, *19*(3), 376–386. https://doi.org/10.5829/idosi.wasj.2012.19.03.1070

Shahrim, M. F., & Ros, F. C. (2020). Dam Break Analysis of Temenggor Dam Using HEC-RAS. *IOP Conference Series: Earth and Environmental Science*, *479*(1), 012041. https://doi.org/10.1088/1755-1315/479/1/012041

Sharma, G. (2017). *Impact factor: 5.2 IJAR*. *3*(7), 749–752. www.allresearchjournal.com

Shuka, K. A. M., Wang, K., Abubakar, G. A., & Xu, T. (2024). Impact of Structural and Non-Structural Measures on the Risk of Flash Floods in Arid and Semi-Arid Regions: A Case Study of the Gash River, Kassala, Eastern Sudan. *Sustainability*, *16*(5), 1752. https://doi.org/10.3390/su16051752

Silva, A. F. R., & Eleutério, J. C. (2023). Effectiveness of a Dam-Breach Flood Alert in Mitigating Life Losses: A Spatiotemporal Sectorisation Analysis in a High-Density Urban Area in Brazil. *Water*, *15*(19), 3433. https://doi.org/10.3390/w15193433

Silva Rotta, L. H., Alcântara, E., Park, E., Negri, R. G., Lin, Y. N., Bernardo, N., Mendes, T. S. G., & Souza Filho, C. R. (2020). The 2019 Brumadinho tailings dam collapse: Possible cause and impacts of the worst human and environmental disaster in Brazil. *International Journal of Applied Earth Observation and Geoinformation*, *90*, 102119. https://doi.org/10.1016/j.jag.2020.102119

Singh, A. (2021). *Significance of research process in research work*. https://doi.org/10.13140/RG.2.2.32664.93445/1

Singh, V. K., Singh, P., Karmakar, M., Leta, J., & Mayr, P. (2021). The journal coverage of Web of Science, Scopus and Dimensions: A comparative analysis. *Scientometrics*, *126*(6), 5113–5142. https://doi.org/10.1007/s11192-021-03948-5

Smith, D. (2024). The social impacts of dams and hydropower. In *Handbook of Social Impact Assessment and Management* (pp. 51–66). Edward Elgar Publishing. https://doi.org/10.4337/9781802208870.00011

Solinska-Nowak, A., Magnuszewski, P., Curl, M., French, A., Keating, A., Mochizuki, J., Liu, W., Mechler, R., Kulakowska, M., & Jarzabek, L. (2018). An overview of serious games for disaster risk management – Prospects and limitations for informing actions to arrest increasing risk. *International Journal of Disaster Risk Reduction*, *31*, 1013–1029. https://doi.org/10.1016/j.ijdrr.2018.09.001

Sreekumar, U., Gildeh, H. K., Mohammadian, A., Rennie, C., & Nistor, I. (2024). Tailings Dam Breach Outflow Modelling: A Review. *Mine Water and the Environment*, *43*(4), 563–587. https://doi.org/10.1007/s10230-024-01015-y

Stuckey, H. (2015). The second step in data analysis: Coding qualitative research data. *Journal of Social Health and Diabetes*, *03*(01), 007–010. https://doi.org/10.4103/2321-0656.140875

Sun, M.-C., Sakai, K., Chen, A. Y., & Hsu, Y.-T. (2022). Location problems of vertical evacuation structures for dam-failure floods: Considering shelter-in-place and horizontal evacuation. *International Journal of Disaster Risk Reduction*, *77*, 103044. https://doi.org/10.1016/j.ijdrr.2022.103044

Taherdoost, H. (2021). Data collection methods and tools for research; a step-by-step guide to choose data collection technique for academic and business research projects. In *International Journal of Academic Research in Management (IJARM)* (Vol. 2021, Issue 1). https://hal.science/hal-03741847

Taherdoost, H. (2022). What are different research approaches? comprehensive review of qualitative, quantitative, and mixed method research, their applications, types, and limitations. *Journal of Management Science & Engineering Research*, *5*(1), 53–63. https://doi.org/10.30564/jmser.v5i1.4538

Taillandier, F., Di Maiolo, P., Taillandier, P., Jacquenod, C., Rauscher-Lauranceau, L., & Mehdizadeh, R. (2021). An agent-based model to simulate inhabitants' behavior during a flood event. *International Journal of Disaster Risk Reduction*, *64*, 102503. https://doi.org/10.1016/j.ijdrr.2021.102503

Tariq, M. A. U. R., Rajabi, Z., & Muttil, N. (2021). An Evaluation of Risk-Based Agricultural Land-Use Adjustments under a Flood Management Strategy in a Floodplain. *Hydrology*, *8*(1), 53. https://doi.org/10.3390/hydrology8010053

Tesfatsion, L., Rehmann, C. R., Cardoso, D. S., Jie, Y., & Gutowski, W. J. (2017). An agent-based platform for the study of watersheds as coupled natural and human systems. *Environmental Modelling & Software*, *89*, 40–60. https://doi.org/10.1016/j.envsoft.2016.11.021

Tessema, B. H., Gebremedhn, A. Y., & Getahun, Y. S. (2024). Dam breach analysis and flood inundation mapping of Dire Dam, using HEC-HMS and HEC-RAS models. *Sustainable Water Resources Management*, *10*(2), 45. https://doi.org/10.1007/s40899-023-01015-w

Tingey-Holyoak, J. L., Pisaniello, J. D., Burritt, R. L., & Spassis, A. (2013). Incorporating on-farm water storage safety into catchment policy frameworks: International best practice policy for private dam safety accountability and assurance. *Land Use Policy*, *33*, 61–70. https://doi.org/10.1016/j.landusepol.2012.12.011

Tortajada, C. (2015). Dams: An Essential Component of Development. *Journal of Hydrologic Engineering*, *20*(1). https://doi.org/10.1061/(ASCE)HE.1943-5584.0000919

Tsai, M.-H., Chang, Y.-L., Shiau, J.-S., & Wang, S.-M. (2020). Exploring the effects of a serious game-based learning package for disaster prevention education: The case of Battle of Flooding Protection. *International Journal of Disaster Risk Reduction*, *43*, 101393. https://doi.org/10.1016/j.ijdrr.2019.101393

Tukiman, I., Ramzi, Z., Rahsidi Izawati TNB Sdn Bhd, S. T., Mohd Ramzi Ismawi, M. Z., & Lumpur, K. (2017). Shaping the Future of Hydropower. In *International Journal of Hydropower and Dam*. https://www.researchgate.net/publication/349988315

United Nations Environment Programme (UNEP), Principles for Responsible Investment (PRI), & International Council on Mining and Metals (ICMM). (2020). *Global Industry Standard on Tailings Management*.

Vallance, S., & Carlton, S. (2015). First to respond, last to leave: Communities' roles and resilience across the '4Rs.' *International Journal of Disaster Risk Reduction*, *14*, 27–36. https://doi.org/10.1016/j.ijdrr.2014.10.010

Vamvakeridou-Lyroudia, L. S., Chen, A. S., Khoury, M., Gibson, M. J., Kostaridis, A., Stewart, D., Wood, M., Djordjevic, S., & Savic, D. A. (2020). Assessing and visualising hazard impacts to enhance the resilience of Critical Infrastructures to urban flooding. *Science of The Total Environment*, *707*, 136078. https://doi.org/10.1016/j.scitotenv.2019.136078

Victoria Department of Environment, L. W. and P. (2015). *Engaging communities on dam safety: A guide for dam owners*.

https://www.water.vic.gov.au/__data/assets/pdf_file/0036/671949/engaging-communities-on-dam-safety-a-guide-for-dam-owners.pdf

Vogel, A. (2013). *Failures of Dams – Challenges to the Present and the Future*. 178–185. https://doi.org/10.2749/222137813807018908

Wang, Y., Fu, Z., Cheng, Z., Xiang, Y., Chen, J., Zhang, P., & Yang, X. (2024). Uncertainty analysis of dam-break flood risk consequences under the influence of non-structural measures. *International Journal of Disaster Risk Reduction*, *102*, 104265. https://doi.org/10.1016/j.ijdrr.2024.104265

Wang, Y., Xiang, Y., Dai, B., & Li, J. (2025). Dam early warning model based on structural anomaly identification and dynamic effect variables selection. *Structures*, *74*, 108507. https://doi.org/10.1016/j.istruc.2025.108507

Weerasinghe, L., Thayaparan, M., & Fernando, T. (2022). Functional characteristics of an early warning system to minimise the risks of dam breaks in Sri Lanka. *Proceedings of 10th World Construction Symposium 2022*, 506–518. https://doi.org/10.31705/WCS.2022.41

Whitney, D. J., Lindell, M. K., & Nguyen, H. D. (2004). Earthquake Beliefs and Adoption of Seismic Hazard Adjustments. *Risk Analysis*, *24*(1), 87–102. https://doi.org/10.1111/j.0272-4332.2004.00414.x

Wilk-Woźniak, E., Krztoń, W., & Górnik, M. (2021). Synergistic impact of socio-economic and climatic changes on the ecosystem of a deep dam reservoir: Case study of the Dobczyce dam reservoir based on a 30-year monitoring study. *Science of The Total Environment*, *756*, 144055. https://doi.org/10.1016/j.scitotenv.2020.144055

Wouters, P., van Nimwegen, C., van Oostendorp, H., & van der Spek, E. D. (2013). A meta-analysis of the cognitive and motivational effects of serious games. *Journal of Educational Psychology*, *105*(2), 249–265. https://doi.org/10.1037/a0031311

Wu, M., Ge, W., Li, Z., Wu, Z., Zhang, H., Li, J., & Pan, Y. (2019). Improved Set Pair Analysis and Its Application to Environmental Impact Evaluation of Dam Break. *Water*, *11*(4), 821. https://doi.org/10.3390/w11040821

Wu, M., YE, Y., Hu, N., Wang, Q., & Tan, W. (2022). Scientometric analysis on the review research evolution of tailings dam failure disasters. *Environmental Science and Pollution Research*, *30*(6), 13945–13959. https://doi.org/10.1007/s11356-022-24937-y

Wu, S., Lei, Y., Yang, S., Cui, P., & Jin, W. (2022). An Agent-Based Approach to Integrate Human Dynamics Into Disaster Risk Management. *Frontiers in Earth Science*, *9*. https://doi.org/10.3389/feart.2021.818913

Xie, L., Xu, W., Ding, X., Bürgmann, R., Giri, S., & Liu, X. (2022). A multi-platform, open-source, and quantitative remote sensing framework for dam-related hazard investigation: Insights into the 2020 Sardoba dam collapse. In *International Journal of Applied Earth Observation and Geoinformation* (Vol. 111). Elsevier B.V. https://doi.org/10.1016/j.jag.2022.102849

Xiong, Y. (2011). A Dam Break Analysis Using HEC-RAS. *Journal of Water Resource and Protection*, *03*(06), 370–379. https://doi.org/10.4236/jwarp.2011.36047

Yochum, S. E., Goertz, L. A., & Jones, P. H. (2008). Case Study of the Big Bay Dam Failure: Accuracy and Comparison of Breach Predictions. *Journal of Hydraulic Engineering*, *134*(9), 1285–1293. https://doi.org/10.1061/(ASCE)0733-9429(2008)134:9(1285)

Zaharaddeen Kado, S., Ibrahim, R., & Mohamed Khaidzir, K. A. (2014). Agent parameters for building consultant teamwork in the agent-based simulation model development. *2014 International Symposium on Technology Management and Emerging Technologies*, 212–217. https://doi.org/10.1109/ISTMET.2014.6936508

Zhang, J., Yang, X., Fan, G., Li, H., & Zhou, J. (2024). Physical and numerical modeling of a landslide dam breach and flood routing process. *Journal of Hydrology*, *628*, 130552. https://doi.org/10.1016/j.jhydrol.2023.130552

Zhang, X., Wang, C.-Y., Wong, H., Jiang, T., & Dong, J. (2022). Modeling dam deformation in the early stage of internal seepage erosion – Application to the Teton Dam, Idaho, before the 1976 incident. *Journal of Hydrology*, *605*, 127378. https://doi.org/10.1016/j.jhydrol.2021.127378

Zhong, B., Wu, H., Li, H., Sepasgozar, S., Luo, H., & He, L. (2019). A scientometric analysis and critical review of construction related ontology research. *Automation in Construction*, *101*, 17–31. https://doi.org/10.1016/j.autcon.2018.12.013

Zhuo, L., & Han, D. (2020). Agent-based modelling and flood risk management: A compendious literature review. *Journal of Hydrology*, *591*, 125600. https://doi.org/10.1016/j.jhydrol.2020.125600

Zio, E., & Duffey, R. B. (2021). The risk of the electrical power grid due to natural hazards and recovery challenge following disasters and record floods: What next? In *Climate Change and Extreme Events* (pp. 215–238). Elsevier. https://doi.org/10.1016/B978-0-12-822700-8.00008-1

Žukauskas, P., Vveinhardt, J., & Andriukaitienė, R. (2018). Philosophy and Paradigm of Scientific Research. In *Management Culture and Corporate Social Responsibility*. InTech. https://doi.org/10.5772/intechopen.70628

APPENDICES

Appendix A – Interview Guideline

<u>Section 1: Background and Context</u>

1. **Participant Information**
   - **Name, Profession, years of experience, highest education level**
   - Could you tell me about your experience and background in relation to dam infrastructure or disaster management?
   - What roles have you played in planning, implementing, or managing responses to dam-related disasters?

<u>Section 2: Socio-Economic Impacts of Dam Failures</u>

1. **Economic Impacts**
   - How do you perceive the economic impacts of dam failures on communities and regions?
   - Could you describe some specific ways in which dam failures can disrupt local and regional economies?
   - In your experience, what industries or sectors are most affected by dam failures? Why?
   - How significant is the financial cost of recovery from dam failures in terms of government and private resources?
2. **Social and Community Impacts**
   - What are some of the most noticeable social impacts of dam failures on local communities?
   - How do dam failures impact community structures, social cohesion, and displacement of populations?
   - Can you discuss the long-term social consequences of dam failures for affected populations?
3. **Health and Safety Impacts**
   - What are the key health and safety challenges associated with dam failures?
   - In what ways do dam failures affect public health infrastructure and services?
   - How do these failures impact emergency response and healthcare systems?

Section 3: Preparedness and Risk Mitigation

1. **Preparedness and Community Resilience**
    - From your perspective, how prepared are most communities in dealing with potential dam failures?
    - What role does community resilience play in mitigating the socio-economic impacts of dam failures?
2. **Policy and Governance**
    - What policy or governance issues do you think play a role in managing the socio-economic impacts of dam failures?
    - Can you identify specific regulatory or policy changes that could reduce the socio-economic risks associated with dam infrastructure?

Section 4: Recommendations and Conclusion

1. **Mitigation Strategies**
    - What strategies would you recommend for minimizing the socio-economic impacts of dam failures?
    - Are there specific socio-economic mitigation measures that have proven effective in past dam-related incidents?
2. **Closing Remarks**
    - Is there anything else you would like to add regarding the socio-economic impacts of dam failures?
    - Do you have any recommendations for further research or policy improvements?

Appendix B – Events and the Decision Ranking

Engineer

Event	1st	2nd	3rd	4th	5th	6th
1. Heavy Rainfall	Activate emergency spillways to relieve upstream pressure	Deploy reinforcements to weak zones	Install steel buttresses along the downstream face	Construct temporary cofferdams to divert water flow	Seal cracks and joints with epoxy grout under pressure	Apply shotcrete (sprayed concrete) on eroded surfaces
2. Cracked Concrete	Seal cracks and joints with epoxy grout under pressure	Deploy reinforcements to weak zones	Install steel buttresses along the downstream face	Apply shotcrete (sprayed concrete) on eroded surfaces	Activate emergency spillways to relieve upstream pressure	Construct temporary cofferdams to divert water flow
3. Seismic Tremor	Apply shotcrete (sprayed concrete) on eroded surfaces	Install steel buttresses along the downstream face	Deploy reinforcements to weak zones	Construct temporary cofferdams to divert water flow	Seal cracks and joints with epoxy grout under pressure	Activate emergency spillways to relieve upstream pressure
4. Blocked Spillway	Construct temporary cofferdams to divert water flow	Activate emergency spillways to relieve upstream pressure	Deploy reinforcements to weak zones	Install steel buttresses along the downstream face	Apply shotcrete (sprayed concrete) on eroded surfaces	Seal cracks and joints with epoxy grout under pressure

5. Sabotage Suspected	Deploy reinforcements to weak zones	Install steel buttresses along the downstream face	Construct temporary cofferdams to divert water flow	Activate emergency spillways to relieve upstream pressure	Seal cracks and joints with epoxy grout under pressure	Apply shotcrete (sprayed concrete) on eroded surfaces
6. Control Room Malfunction	Activate emergency spillways to relieve upstream pressure	Deploy reinforcements to weak zones	Install steel buttresses along the downstream face	Seal cracks and joints with epoxy grout under pressure	Construct temporary cofferdams to divert water flow	Apply shotcrete (sprayed concrete) on eroded surfaces
7. Landslide Nearby	Install steel buttresses along the downstream face	Deploy reinforcements to weak zones	Seal cracks and joints with epoxy grout under pressure	Construct temporary cofferdams to divert water flow	Apply shotcrete (sprayed concrete) on eroded surfaces	Activate emergency spillways to relieve upstream pressure
8. Communication Breakdown	Construct temporary cofferdams to divert water flow	Deploy reinforcements to weak zones	Install steel buttresses along the downstream face	Apply shotcrete (sprayed concrete) on eroded surfaces	Seal cracks and joints with epoxy grout under pressure	Activate emergency spillways to relieve upstream pressure
9. Flash Flood Warning	Activate emergency spillways to	Install steel buttresses along the downstream face	Construct temporary cofferdams to divert water flow	Apply shotcrete (sprayed concrete) on eroded surfaces	Seal cracks and joints with epoxy grout under pressure	Deploy reinforcements to weak zones

	relieve upstream pressure					
10. Budget Cut	Apply shotcrete (sprayed concrete) on eroded surfaces	Seal cracks and joints with epoxy grout under pressure	Deploy reinforcements to weak zones	Install steel buttresses along the downstream face	Construct temporary cofferdams to divert water flow	Activate emergency spillways to relieve upstream pressure
11. Evacuation Panic	Deploy reinforcements to weak zones	Activate emergency spillways to relieve upstream pressure	Install steel buttresses along the downstream face	Seal cracks and joints with epoxy grout under pressure	Apply shotcrete (sprayed concrete) on eroded surfaces	Construct temporary cofferdams to divert water flow
12. Algae Bloom	Seal cracks and joints with epoxy grout under pressure	Deploy reinforcements to weak zones	Construct temporary cofferdams to divert water flow	Install steel buttresses along the downstream face	Apply shotcrete (sprayed concrete) on eroded surfaces	Activate emergency spillways to relieve upstream pressure
13. Construction Delay	Construct temporary cofferdams to divert water flow	Seal cracks and joints with epoxy grout under pressure	Deploy reinforcements to weak zones	Apply shotcrete (sprayed concrete) on eroded surfaces	Activate emergency spillways to relieve upstream pressure	Install steel buttresses along the downstream face
14. Downstream Protest	Activate emergency spillways to	Deploy reinforcements to weak zones	Install steel buttresses along	Construct temporary	Seal cracks and joints with epoxy	Apply shotcrete (sprayed

	relieve upstream pressure		the downstream face	cofferdams to divert water flow	grout under pressure	concrete) on eroded surfaces
15. Seepage Detected	Seal cracks and joints with epoxy grout under pressure	Deploy reinforcements to weak zones	Apply shotcrete (sprayed concrete) on eroded surfaces	Construct temporary cofferdams to divert water flow	Install steel buttresses along the downstream face	Activate emergency spillways to relieve upstream pressure
16. Drought-Lifted Suddenly	Activate emergency spillways to relieve upstream pressure	Install steel buttresses along the downstream face	Construct temporary cofferdams to divert water flow	Deploy reinforcements to weak zones	Seal cracks and joints with epoxy grout under pressure	Apply shotcrete (sprayed concrete) on eroded surfaces
17. Overflow Alarm Triggered	Deploy reinforcements to weak zones	Seal cracks and joints with epoxy grout under pressure	Apply shotcrete (sprayed concrete) on eroded surfaces	Install steel buttresses along the downstream face	Construct temporary cofferdams to divert water flow	Activate emergency spillways to relieve upstream pressure
18. Media Scrutiny	Apply shotcrete (sprayed concrete) on eroded surfaces	Activate emergency spillways to relieve upstream pressure	Deploy reinforcements to weak zones	Install steel buttresses along the downstream face	Construct temporary cofferdams to divert water flow	Seal cracks and joints with epoxy grout under pressure
19. Downstream Levee Breach	Deploy reinforcements to weak zones	Install steel buttresses along the downstream face	Construct temporary	Apply shotcrete (sprayed concrete)	Seal cracks and joints with epoxy	Activate emergency spillways to

			cofferdams to divert water flow	on eroded surfaces	grout under pressure	relieve upstream pressure
20. Structural Resonance	Install steel buttresses along the downstream face	Deploy reinforcements to weak zones	Construct temporary cofferdams to divert water flow	Seal cracks and joints with epoxy grout under pressure	Apply shotcrete (sprayed concrete) on eroded surfaces	Activate emergency spillways to relieve upstream pressure

Evacuation Specialist

Event	1st	2nd	3rd	4th	5th	6th
1. Heavy Rainfall	Initiate full evacuation of high-risk downstream zones	Deploy rescue boats and trucks to submerged or trapped areas	Mobilize rapid-response evacuation units via radio alert	Set up and operate emergency evacuation shelters	Clear and secure evacuation routes from debris and blockages	Coordinate transport for vulnerable groups (elderly, disabled, children)
2. Cracked Concrete	Coordinate transport for vulnerable groups (elderly, disabled, children)	Initiate full evacuation of high-risk downstream zones	Mobilize rapid-response evacuation units via radio alert	Clear and secure evacuation routes from debris and blockages	Set up and operate emergency evacuation shelters	Deploy rescue boats and trucks to submerged or trapped areas
3. Seismic Tremor	Mobilize rapid-response	Initiate full evacuation of	Coordinate transport for	Set up and operate	Clear and secure evacuation routes	Deploy rescue boats and trucks

	evacuation units via radio alert	high-risk downstream zones	vulnerable groups (elderly, disabled, children)	emergency evacuation shelters	from debris and blockages	to submerged or trapped areas
4. Blocked Spillway	Deploy rescue boats and trucks to submerged or trapped areas	Mobilize rapid-response evacuation units via radio alert	Clear and secure evacuation routes from debris and blockages	Set up and operate emergency evacuation shelters	Initiate full evacuation of high-risk downstream zones	Coordinate transport for vulnerable groups (elderly, disabled, children)
5. Sabotage Suspected	Clear and secure evacuation routes from debris and blockages	Mobilize rapid-response evacuation units via radio alert	Initiate full evacuation of high-risk downstream zones	Set up and operate emergency evacuation shelters	Coordinate transport for vulnerable groups (elderly, disabled, children)	Deploy rescue boats and trucks to submerged or trapped areas
6. Control Room Malfunction	Set up and operate emergency evacuation shelters	Initiate full evacuation of high-risk downstream zones	Mobilize rapid-response evacuation units via radio alert	Deploy rescue boats and trucks to submerged or trapped areas	Clear and secure evacuation routes from debris and blockages	Coordinate transport for vulnerable groups (elderly, disabled, children)
7. Landslide Nearby	Initiate full evacuation of high-risk downstream zones	Coordinate transport for vulnerable groups	Mobilize rapid-response evacuation units via radio alert	Deploy rescue boats and trucks to submerged or trapped areas	Clear and secure evacuation routes from debris and blockages	Set up and operate emergency

		(elderly, disabled, children)				evacuation shelters
8. Communication Breakdown	Mobilize rapid-response evacuation units via radio alert	Clear and secure evacuation routes from debris and blockages	Initiate full evacuation of high-risk downstream zones	Coordinate transport for vulnerable groups (elderly, disabled, children)	Deploy rescue boats and trucks to submerged or trapped areas	Set up and operate emergency evacuation shelters
9. Flash Flood Warning	Initiate full evacuation of high-risk downstream zones	Deploy rescue boats and trucks to submerged or trapped areas	Mobilize rapid-response evacuation units via radio alert	Clear and secure evacuation routes from debris and blockages	Set up and operate emergency evacuation shelters	Coordinate transport for vulnerable groups (elderly, disabled, children)
10. Budget Cut	Set up and operate emergency evacuation shelters	Coordinate transport for vulnerable groups (elderly, disabled, children)	Initiate full evacuation of high-risk downstream zones	Mobilize rapid-response evacuation units via radio alert	Clear and secure evacuation routes from debris and blockages	Deploy rescue boats and trucks to submerged or trapped areas
11. Evacuation Panic	Set up and operate emergency evacuation shelters	Clear and secure evacuation routes from debris and blockages	Initiate full evacuation of high-risk downstream zones	Coordinate transport for vulnerable groups (elderly, disabled, children)	Deploy rescue boats and trucks to submerged or trapped areas	Mobilize rapid-response evacuation units via radio alert

12. Algae Bloom	Coordinate transport for vulnerable groups (elderly, disabled, children)	Set up and operate emergency evacuation shelters	Initiate full evacuation of high-risk downstream zones	Clear and secure evacuation routes from debris and blockages	Mobilize rapid-response evacuation units via radio alert	Deploy rescue boats and trucks to submerged or trapped areas
13. Construction Delay	Set up and operate emergency evacuation shelters	Initiate full evacuation of high-risk downstream zones	Clear and secure evacuation routes from debris and blockages	Mobilize rapid-response evacuation units via radio alert	Deploy rescue boats and trucks to submerged or trapped areas	Coordinate transport for vulnerable groups (elderly, disabled, children)
14. Downstream Protest	Mobilize rapid-response evacuation units via radio alert	Clear and secure evacuation routes from debris and blockages	Initiate full evacuation of high-risk downstream zones	Deploy rescue boats and trucks to submerged or trapped areas	Coordinate transport for vulnerable groups (elderly, disabled, children)	Set up and operate emergency evacuation shelters
15. Seepage Detected	Initiate full evacuation of high-risk downstream zones	Coordinate transport for vulnerable groups (elderly, disabled, children)	Clear and secure evacuation routes from debris and blockages	Deploy rescue boats and trucks to submerged or trapped areas	Mobilize rapid-response evacuation units via radio alert	Set up and operate emergency evacuation shelters
16. Drought-Lifted Suddenly	Initiate full evacuation of	Set up and operate emergency evacuation shelters	Clear and secure evacuation routes	Coordinate transport for vulnerable groups	Deploy rescue boats and trucks	Mobilize rapid-response

	high-risk downstream zones		from debris and blockages	(elderly, disabled, children)	to submerged or trapped areas	evacuation units via radio alert
17. Overflow Alarm Triggered	Set up and operate emergency evacuation shelters	Mobilize rapid-response evacuation units via radio alert	Clear and secure evacuation routes from debris and blockages	Initiate full evacuation of high-risk downstream zones	Deploy rescue boats and trucks to submerged or trapped areas	Coordinate transport for vulnerable groups (elderly, disabled, children)
18. Media Scrutiny	Set up and operate emergency evacuation shelters	Coordinate transport for vulnerable groups (elderly, disabled, children)	Initiate full evacuation of high-risk downstream zones	Clear and secure evacuation routes from debris and blockages	Deploy rescue boats and trucks to submerged or trapped areas	Mobilize rapid-response evacuation units via radio alert
19. Downstream Levee Breach	Deploy rescue boats and trucks to submerged or trapped areas	Initiate full evacuation of high-risk downstream zones	Mobilize rapid-response evacuation units via radio alert	Clear and secure evacuation routes from debris and blockages	Set up and operate emergency evacuation shelters	Coordinate transport for vulnerable groups (elderly, disabled, children)
20. Structural Resonance	Initiate full evacuation of high-risk downstream zones	Mobilize rapid-response evacuation units via radio alert	Clear and secure evacuation routes from debris and blockages	Coordinate transport for vulnerable groups (elderly, disabled, children)	Deploy rescue boats and trucks to submerged or trapped areas	Set up and operate emergency evacuation shelters

Government Official

Event	1st	2nd	3rd	4th	5th	6th
1. Heavy Rainfall	Issues a region-wide emergency broadcast with clear evacuation instructions	Release emergency disaster relief funds for structural repair and evacuation	Deploy national guards or military to assist in evacuations and flood control	Declare a state of emergency to fast-track decision-making and bypass bureaucracy	Authorize aerial support (helicopters, drones) to assist evacuation and supply drops	Enforce mandatory evacuation in all red-zone areas
2. Cracked Concrete	Release emergency disaster relief funds for structural repair and evacuation	Deploy national guards or military to assist in evacuations and flood control	Issues a region-wide emergency broadcast with clear evacuation instructions	Authorize aerial support (helicopters, drones) to assist evacuation and supply drops	Enforce mandatory evacuation in all red-zone areas	Declare a state of emergency to fast-track decision-making and bypass bureaucracy
3. Seismic Tremor	Enforce mandatory evacuation in all red-zone areas	Deploy national guards or military to assist in evacuations and flood control	Release emergency disaster relief funds for structural repair and evacuation	Issues a region-wide emergency broadcast with clear evacuation instructions	Declare a state of emergency to fast-track decision-making and bypass bureaucracy	Authorize aerial support (helicopters, drones) to assist evacuation and supply drops
4. Blocked Spillway	Deploy national guards or military to assist in	Issues a region-wide emergency broadcast with	Release emergency disaster relief funds for structural repair and evacuation	Authorize aerial support (helicopters, drones) to assist	Enforce mandatory evacuation in all red-zone areas	Declare a state of emergency to fast-track decision-making

	evacuations and flood control	clear evacuation instructions		evacuation and supply drops		and bypass bureaucracy
5. Sabotage Suspected	Declare a state of emergency to fast-track decision-making and bypass bureaucracy	Authorize aerial support (helicopters, drones) to assist evacuation and supply drops	Issues a region-wide emergency broadcast with clear evacuation instructions	Release emergency disaster relief funds for structural repair and evacuation	Deploy national guards or military to assist in evacuations and flood control	Enforce mandatory evacuation in all red-zone areas
6. Control Room Malfunction	Issues a region-wide emergency broadcast with clear evacuation instructions	Authorize aerial support (helicopters, drones) to assist evacuation and supply drops	Release emergency disaster relief funds for structural repair and evacuation	Declare a state of emergency to fast-track decision-making and bypass bureaucracy	Deploy national guards or military to assist in evacuations and flood control	Enforce mandatory evacuation in all red-zone areas
7. Landslide Nearby	Enforce mandatory evacuation in all red-zone areas	Release emergency disaster relief funds for structural repair and evacuation	Deploy national guards or military to assist in evacuations and flood control	Issues a region-wide emergency broadcast with clear evacuation instructions	Authorize aerial support (helicopters, drones) to assist evacuation and supply drops	Declare a state of emergency to fast-track decision-making and bypass bureaucracy
8. Communication Breakdown	Issues a region-wide emergency broadcast with	Authorize aerial support (helicopters, drones) to assist	Release emergency disaster relief funds for structural repair and evacuation	Deploy national guards or military to assist in	Declare a state of emergency to fast-track decision-making	Enforce mandatory evacuation in all red-zone areas

	clear evacuation instructions	evacuation and supply drops		evacuations and flood control	and bypass bureaucracy	
9. Flash Flood Warning	Issues a region-wide emergency broadcast with clear evacuation instructions	Deploy national guards or military to assist in evacuations and flood control	Enforce mandatory evacuation in all red-zone areas	Release emergency disaster relief funds for structural repair and evacuation	Declare a state of emergency to fast-track decision-making and bypass bureaucracy	Authorize aerial support (helicopters, drones) to assist evacuation and supply drops
10. Budget Cut	Release emergency disaster relief funds for structural repair and evacuation	Declare a state of emergency to fast-track decision-making and bypass bureaucracy	Issues a region-wide emergency broadcast with clear evacuation instructions	Authorize aerial support (helicopters, drones) to assist evacuation and supply drops	Enforce mandatory evacuation in all red-zone areas	Deploy national guards or military to assist in evacuations and flood control
11. Evacuation Panic	Issues a region-wide emergency broadcast with clear evacuation instructions	Declare a state of emergency to fast-track decision-making and bypass bureaucracy	Release emergency disaster relief funds for structural repair and evacuation	Authorize aerial support (helicopters, drones) to assist evacuation and supply drops	Deploy national guards or military to assist in evacuations and flood control	Enforce mandatory evacuation in all red-zone areas
12. Algae Bloom	Declare a state of emergency to fast-track decision-	Release emergency disaster relief funds for	Issues a region-wide emergency broadcast with clear	Enforce mandatory evacuation in all red-zone areas	Authorize aerial support (helicopters, drones) to assist	Deploy national guards or military to assist

	making and bypass bureaucracy	structural repair and evacuation	evacuation instructions		evacuation and supply drops	in evacuations and flood control
13. Construction Delay	Release emergency disaster relief funds for structural repair and evacuation	Declare a state of emergency to fast-track decision-making and bypass bureaucracy	Issues a region-wide emergency broadcast with clear evacuation instructions	Deploy national guards or military to assist in evacuations and flood control	Enforce mandatory evacuation in all red-zone areas	Authorize aerial support (helicopters, drones) to assist evacuation and supply drops
14. Downstream Protest	Declare a state of emergency to fast-track decision-making and bypass bureaucracy	Issues a region-wide emergency broadcast with clear evacuation instructions	Deploy national guards or military to assist in evacuations and flood control	Release emergency disaster relief funds for structural repair and evacuation	Authorize aerial support (helicopters, drones) to assist evacuation and supply drops	Enforce mandatory evacuation in all red-zone areas
15. Seepage Detected	Authorize aerial support (helicopters, drones) to assist evacuation and supply drops	Issues a region-wide emergency broadcast with clear evacuation instructions	Release emergency disaster relief funds for structural repair and evacuation	Declare a state of emergency to fast-track decision-making and bypass bureaucracy	Deploy national guards or military to assist in evacuations and flood control	Enforce mandatory evacuation in all red-zone areas
16. Drought-Lifted Suddenly	Issues a region-wide emergency broadcast with	Release emergency disaster relief funds for	Declare a state of emergency to fast-track decision-	Authorize aerial support (helicopters, drones) to assist	Deploy national guards or military to assist in	Enforce mandatory evacuation in all red-zone areas

	clear evacuation instructions	structural repair and evacuation	making and bypass bureaucracy	evacuation and supply drops	evacuations and flood control	
17. Overflow Alarm Triggered	Issues a region-wide emergency broadcast with clear evacuation instructions	Authorize aerial support (helicopters, drones) to assist evacuation and supply drops	Release emergency disaster relief funds for structural repair and evacuation	Declare a state of emergency to fast-track decision-making and bypass bureaucracy	Deploy national guards or military to assist in evacuations and flood control	Enforce mandatory evacuation in all red-zone areas
18. Media Scrutiny	Declare a state of emergency to fast-track decision-making and bypass bureaucracy	Issues a region-wide emergency broadcast with clear evacuation instructions	Release emergency disaster relief funds for structural repair and evacuation	Authorize aerial support (helicopters, drones) to assist evacuation and supply drops	Deploy national guards or military to assist in evacuations and flood control	Enforce mandatory evacuation in all red-zone areas
19. Downstream Levee Breach	Deploy national guards or military to assist in evacuations and flood control	Issues a region-wide emergency broadcast with clear evacuation instructions	Release emergency disaster relief funds for structural repair and evacuation	Authorize aerial support (helicopters, drones) to assist evacuation and supply drops	Declare a state of emergency to fast-track decision-making and bypass bureaucracy	Enforce mandatory evacuation in all red-zone areas
20. Structural Resonance	Enforce mandatory evacuation in all red-zone areas	Authorize aerial support (helicopters, drones) to assist	Issues a region-wide emergency broadcast with clear	Release emergency disaster relief funds for	Deploy national guards or military to assist in	Declare a state of emergency to fast-track decision-making

		evacuation and supply drops	evacuation instructions	structural repair and evacuation	evacuations and flood control	and bypass bureaucracy

City Planner

Event	1st	2nd	3rd	4th	5th	6th
1. Heavy Rainfall	Divert stormwater using emergency drainage channels and retention basins	Construct temporary flood barriers and levees in key urban zones	Sandbag entrances to essential buildings (hospitals, shelters, utilities)	Shut down power grids and gas lines in flood-prone districts	Reroute public transportation away from at-risk corridors	Convert public buildings (schools, community centers) into flood shelters
2. Cracked Concrete	Sandbag entrances to essential buildings (hospitals, shelters, utilities)	Construct temporary flood barriers and levees in key urban zones	Shut down power grids and gas lines in flood-prone districts	Convert public buildings (schools, community centers) into flood shelters	Divert stormwater using emergency drainage channels and retention basins	Reroute public transportation away from at-risk corridors
3. Seismic Tremor	Shut down power grids and gas lines in flood-prone districts	Sandbag entrances to essential buildings (hospitals, shelters, utilities)	Construct temporary flood barriers and levees in key urban zones	Convert public buildings (schools, community centers) into flood shelters	Divert stormwater using emergency drainage channels and retention basins	Reroute public transportation away from at-risk corridors

4. Blocked Spillway	Divert stormwater using emergency drainage channels and retention basins	Construct temporary flood barriers and levees in key urban zones	Sandbag entrances to essential buildings (hospitals, shelters, utilities)	Shut down power grids and gas lines in flood-prone districts	Reroute public transportation away from at-risk corridors	Convert public buildings (schools, community centers) into flood shelters
5. Sabotage Suspected	Convert public buildings (schools, community centers) into flood shelters	Sandbag entrances to essential buildings (hospitals, shelters, utilities)	Construct temporary flood barriers and levees in key urban zones	Shut down power grids and gas lines in flood-prone districts	Reroute public transportation away from at-risk corridors	Divert stormwater using emergency drainage channels and retention basins
6. Control Room Malfunction	Shut down power grids and gas lines in flood-prone districts	Reroute public transportation away from at-risk corridors	Construct temporary flood barriers and levees in key urban zones	Convert public buildings (schools, community centers) into flood shelters	Sandbag entrances to essential buildings (hospitals, shelters, utilities)	Divert stormwater using emergency drainage channels and retention basins
7. Landslide Nearby	Construct temporary flood barriers and levees in key urban zones	Divert stormwater using emergency drainage channels and retention basins	Shut down power grids and gas lines in flood-prone districts	Sandbag entrances to essential buildings (hospitals, shelters, utilities)	Convert public buildings (schools, community centers) into flood shelters	Reroute public transportation away from at-risk corridors

8. Communication Breakdown	Convert public buildings (schools, community centers) into flood shelters	Sandbag entrances to essential buildings (hospitals, shelters, utilities)	Construct temporary flood barriers and levees in key urban zones	Reroute public transportation away from at-risk corridors	Divert stormwater using emergency drainage channels and retention basins	Shut down power grids and gas lines in flood-prone districts
9. Flash Flood Warning	Divert stormwater using emergency drainage channels and retention basins	Sandbag entrances to essential buildings (hospitals, shelters, utilities)	Construct temporary flood barriers and levees in key urban zones	Shut down power grids and gas lines in flood-prone districts	Convert public buildings (schools, community centers) into flood shelters	Reroute public transportation away from at-risk corridors
10. Budget Cut	Convert public buildings (schools, community centers) into flood shelters	Construct temporary flood barriers and levees in key urban zones	Sandbag entrances to essential buildings (hospitals, shelters, utilities)	Divert stormwater using emergency drainage channels and retention basins	Shut down power grids and gas lines in flood-prone districts	Reroute public transportation away from at-risk corridors
11. Evacuation Panic	Reroute public transportation away from at-risk corridors	Convert public buildings (schools, community centers) into flood shelters	Construct temporary flood barriers and levees in key urban zones	Sandbag entrances to essential buildings (hospitals, shelters, utilities)	Divert stormwater using emergency drainage channels and retention basins	Shut down power grids and gas lines in flood-prone districts

12. Algae Bloom	Shut down power grids and gas lines in flood-prone districts	Sandbag entrances to essential buildings (hospitals, shelters, utilities)	Convert public buildings (schools, community centers) into flood shelters	Construct temporary flood barriers and levees in key urban zones	Divert stormwater using emergency drainage channels and retention basins	Reroute public transportation away from at-risk corridors
13. Construction Delay	Convert public buildings (schools, community centers) into flood shelters	Construct temporary flood barriers and levees in key urban zones	Sandbag entrances to essential buildings (hospitals, shelters, utilities)	Divert stormwater using emergency drainage channels and retention basins	Shut down power grids and gas lines in flood-prone districts	Reroute public transportation away from at-risk corridors
14. Downstream Protest	Reroute public transportation away from at-risk corridors	Construct temporary flood barriers and levees in key urban zones	Divert stormwater using emergency drainage channels and retention basins	Sandbag entrances to essential buildings (hospitals, shelters, utilities)	Shut down power grids and gas lines in flood-prone districts	Convert public buildings (schools, community centers) into flood shelters
15. Seepage Detected	Construct temporary flood barriers and levees in key urban zones	Sandbag entrances to essential buildings (hospitals, shelters, utilities)	Shut down power grids and gas lines in flood-prone districts	Divert stormwater using emergency drainage channels and retention basins	Convert public buildings (schools, community centers) into flood shelters	Reroute public transportation away from at-risk corridors

16. Drought-Lifted Suddenly	Divert stormwater using emergency drainage channels and retention basins	Construct temporary flood barriers and levees in key urban zones	Sandbag entrances to essential buildings (hospitals, shelters, utilities)	Shut down power grids and gas lines in flood-prone districts	Convert public buildings (schools, community centers) into flood shelters	Reroute public transportation away from at-risk corridors
17. Overflow Alarm Triggered	Convert public buildings (schools, community centers) into flood shelters	Shut down power grids and gas lines in flood-prone districts	Sandbag entrances to essential buildings (hospitals, shelters, utilities)	Construct temporary flood barriers and levees in key urban zones	Divert stormwater using emergency drainage channels and retention basins	Reroute public transportation away from at-risk corridors
18. Media Scrutiny	Sandbag entrances to essential buildings (hospitals, shelters, utilities)	Convert public buildings (schools, community centers) into flood shelters	Construct temporary flood barriers and levees in key urban zones	Divert stormwater using emergency drainage channels and retention basins	Reroute public transportation away from at-risk corridors	Shut down power grids and gas lines in flood-prone districts
19. Downstream Levee Breach	Construct temporary flood barriers and levees in key urban zones	Divert stormwater using emergency drainage channels and retention basins	Sandbag entrances to essential buildings (hospitals, shelters, utilities)	Shut down power grids and gas lines in flood-prone districts	Convert public buildings (schools, community centers) into flood shelters	Reroute public transportation away from at-risk corridors

20. Structural Resonance	Shut down power grids and gas lines in flood-prone districts	Construct temporary flood barriers and levees in key urban zones	Sandbag entrances to essential buildings (hospitals, shelters, utilities)	Divert stormwater using emergency drainage channels and retention basins	Convert public buildings (schools, community centers) into flood shelters	Reroute public transportation away from at-risk corridors

Appendix C - Questionnaire 1 for the pilot test 1

Section 1: General Experience

How engaging did you find the game? *

- ◯ Very engaging
- ◯ Somewhat engaging
- ◯ Neutral
- ◯ Not very engaging
- ◯ Not engaging at all

Did the game motivate you to learn more about dam safety and disaster management? *

- ◯ Yes, strongly
- ◯ Yes, somewhat
- ◯ Neutral
- ◯ Not much
- ◯ Not at all

Section 2: Knowledge & Awareness

Before playing the game, how much did you know about dam failure risks? *

- ◯ Very knowledgeable
- ◯ Somewhat knowledgeable
- ◯ Neutral
- ◯ Slightly knowledgeable
- ◯ Not knowledgeable at all

After playing the game, how much do you now understand about dam failure risks? *

- ◯ Very knowledgeable
- ◯ Somewhat knowledgeable
- ◯ Neutral
- ◯ Slightly knowledgeable
- ◯ Not knowledgeable at all

Which of the following dam-related challenges did the game help you understand better? (check all that apply) *

- ☐ Structural risks (cracks, spillway blockages, resonance, etc.)
- ☐ Emergency evacuation procedures
- ☐ Role of government coordination and funding
- ☐ Urban planning and flood prevention measures
- ☐ Public communication during crises

Section 3: Skills & Decision-Making

Did the game improve your ability to think critically about disaster response? *

- ◯ Yes, greatly
- ◯ Yes, somewhat
- ◯ Neutral
- ◯ Not much
- ◯ Not at all

Which role did you play in the game? *

- ◯ Dam Engineer
- ◯ Evacuation Specialist
- ◯ Government Official
- ◯ City Planner

What decisions did you find most impactful in your role?

Your answer

Did the game make you more confident about how to respond in a real flood or dam emergency? *

- Much more confident
- Somewhat more confident
- Neutral
- Slightly more confident
- Not confident at all

Section 4: Teamwork & Collaboration

How well did your team work together during the game? *

- Very well
- Somewhat well
- Neutral
- Poorly
- Very poorly

Did the game help you understand the importance of collaboration between different roles (engineer, responder, government, planner)? *

- Understood very clearly
- Understood somewhat clearly
- Neutral
- Understood slightly
- Did not understand at all

Section 5: Feedback & Suggestions

Did you have fun while playing *Breach Patrol*? *

- Had a lot of fun
- Had fun
- Neutral
- Had little fun
- Did not have fun at all

What part of the game did you enjoy the most?

Your answer

What improvements would you suggest for the game?

Your answer

Would you recommend this game to others as a way to learn about disaster preparedness? *

- Definitely yes
- Probably yes
- Neutral
- Probably not
- Definitely not

Which age group or educational level do you think this game is most suitable for? *

- Middle school students (ages 11–14)
- High school students (ages 15–18)
- University/college students
- Adults in professional training (engineers, planners, responders)
- All age/education levels

Appendix D – Questionnaire 2 for pilot test 2

How engaging did you find the game-based learning method you experienced? *

- ◯ Extremely engaging
- ◯ Very engaging
- ◯ Moderately engaging
- ◯ Slightly engaging
- ◯ Not engaging at all

Which method keep your attention better? *

- ◯ Game-based learning much better
- ◯ Game-based learning somewhat better
- ◯ Both equally
- ◯ Lecture somewhat better
- ◯ Lecture much better

Please rate each statement based on your experience. *
Scale:
1 = Strongly Disagree
2 = Disagree
3 = Neutral
4 = Agree
5 = Strongly Agree

	1	2	3	4	5
I found the game-based learning method engaging.	○	○	○	○	○
I found the lecture-based learning method engaging.	○	○	○	○	○
The game-based learning method captured and held my attention throughout the session	○	○	○	○	○
The lecture-based learning method captured and held my attention throughout the session	○	○	○	○	○
I felt actively involved in the learning process	○	○	○	○	○

The learning method made the topic more enjoyable compared to traditional study materials	◯	◯	◯	◯	◯

How well did you understand dam failure risks through the session? *

- ◯ Very well
- ◯ Well
- ◯ Moderately well
- ◯ Slightly
- ◯ Not at all

Which method would you prefer for future disaster education *

- ◯ Definitely game-based
- ◯ Probably game-based
- ◯ Neutral
- ◯ Probably lecture-based
- ◯ Definitely lecture-based

How confident do you feel about applying what you learned in a real dam failure scenario? *

- ◯ Very confident
- ◯ Confident
- ◯ Neutral
- ◯ Slightly confident
- ◯ Not confident at all

Which method better simulated real-life decision-making challenges? *

- ◯ Game-based learning much better
- ◯ Game-based learning somewhat better
- ◯ Both equally
- ◯ Lecture somewhat better
- ◯ Lecture much better

Did you improve your teamwork and communication skills during the session? *

- Improved greatly
- Improved somewhat
- Neutral
- Improved slightly
- Did not improve

Which method do you think better develops teamwork and collaboration skills? *

- Game-based learning much better
- Game-based learning somewhat better
- Both equally
- Lecture somewhat better
- Lecture much better

Would you recommend game-based education like *Breach Patrol* for disaster awareness training? *

- Definitely yes
- Probably yes
- Neutral
- Probably not
- Definitely not

Game-Based Learning (Breach Patrol) *

	1	2	3	4	5
The session kept me engaged from start to finish.	◯	◯	◯	◯	◯
The scenarios helped me understand dam failure risks.	◯	◯	◯	◯	◯
The actions linked clearly to real-world mitigation strategies.	◯	◯	◯	◯	◯
The role-play improved my decision-making skills.	◯	◯	◯	◯	◯
The activity increased my motivation to learn more.	◯	◯	◯	◯	◯
I can recall key concepts after the session.	◯	◯	◯	◯	◯

The session improved my teamwork & communication.	○	○	○	○	○
The method feels suitable for my education level.	○	○	○	○	○
I feel confident applying what I learned in practice.	○	○	○	○	○
Overall, this method is effective for disaster education.	○	○	○	○	○

Lecture-Based Learning *

	1	2	3	4	5
The session kept me engaged from start to finish.	○	○	○	○	○
The examples helped me understand dam failure risks.	○	○	○	○	○
The content linked clearly to real-world mitigation strategies.	○	○	○	○	○
The session improved my decision-making skills.	○	○	○	○	○
The lecture increased my motivation to learn more.	○	○	○	○	○
I can recall key concepts after the session.	○	○	○	○	○

The session improved my teamwork & communication.	○	○	○	○	○
The method feels suitable for my education level.	○	○	○	○	○
I feel confident applying what I learned in practice.	○	○	○	○	○
Overall, this method is effective for disaster education.	○	○	○	○	○