COMPREHENSIVE DAM FAILURE IMPACT FRAMEWORK

by

Fatemehossadat Mirhosseini

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ABSTRACT

While dams offer substantial benefits, they also present considerable risks in the event of failure, particularly in light of increasing climate change concerns. Policymakers and risk assessors are therefore intensifying efforts to enhance risk assessment practices and implement preventative measures. A comprehensive understanding of the impacts associated with dam failures is critical to improving these efforts and supporting evidence-based policy development. Although previous studies have examined various impacts and some have attempted to integrate them within the context of sustainability, a unified and realistic framework capturing both the short-term and long-term consequences, along with sustainability pillars interdependencies, has remained absent. To address this gap, this study was conducted in three stages. In the first stage, the initial version of the impact framework based on a systematic review of the literature was developed. In the second stage, the framework was enhanced and expanded using artificial intelligence and data mining techniques to ensure depth, accuracy, and relevance. In the third stage, the framework was validated through a real-world case study: the Fundão Dam failure in Brazil. The resulting comprehensive framework enables systematic comparison and analysis of dam failure impacts, highlights under-researched areas, and provides a practical tool for decision-makers to prioritize interventions and formulate targeted policies grounded in the significance of each impact.

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CHAPTER 1: INTRODUCTION

I. BACKGROUND

There are primarily two types of dams: water dams and tailings dams. The construction of dams serves various purposes, including flood control, irrigation, hydropower generation, water supply provision, recreational activities, and containment of environmentally hazardous sediments resulting from mineral extraction processes (Limin Zhang 2016; Rana et al. 2022). While dams offer numerous benefits, they also bring about potential risks to the environment, economy, and human life. Dam failures represent one of the most catastrophic non-natural disasters, often resulting from uncontrolled water release triggered by natural events, such as extreme weather and earthquakes, structural deficiencies, or equipment malfunctions (Ramirez et al. 2022; Rana et al. 2022; Xiong. Y. 2011). Around 300 out of 36,000 large dams listed in the World Register of dams have experienced accidents, as reported by the International Commission on Large Dams (ICOLD 2024). The inundation zone is the region impacted by the flow resulting from a dam break (FEMA 2013). One of the most prevalent disasters worldwide, comprising 34% of total catastrophes, is floods. The frequency of flood occurrences, including those resulting from dam failures, is on the rise and believed to be significantly due to the impacts of climate change and intensified precipitation patterns (Zhang et al. 2022). Despite an increase in the number of tailings dams in recent years, the number of tailings dams' failure has remained relatively constant since 1966. The most common causes of tailings dam failure are overtopping, construction quality issues, poor management, weather hazards such as heavy rain and natural disasters such as earthquakes(Limin Zhang 2016; Rana et al. 2022; Xiong. Y. 2011). The repercussions of dam failures encompass environmental, social, and economic impacts (Zhang et al. 2022; Ge et al. 2019).

Notably, floods triggered by dam failures have accounted for over 40,000 deaths globally since 1965. Emphasizing safety as a fundamental principle, engineers design dams with the aim of preventing such catastrophic events. In light of the increased awareness of dam failures since 1966, and their consequences, coupled with the changing climate, the safety of dams and effective risk management have become growing concerns (Rana et al. 2022).

Assessing the consequences of dam failure is crucial as it can offer valuable insights and recommendations for enhancing dam safety. By understanding and mitigating the potential consequences, it becomes possible to prevent or minimize the impacts of dam failures, thereby safeguarding lives, infrastructure, and the environment (Ji et al. 2021). Different methods of evaluating the impacts of dam failures were employed over time (EL Bilali et al. 2022). Numerous studies have delved into the examination of the social, environmental, and economic repercussions of dam breaks. For instance, Islam and Murakami (2021) conducted research on the environmental impacts of mine tailings dam failures spanning from 1915 to 2020. Ji et al. (2021) explored the environmental, social, and economic impacts of dam breaks, utilizing indicators such as drinking water pollution, loss of life, and building damage. Many of these indicators, reflecting the impacts of dam failures, are complex and sometimes difficult to measure. Additionally, some of them are connected, such as the loss of life and economic ramifications (Ji et al. 2021). Kibler (2012) proposed a Dam Assessment Model considering political, social, economic and environmental impacts of dams but not the impacts of dam failures. Scarpelin et al. (2022) considered some interactions between socioeconomic and environmental impacts of dam failure and proposed a framework for a dam failure in Brazil. Gu et al. (2020) suggested a framework including some factors related to social and environmental impacts after failure. Zhang et al. (2022) proposed a framework for the environmental impacts after dam failure. Aqilah et al. (2024) considered the dynamic aspect and interconnection between environmental, social, and monetary values in a framework regarding the flood risk management after dam failure. The analysis was based on the Triple Bottom Line (TBL) and sustainable Development Goals (SDG). Also, some researchers worked on frameworks for a specific topic in one of those 3 main impacts. For instance, Wu et al. (2019) and Mahmoud, Wang, and Jin (2020) suggested frameworks focusing on loss of life after dam failure.

II. RESEARCH GAP ANALYSIS AND GOAL

While numerous publications have explored various aspects of dam failures and some studies proposed frameworks including the impacts after failure, there are some limitations such as each study employs distinct impact indicators based on different criteria, making it challenging to establish consistent comparisons. Some studies aim to cover all potential impacts of dam failures but often rely on a limited set of indicators, with little attention to how these impacts interact. There is still no comprehensive approach that provides a complete "big picture" of all impact classes and indicators. Comprehensive assessments of both short- and long-term impacts based on sustainability criteria are largely lacking.

Existing frameworks have several notable limitations. Most lack an explicit time structure and do not clearly differentiate between short-term and long-term impacts. Also, many focus on only one or two categories of impacts (e.g., a mix of social and environmental), excluding others and providing limited category coverage. Even when all three categories are considered, only a few impact classes within each are included, with minimal explanation that each class may have multiple indices and indicators. In most impact cases, only a few indicators are listed, and the specific impact indicators, indices, and classes requiring data collection are not clearly identified or listed.

Many frameworks are designed specifically for mining dams or water dams, limiting generalizability. In addition, some frameworks rely on a single indicator to represent an entire category of impacts, and they over-simplify the indicators. Moreover, none explicitly address the impacts associated with dam removal after failure. Minimal consideration of interconnections of impacts is the other limitation, and rarely do existing frameworks examine how different impact categories influence and interact with each other.

Sustainable development originated from environmental concerns and has been clearly defined from the start, with quantitative indicators playing a key role in its framework (Hák, Janoušková, and Moldan 2016) . In 2015, after numerous efforts to promote sustainability, global leaders came together to adopt the 2030 Agenda for Sustainable Development, a landmark commitment to uphold human rights and well-being while ensuring a sustainable planet. This agenda includes 17 Sustainable Development Goals (SDGs), which address the social, environmental, and economic dimensions of sustainability (United Nations 2022). The framework developed in this study aligns with these dimensions by encompassing all three categories of impacts—social, environmental, and economic—thereby supporting the objectives of the SDGs.

This thesis addresses a critical gap in dam failure research: the lack of a comprehensive, systematic framework that integrates all known impacts of dam failures from a sustainability perspective. Such a framework is vital not only for capturing the full range of consequences but also for guiding researchers, policymakers, and practitioners. It enables comparative analysis of different impact types and supports meaningful comparisons between dam failure events by identifying the data needed for robust risk assessment and informed decision-making. The framework developed in this research is not specific to any particular type of dam, such as water or tailings dams. It was built using data from a comprehensive database of dam failure impacts, aiming to include all potential impacts that could occur following any type of dam failure—whether water, tailings, or others.

The Dam Failure Impact Framework developed in this study was created through a three-phase process. Accordingly, the thesis is organized into four chapters.

III. THESIS STRUCTURE

The structure of this thesis is as follows:

- Chapter 1 introduces the thesis and outlines the main research objectives.
- Chapter 2 details the development of the Dam Failure Impact Framework in two stages. Stage one involved a comprehensive literature review to establish the initial framework. In stage two, the framework was expanded using artificial intelligence and data mining techniques to identify, organize, and categorize indicators with greater accuracy. This stage included contributions from Afrin Naz, a B.Tech student from NIT Trichy, through the 2024 Mitacs Globalink Research Internship. This chapter is an updated version of a paper published by the Canadian Dam Association (CDA) in 2024.
- Chapter 3 validates the framework through a case study of the Fundão Dam failure in Brazil. This expanded version builds on a paper accepted for presentation at the CDA 2025 conference.
- Chapter 4 summarizes the key findings, discusses limitations, and proposes directions for future research.

Chapters 2 and 3 are presented as standalone studies, each with its own methodology, analysis, and conclusions, rather than a unified approach across the thesis.

Together, these chapters represent a comprehensive effort to develop, refine, and validate a robust framework for assessing dam failure impacts. The structure reflects the sequential progression of the research and aims to support future work in this field.

All results and supporting materials are included in Appendices A, B, and C to ensure transparency and enable further analysis.

CHAPTER 2: DAM FAILURE IMPACT ASSESSMENT FRAMEWORK

Fatemehossadat Mirhosseini, M.Sc. student at UNBC

Afrin Naz, Btech student, NIT Trichy

Mauricio Dziedzic, Chair, School of Engineering, UNBC

ABSTRACT

While previous studies have explored the environmental, social, and economic impacts of dam failures, they often use inconsistent criteria and isolated indicators, making it difficult to compare results or conduct comprehensive assessments. Additionally, many focus mainly on short-term effects, overlooking long-term consequences and the interplay between different impact types.

This study addresses these gaps in two stages. First, a broad literature review identified key impact areas and established the initial structure of an impact assessment framework based on sustainability principles. In the second stage, artificial intelligence (AI) and data mining techniques were applied to extract a more comprehensive set of impact indicators from the literature. Various AI tools were evaluated to determine the most effective methods for indicator extraction and classification, and the identified indicators were integrated into the framework. The resulting Dam Failure Impact Framework provides a clear, holistic tool for assessing both short- and long-term impacts. It supports policymakers, engineers, and researchers by enabling more informed evaluations of environmental, economic, and social consequences, ultimately contributing to better decision-making.

2.1. INTRODUCTION

The rapid growth of dam construction and increased development in downstream areas have contributed to a significant global rise in potential high-hazard dams (FEMA 2013). In the United States, the number of such dams grew from 14,726 in 2015 to 15,600 in 2021, according to the American Society of Civil Engineers (ASCE 2021). The National Inventory of Dams (NID) 2022 update further reported a sharp increase to 17,387 high-hazard potential dams (FEMA 2025).

Recent dam failures have underscored the severe consequences of such incidents for human life, the economy, and the environment. The 2019 Brumadinho dam collapse in Brazil claimed 270 lives and caused widespread environmental damage, contaminating over 300 kilometers of rivers with toxic mud (Czajkowski et al. 2023). Similarly, the 2018 Xe-Pian Xe-Namnoy dam failure in Laos resulted in 71 deaths and affected more than 14,000 people (Baird 2021).

Recent research has increasingly focused on developing frameworks to assess dam break impacts and risks. For example, a review of 179 relevant studies led to a proposed framework centered on three key impact areas: social, economic, and environmental. This framework incorporates factors such as flood duration, depth, and inundation area, with the potential for future expansion to include additional variables (Aqilah et al. 2024).

Other studies have introduced innovative approaches to dam safety assessment. One comprehensive study applied a multi-criteria decision-making method to evaluate dam risk, integrating structural integrity, hydrological conditions, and potential downstream impacts (Zhang et al. 2022). Together, these studies highlight the need for comprehensive and flexible frameworks to effectively assess and manage dam break risks.

A Systematic Literature Review (SLR) is a structured method used to identify, evaluate, and organize existing research in a specific field. Its main goal is to compile all relevant studies to identify research gaps and reduce bias in knowledge synthesis. While highly valuable, the SLR process is often time-consuming and complex, sometimes taking over a year to complete the stages of identification, screening, and analysis. To streamline this process, various tools have been developed, among them, artificial intelligence (AI) has recently emerged as a powerful aid (Bolaños et al. 2024).

In this study, a comprehensive dam impact framework was developed by combining insights from the literature with AI and data mining techniques to enable a more robust and complete assessment. AI refers to the simulation of human cognitive functions—such as learning, reasoning, and problem-solving—by machines. One of its key strengths is the ability to learn from data and improve performance over time (Fitria 2021). Although AI originated in the mid-1950s, its early development was limited by data processing constraints and the complexity of mimicking human thought. Recent technological advances have renewed interest in AI, driving its widespread adoption across sectors as a tool for improving efficiency, gaining competitive advantages, and enhancing performance (Venkatesh 2022).

Data mining, in simple terms, involves extracting meaningful and useful information from large datasets. It helps structure and organize data into clear, analyzable patterns, making it easier to interpret and apply (Sinha 2018).

The aim of this study is to apply SLR, AI, and data mining techniques to analyze existing information from both academic and non-academic sources. The research was conducted in two stages, described in detail in the methodology section.

2.2 METHODOLOGY

In the first stage of this study, a comprehensive literature review was conducted to examine the impacts of dam failures. Searches were performed using Google Scholar and ScienceDirect. The initial search used broad keywords such as “dam failure impacts” and “dam breach impacts,” with article selection based on abstract review. A more focused search followed, targeting sustainability-related impacts using keywords like “environmental impacts of dam failure,” “social impacts of dam failure,” “economic impacts of dam break,” and “impacts framework.” Additional keywords included “dam break and water quality,” “dam break flood,” “loss of life due to dam failure,” “water dam failure,” and “tailings dam failure.” Only English-language publications were considered.

The abstract-based screening yielded 140 articles. After full-text review, studies that focused solely on dam structure or flood mapping were excluded, resulting in 62 articles for analysis. These were categorized into seven groups based on the type of impacts addressed:

1. Social impacts
2. Environmental impacts
3. Economic impacts
4. Economic and social impacts
5. Environmental and social impacts
6. Environmental and economic impacts
7. Environmental, social, and economic impacts

No publication date restrictions were applied, though most articles were recent. Few studies offered a comprehensive framework that integrated all aspects of sustainability or aligned with the Sustainable Development Goals (SDGs). Most research was case-specific, focused on particular geographic regions.

Based on this review, a general framework was developed by identifying common impact themes, classes, and patterns found in the literature. This initial structure laid the foundation for a more detailed framework by organizing dam failure impacts into thematic categories.

After developing a general framework based on a comprehensive literature review of dam failure impacts—covering environmental, social, and economic dimensions—an integrated structure was created to account for both short-term and long-term consequences within each category. This served as the initial version of the Dam Failure Impact Framework.

To refine and expand this framework, more detailed research was needed to identify specific impact indicators within each category. The preliminary framework provided a category-based classification, which was enhanced in Stage Two by incorporating relevant indicators from the literature.

To ensure comprehensive coverage, the original set of sources was revisited, and additional systematic searches were conducted using the same keyword strategy as in Stage One. Search terms included: "dam failure impacts," "dam breach impacts," "environmental impacts of dam failure," "social impacts of dam failure," "economic impacts of dam break," "impacts framework," "dam break and water quality," "dam break flood," "loss of life due to dam failure," "water dam failure," and "tailings dam failure."

In addition to peer-reviewed academic publications, grey literature—such as industry reports, government documents, and other non-academic sources—was included through targeted searches on Google to broaden the study's scope.

Given the large volume of literature and the potential for future expansion of the framework, this study explored the use of data analytics tools to efficiently extract relevant indicators from academic texts. This led to an investigation of artificial intelligence (AI) tools and their suitability for academic research, specifically in the context of dam failure impact analysis.

With AI increasingly applied across disciplines, the study aimed to assess its potential to systematically identify impact indicators from scholarly sources. However, concerns about the reliability and accuracy of AI-generated results required a comparative evaluation of multiple tools. The focus was on each tool's ability to extract precise, contextually relevant indicators based on user-defined queries—effectively testing their academic research capabilities in this domain.

A total of 42 AI tools were initially identified for potential use. The first round of screening excluded tools that did not support PDF uploads in their free versions, as PDF is the standard format for academic articles. This reduced the list to 20 tools.

In the second round, tools with excessive limitations—such as word count caps, slow response times, low response relevance, or restricted feature access—were eliminated. The goal was to ensure adequate functionality without requiring paid subscriptions. Selected tools were tested using random academic articles uploaded manually. Tools that produced inaccurate, irrelevant, or overly verbose responses, even after prompts were refined, were excluded.

Ultimately, 11 AI tools were retained for detailed comparison. These were assessed for accuracy, contextual awareness, and responsiveness. The final recommended tools for indicator extraction in dam failure research are: PopAi, ChatGPT, Perplexity, PDF.ai, ChatPDF, Sharly, TextCortex, AvidNotes, LightPDF, Humata, and ChatDoc.

To evaluate and compare the performance of AI tools in extracting impact indicators from academic literature, a random sample of 11 articles was selected. Key indicators were manually extracted from these articles to serve as a benchmark.

A set of 12 standardized questions was then developed to test each AI tool's ability to identify and present relevant indicators. These questions were refined for clarity, consistency, and grammatical accuracy to ensure optimal processing by the AI tools and to support the generation of accurate and comprehensive responses.

Each AI tool was prompted with the finalized questions for all 11 articles, and their outputs were compared to the manually extracted benchmarks. The initial evaluation used qualitative analysis to assess the accuracy and completeness of responses. To improve objectivity and reduce bias, the analysis then shifted to a quantitative approach, measuring each tool's performance by the number of correctly identified indicators.

The questions guided the AI tools to categorize impacts into environmental, economic, and social domains and to distinguish between direct and indirect indicators. Additional questions requested information on indicators used in cited research, enhancing the depth and relevance of the extracted data. This approach maximized the tools' effectiveness in producing a detailed and accurate inventory of dam failure impact indicators.

The 12 questions used for evaluation were:

1-In this paper, are impacts of dam failure assessed or an assessment method proposed?

a. If yes:

2-What categories of impacts?

3-Which direct impact indicators/indices of dam failure were used to calculate the target impact category to achieve the goal of the author?

4-Which indirect dam failure impact indicators/indices were used to calculate direct indicators/indices to show the impacts after dam failure?

5-Which direct indicators and/or indices are used or proposed to assess environmental impacts of dam failure?

6-Which indirect indicators and/or indices are used or proposed to assess environmental impacts of dam failure?

7-Which direct indicators and/or indices are used or proposed to assess economic impacts of dam failure?

8-Which indirect indicators and/or indices are used or proposed to assess economic impacts of dam failure?

9-Which direct indicators and/or indices are used or proposed to assess social impacts of dam failure?

10-Which indirect indicators and/or indices are used or proposed to assess social impacts of dam failure?

11-What are the calculated indirect social, economic and environmental impact caused by direct impacts of dam failure?

12-Can you provide details on the indicators used in the cited research papers for dam break impact assessment? Mentioned in the literature review part.

To ensure that AI responses were limited strictly to the content of the uploaded article, a standardized prompt was also included: “Only list the indicators that are mentioned in the paper.” Before recording any data, indicators were divided into two categories: breach parameters and impact indicators. Breach parameters describe the physical characteristics of the dam failure itself (e.g., breach size and rate), while impact indicators reflect the broader consequences—environmental, social, or economic—resulting from the failure. This distinction allowed for a more structured and targeted analysis. As the study focuses on consequences rather than failure mechanics, breach parameters were excluded from further analysis.

Following the comparative evaluation, two AI tools that most closely matched the manually extracted indicators were selected for ongoing use. These tools were considered the most reliable for automated indicator extraction. Using two tools allowed for cross-validation, increasing confidence in the results and improving accuracy. Subscriptions were acquired to unlock full functionality, and the analysis proceeded using both tools in parallel.

After extracting all relevant impact indicators, data mining techniques were applied to refine and consolidate the results into a final set. This involved a data cleaning process to remove irrelevant or non-measurable entries, such as structural or breach-related terms and vague phrases not representing concrete impacts.

Each remaining indicator was assigned a reference number linking it to its source article to ensure traceability. Duplicate or overlapping indicators with similar wording and meaning were then merged into unified entries. For instance, 44 mentions of "life loss," "fatalities," "deaths," and "missing persons" were consolidated into a single indicator labeled "life loss/fatalities/deaths/missing persons," with all associated reference numbers listed in the final table for transparency.

Next, similar indicators were grouped into indices representing specific impact types, making the framework more organized and interpretable. Indicators that did not align with others remained as standalone entries. These indicators and indices were then grouped into broader classes based on common themes and assigned to one of the three primary domains: environmental, economic, or social. Each class was further labeled as short-term or long-term, enabling temporal differentiation within the framework.

All relevant data—indicators, indices, classes, and categories—are compiled in a comprehensive table (Appendix A). This table reflects the hierarchical structure of the framework and includes additional attributes to enhance usability, such as:

- The proposed unit of measurement (from the source or defined by the study's authors if unspecified),

- The method of calculation or the event/condition that triggered the indicator,
- And whether each indicator reflects a direct or indirect impact.

Indicators were classified as indirect if they resulted from a chain of events rather than stemming directly from the dam failure itself.

2.3 RESULTS AND DISCUSSION

In the first stage, 62 articles were reviewed to examine dam failure impacts across three main categories: environmental, social, and economic. Only seven articles addressed all three categories comprehensively or explored the interconnections among them—particularly by incorporating monetary valuations of environmental and social impacts.

For example, Czajkowski et al. (2023) evaluated environmental and cultural/heritage damage using the Contingent Valuation (CV) method. This survey-based approach estimated a lower-bound average willingness-to-pay of USD 137 among 5,195 Brazilians to prevent a similar incident, equating to a total damage valuation of USD 7.69 billion. Ji et al. (2021) analyzed economic losses alongside environmental impacts and fatalities. Fernandes et al. (2016) examined socioeconomic and environmental consequences, including effects on landscapes, habitats, fisheries, and public health. Sánchez et al. (2018) classified impacts into biophysical and socio-economic-cultural aspects, including indirect effects like mine closures and job losses. Azam and (Li 2010) compared dam failures before and after 2000, focusing on environmental pollution, infrastructure damage, public health, and fatalities. Scarpelin et al. (2022) provided integrated cost estimates of environmental, social, and economic impacts. Aqilah et al. (2024) evaluated both direct and indirect impacts in Malaysia and calculated monetary losses across all three categories.

Only two studies focused exclusively on economic impacts. Kulkarni (2016) assessed rehabilitation costs for affected areas, while Muchanga (2023) analyzed income loss, reduced working capital, and business disruption in Zambia.

Four articles explored both environmental and social impacts. Rana et al. (2022) reported rising environmental consequences of tailings dam failures since 2014, while fatalities decreased. Silva Rotta et al. (2020) used satellite imagery and soil moisture indices to assess suspended particulate matter and land use. Gu et al. (2020) applied a fuzzy evaluation model to assess social and environmental impacts of earth-rock dam failures. Guimarães et al. (2023) examined global dam failures, noting their effects on water access, aquatic life, and legal reforms.

Environmental impacts were the most frequently studied, appearing in 29 articles. Examples include: Glotov et al. (2018) : groundwater contamination and harm to river ecosystems; Zhang et al. (2022): plant impacts across multiple species; Hatje et al. (2017): toxic metal contamination in Brazil's Doce River; Aires et al. (2018): post-failure land use and vegetation loss.

Social impacts were addressed in 19 articles, with a primary focus on life loss. Several studies applied modeling approaches to estimate fatalities: EL Bilali et al. (2022) combined Monte Carlo Simulation, HEC-RAS 2D, and HEC-LifeSim in Morocco. Cavalheiro Paulelli et al. (2023) examined human health by analyzing urine samples one year after a dam break. Shandro et al. (2017) uniquely focused on short-term effects on First Nations communities, using indicators such as loss of traditional fishing, emotional stress, and administrative burdens.

Only one article, Ge et al. (2019) analyzed combined social and economic impacts, assessing life loss and economic damage. Notably, no articles examined environmental and economic impacts together.

Seven articles proposed frameworks for assessing dam failure impacts, with varying degrees of comprehensiveness across sustainability dimensions. Two frameworks addressed all three impact categories: Aqilah et al. (2024) assessed social (household, health, education, water/sanitation, livestock, cultural losses), environmental (morphology, water quality, biodiversity), and economic (property damage, lost labor, capital loss) aspects, with monetary valuation.

Scarpelin et al. (2022): used energy accounting to quantify monetary losses from Fundão's dam failure, including ecological degradation, social disruption, and landscape changes. Other framework studies included Ge et al. (2019) who proposed risk factors such as dam height, reservoir capacity, population at risk, and industry vulnerability. Ji et al. (2021) distinguished between direct (life, economic, environmental) and indirect (social) impacts. Zhang et al. (2022) focused on environmental indicators like geomorphic changes, pollution, and biodiversity loss. Mahmoud, Wang, and Jin (2020) developed a life loss framework based on hazard, exposure, and rescue capacity. Gu et al. (2020) proposed a social-environmental framework addressing people at risk, infrastructure, cultural heritage, and ecological effects.

While recent frameworks address multiple impact categories, they often omit certain classes, overlook long-term impacts, or fail to consider post-failure dam removal effects.

In response, this study proposes a new framework that builds on previous classifications and aligns with Sustainable Development by addressing all three pillars—environmental, social, and economic—over both the short and long term.

Table 1 summarizes the reviewed articles, indicating the types of impacts covered and whether a framework was proposed.

Table 1 Articles analysed in the first stage

Articles	Env., economic and social impacts	Economic impacts	Social and env. impacts	Environmental impacts	Social impacts	Social and economic impacts	Impact framework
(Czajkowski et al. 2023)	X						
(G. W. Fernandes et al. 2016)	X						
(Ji et al. 2021)	X						X
(Sánchez et al. 2018)	X						
(Azam and Li 2010)	X						
(Scarpelin et al. 2022)	X						X
(Aqilah et al. 2024)	X						X
(Kulkarni 2016)		X					
(Muchanga 2023)		X					
(Rana et al. 2022)			X				
(Silva Rotta et al. 2020)			X				
(Gu et al. 2020)			X				X
(Guimarães et al. 2023)			X				
(Glotov et al. 2018)				X			
(Zhang et al. 2022)				X			X
(Hatje et al. 2017)				X			
(Aires et al. 2018)				X			
(Lines et al. 2023)				X			
(Santos et al. 2023)				X			

(C. E. D. Vieira et al. 2022)				X			
(Santos-González et al. 2021)				X			
(Islam and Murakami 2021)				X			
(dos Santos Vergilio et al. 2021)				X			
(Zhang et al. 2021)				X			
(Kütter et al. 2023)				X			
(Wu et al. 2019)				X			
(Oliveira-Filho et al. 2023)				X			
(Kossoff et al. 2014)				X			
(Ramirez et al. 2022)				X			
(Moraga, Gurkan, and Sebnem Duzgun 2020)				X			
(Nikl 2016)				X			
(Ge, Li, et al. 2020)				X			
(Mendes et al. 2023)				X			
(Thompson et al. 2020)				X			
(Wang and Zhou 2010)				X			
(Costa et al. 2022)				X			
(De Biasi et al. 2023)				X			
(Quaresma et al. 2020)				X			
(Nascimento et al. 2022)				X			

(Macklin et al. 2003)				X			
(L. Fernandes et al. 2022)				X			
(P. I. N. de Almeida et al. 2023)				X			
(EL Bilali et al. 2022a)					X		
(Mahmoud, Wang, and Jin 2020)					X		X
(Peng and Zhang 2012)					X		
(Jiao, Li, and Ma 2022)					X		
(Cavalheiro Paulelli et al. 2023)					X		
(Huang et al. 2017)					X		
(Ge et al. 2022)					X		
(Ge 2021)					X		
(Shandro et al. 2016)					X		
(Cavalheiro Paulelli et al. 2022)					X		
(Luo 2009)					X		
(Hsiao et al. 2021)					X		
(de Oliveira et al. 2022)					X		
(Lumbroso et al. 2021)					X		
(Liu 2011)					X		
(Faiqa Norkhairi, Thiruchelvam, and Hasini 2018)					X		
(Shandro et al. 2017)					X		
(Buch et al. 2024)					X		

(DOĞAN et al. 2014)					X		
(Ge et al. 2019)						X	X

The proposed dam failure impact framework developed in Stage One is divided into two parts: short-term and long-term impacts. Each part includes social, environmental, and economic categories, further broken down into multiple classes.

The initial version of the framework (Figure 1) also accounts for the impacts of dam removal following a failure—an area receiving growing attention. For example, Martinez et al. (2018) analyzed the environmental footprint of dam removal, including on-site fossil fuel use and indirect energy consumption. Jumani et al. (2023) proposed a framework integrating removal opportunities with hydro-ecological and socio-cultural variables.

The impact categories and their classes in this study—spanning both short- and long-term effects—are derived from both explicit categories and inferred themes identified across the reviewed literature.

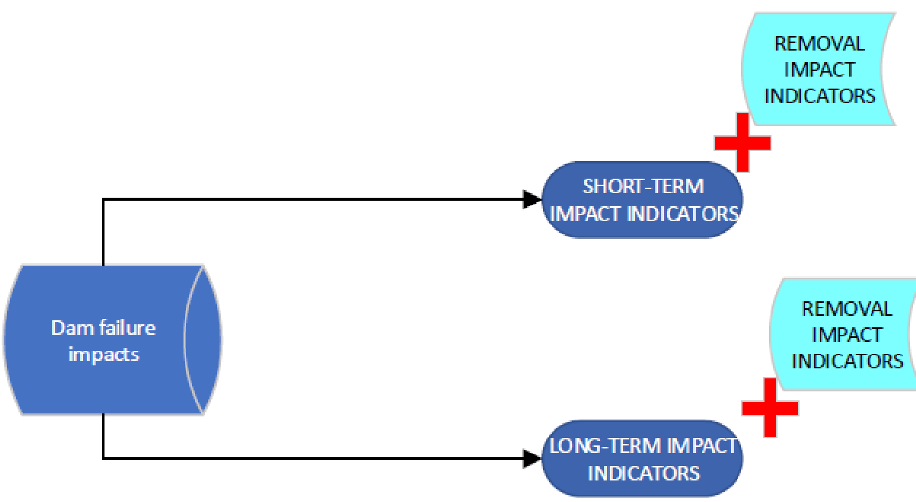

Figure 1 Impacts of dam failure

In Stage Two, a total of 88 documents were analyzed to explore dam failure impacts in greater detail. This included 72 academic publications and 16 grey literature sources, such as technical reports, government documents, and other non-academic studies.

Incorporating both academic and grey literature ensured a more comprehensive understanding by combining peer-reviewed scientific findings with professional insights. Together, these sources formed the basis for extracting relevant impact indicators, which were later used to refine and structure the study's overall impact framework.

2.3.1 AI TOOLS UTILIZED IN THIS STUDY

The results of the AI tool comparison are shown in Figures 2. A quantitative evaluation was performed to measure each tool's accuracy in extracting relevant impact indicators, using a reference set of 101 manually identified indicators.

ChatDoc achieved the highest accuracy, correctly identifying 81 indicators for a match rate of 80.2%. Perplexity ranked second, with 72 matched indicators, yielding a 71.3% match rate. These findings demonstrate that both tools are capable of recognizing complex, context-specific information, with ChatDoc providing more comprehensive results.

This comparison underscores the potential of AI tools to support academic research while also reinforcing the need for manual verification to ensure completeness and accuracy in critical assessments.

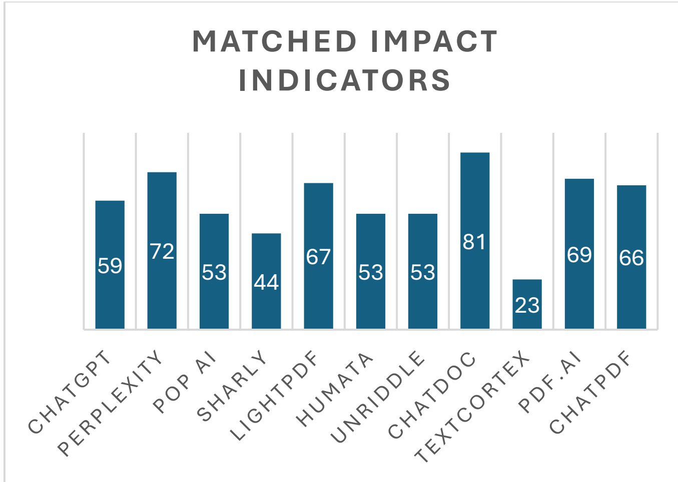

Figure 2 AI comparison

2.3.2. STATISTICAL ANALYSIS

ChatDoc and Perplexity were used to extract impact indicators from a total of 88 sources. Through this process, the AI tools identified 817 impact indicators along with their corresponding units. These indicators were compiled into a comprehensive table, organized by category—environmental, social, or economic—to support structured analysis. All source references are listed in the study's References section.

In this study, short-term impacts are defined as those occurring within the first five years after a dam failure, while long-term impacts refer to those manifesting from year five onward, in alignment with the Canadian Dam Association's consequence classification guidelines (CDA 2016a).

After data cleaning, removal of duplicates, and classification into indices and thematic classes, an initial set of 460 indicators was structured as:

- 80 short-term economic indicators
- 45 long-term economic indicators
- 80 short-term social indicators

- 48 long-term social indicators
- 103 short-term environmental indicators
- 104 long-term environmental indicators

Some indicators appeared in both short- and long-term categories due to variations in how authors interpreted or discussed impact timelines. However, to count unique indicators in the framework (some used in both short- and long-term categories), repeated ones are counted only once. The counts are as follows::

- 80 short-term economic (unchanged)
- 28 long-term economic (after removing 17 duplicates)
- 80 short-term social (unchanged)
- 27 long-term social (after removing 21 duplicates)
- 103 short-term environmental (unchanged)
- 10 long-term environmental (after removing 94 duplicates)

This results in a final total of 328 unique indicators (non-repetitive indicators) in the framework (Figure 3). Many of these indicators appeared in multiple sources, reflecting their broad relevance and recognition across the literature.

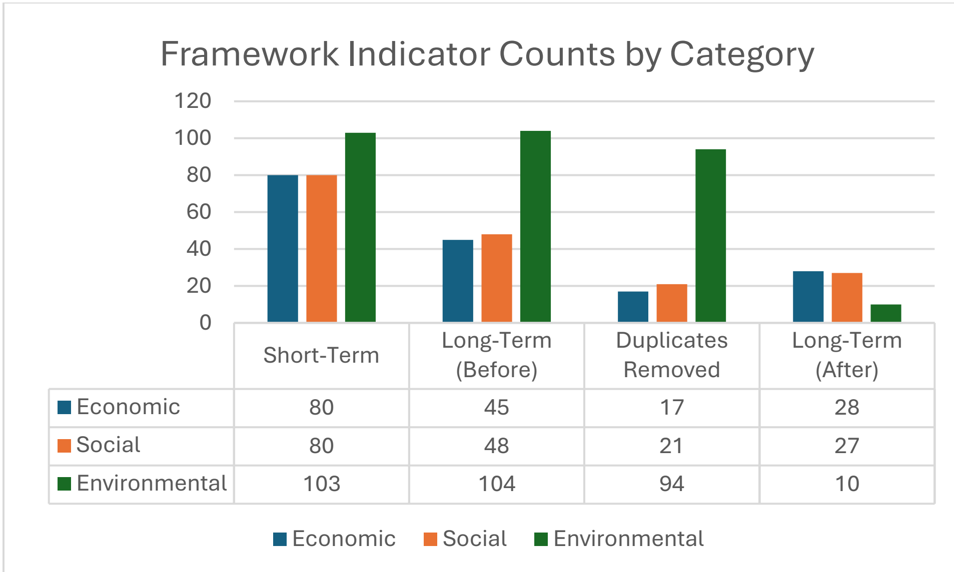

Figure 3 Indicators statistics

The framework is the result of a comprehensive literature review on the classification of post-dam failure impacts. It distinguishes between short- and long-term effects, while also accounting for dam removal impacts. Structured around the three pillars of sustainability—environmental, economic, and social—it organizes impacts into thematic classes, each containing both individual indicators and composite indices for integrated assessment. The impact indicators in this study, including short-term and long-term impacts, are based on both directly considered by authors and those indirectly referred to in the reviewed articles. The indicators and indices selected for the developed framework are based on the literature review, where they were either explicitly mentioned or could be inferred from interpretation of the reviewed studies.

In the environmental dimension, short-term impacts are divided into four main classes. The first class, Geology, includes indicators related to changes in soil and sediment (1-1), and land use and land cover (1-2). The second class, Ecology, covers a range of indicators including biochemical changes (2-1), impacts on flora (2-2), and impacts on fauna (2-3), which are further divided into terrestrial fauna (2-3-1) and aquatic fauna (2-3-2). Water-related impacts are addressed through subcategories on water quality (2-4-1) and water resource availability (2-4-2). The third class covers energy use and carbon emissions resulting from emergency operations and reconstruction. The fourth class includes secondary environmental impacts arising from social and economic disruptions. In the long term, the environmental structure remains largely consistent with the short-term framework, excluding only the energy use and carbon emission class.

The economic dimension follows a similarly structured classification across both timeframes. In the short term, the first class includes immediate economic losses such as service disruptions (1-1), business interruptions (1-2), economic downturns in the affected area (1-3), benefit losses (1-4), property loss (1-5), and infrastructure damage (1-6). The second class captures emergency response and rehabilitation costs, including maintenance and restoration (2-1), alternative supply arrangements (2-2), and evacuation or disaster logistics (2-3). The third class accounts for secondary economic impacts stemming from environmental and social consequences, such as heritage loss (3-1), environmental restoration costs (3-2), and impacts on agriculture and fisheries (3-3). Long-term economic indicators include property and infrastructure rehabilitation (1-1 and 1-2), adaptation and recovery efforts (2-1 and 2-2), long-term economic trends (4), and extended consequences from environmental and social impacts (5), which include environmental degradation (5-1), health-related costs (5-2), and long-term heritage loss (5-3), all reflecting ongoing economic vulnerability.

The social dimension addresses human-centered impacts of dam failure. Short-term social impacts are grouped under immediate losses, including fatalities and life loss (1-1), casualties (1-2), loss of livelihoods (1-3), cultural asset loss (1-4), displacement (1-5), opportunity loss (1-6), and community resilience (1-7). The second class includes the disruption of social services. The third class focuses on health and mental health impacts, covering mental issues (3-1) and physical health problems (3-2). The fourth class represents secondary social impacts driven by environmental and economic effects. In the long term, the social dimension captures broader structural changes, including social cohesion (1), access to services (2), long-term livelihood recovery (3), and chronic physical and mental health challenges (4). It also accounts for long-term vulnerabilities resulting from environmental and economic consequences (5), offering a more complete picture of societal burden. The full list of supporting references is provided in Appendix B.

The indicators and indices in this framework can be quantified through various established or emerging methodologies, and their calculation remains an important area for future research. While some indicators have defined measurement approaches in the literature, others require further development or adaptation. Once quantified, indicators can be scored using standardized scales to enable consistent comparison and evaluation across different cases. This framework serves as a reference for researchers and practitioners by identifying key indicators relevant to dam failure impact assessments. It is also designed to be flexible—new indicators can be added, and existing ones refined over time to reflect updated knowledge, local priorities, or changes in policy. Its adaptability ensures relevance across diverse assessment contexts while maintaining alignment with evidence-based classifications.

While each classification includes numerous indicators, Figure 4 presents only the classification levels and the associated indices, which themselves encompass multiple indicators. Due to the large volume of data, individual indicators are not displayed in the figure. Instead, a full table of indicators—including units and, where applicable, calculation methods sourced from the literature—is provided in Appendix A. This appendix offers the complete dataset underlying the framework and supports future analysis.

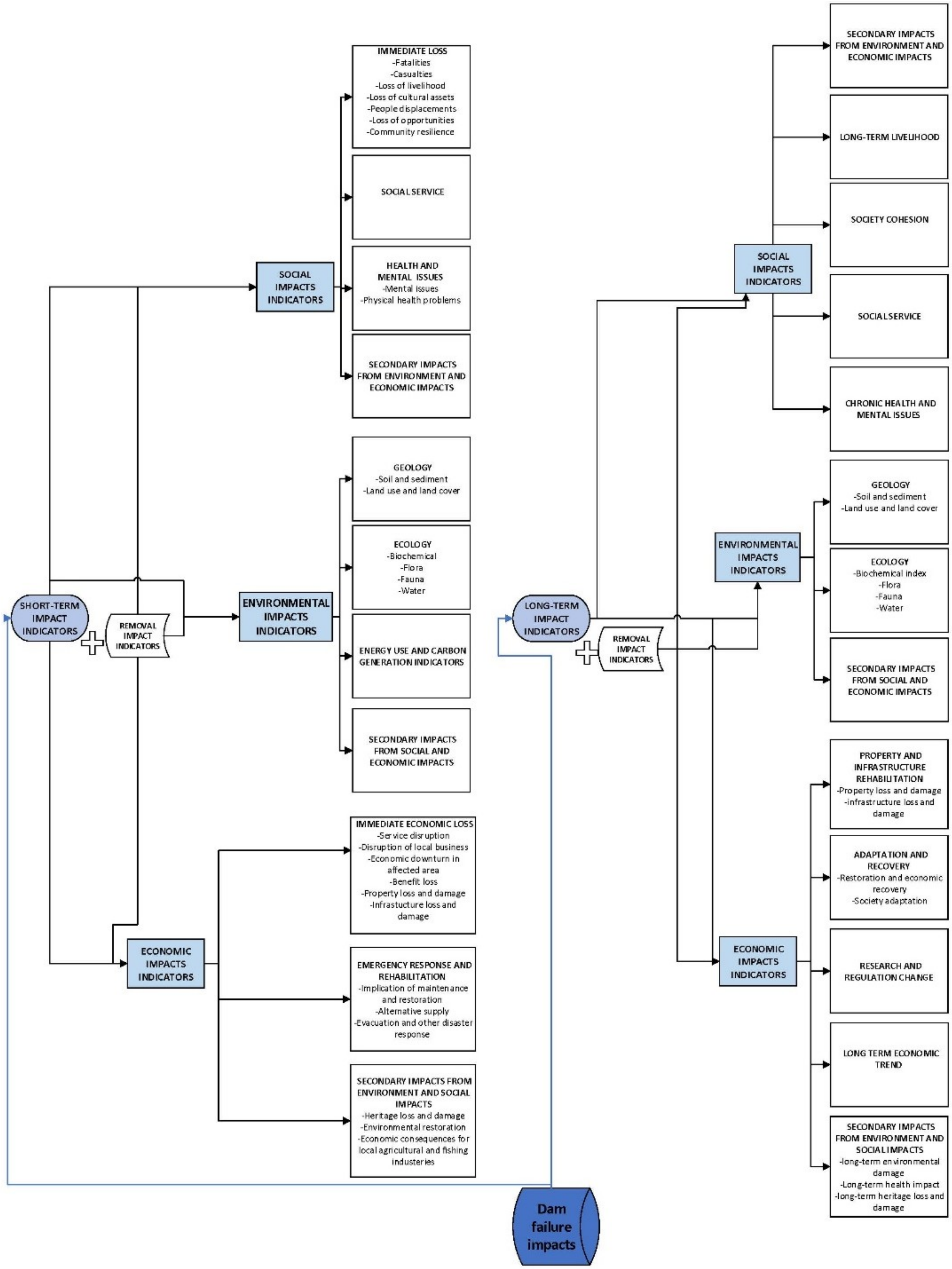

Figure 4 Comprehensive dam impacts framework

2.4. CONCLUSION AND FUTURE WORK

Dams provide significant benefits but also pose serious risks to downstream communities, ecosystems, and economies. Dam failures are among the most destructive non-natural disasters, often caused by earthquakes, structural weaknesses, or equipment malfunctions that lead to uncontrolled water release.

The global increase in dam construction, along with intensified development in downstream areas, has led to a sharp rise in high-hazard potential dams. In response, researchers have conducted numerous studies to better understand and mitigate the consequences of dam failures. While some of these studies proposed frameworks for impact analysis, many failed to account for important factors—particularly the distinction between short- and long-term impacts. Although various models have been developed to assess environmental, social, and economic effects, comprehensive studies addressing all three domains remain limited.

Many existing studies rely on narrow sets of indicators, assumptions, or data availability, and often focus on specific dams or dam types. Some assessments even use single indicators to represent entire impact categories. As a result, a systematic framework capable of capturing the full range of dam failure impacts and enabling cross-event comparisons had not yet been developed.

This research addresses that gap through a two-phase process to develop a comprehensive Dam Failure Impact Assessment Framework. In Phase One, a foundational structure was built through a systematic literature review. Impacts were categorized as short-term or long-term across three main domains: economic, social, and environmental. Consideration was also given to impacts associated with dam removal. This phase aimed to conceptually map how dam failure consequences evolve over time and how they are commonly discussed in scholarly and professional literature.

In Phase Two, the framework was expanded to include a complete set of indicators under each category and index. The goal was to build the most inclusive and representative framework possible. To achieve this, AI-assisted indicator extraction and data mining techniques were applied to academic and grey literature, enabling the identification, classification, and refinement of hundreds of relevant indicators. The result is a comprehensive, data-informed framework for assessing the diverse consequences of dam failure.

The framework is both academically rigorous and feasible to apply. It is designed to support a wide range of stakeholders—researchers, policymakers, emergency planners, and dam safety engineers—in conducting thorough risk assessments, developing mitigation strategies, and guiding policy and research efforts. Its transparent structure helps identify well-studied impact areas and highlight those requiring further exploration. Additionally, it supports cross-comparison of indicators, allowing users to evaluate trade-offs and synergies among different impact types.

Importantly, the framework is dynamic and adaptable. It can be customized to suit local, regional, or sector-specific needs, and new indicators can be added as data and knowledge evolve. Future work should focus on developing a scoring system to quantify the severity of each indicator and a weighting method to assess their relative importance.

Finally, applying the framework to real-world case studies is essential for validation and improvement. Case study applications will demonstrate its practical utility and help refine its accuracy and relevance across diverse contexts. Each application offers feedback that can strengthen the framework, ensuring it remains current, evidence-based, and fit for purpose.

CHAPTER 3: ADVANCING THE UNDERSTANDING OF DAM FAILURE IMPACTS: FRAMEWORK VALIDATION WITH FUNDÃO DAM

Fatemehossadat Mirhosseini, M.Sc. student at UNBC
Maurício Dziedzic, Chair, School of Engineering, UNBC

ABSTRACT

The Rio Doce Basin, Brazil's fifth-largest hydrographic basin, covers 83,400 km² across the states of Minas Gerais and Espírito Santo. It includes 230 municipalities and is home to 3.5 million people. In 2015, the catastrophic failure of the Fundão Dam released an initial 33 million m³ of mining tailings, which flowed through the collapsed Santarém Dam, contaminating the Gualaxo do Norte and Carmo Rivers before reaching the Atlantic Ocean. Heavy rains worsened the disaster, increasing the total volume to 44 million m³. The event affected approximately 1.4 million people across 40 municipalities, becoming the largest socio-environmental disaster in Brazil's history.

Building on the author's earlier work, which proposed a comprehensive framework for assessing short- and long-term dam failure impacts, this article applies and refines that framework using data from the Fundão Dam failure. The results help identify impact areas that require further research and data collection.

Applying the framework to this event showed that while environmental impacts have been widely studied—and remain an area for continued research—economic and social impacts require significantly more in-depth investigation. Impact indicator values from the Fundão Dam failure were normalized within the framework to support weighting and prioritization, as well as comparison with other such events. This process helps guide policy decisions based on impact significance and highlights key research gaps.

3.1. INTRODUCTION

The rising demand for raw materials to support infrastructure and human development has led to a significant increase in natural resource extraction, particularly through mining. Today, mining is one of the most widespread human activities globally. As a consequence, the volume of mining waste—especially tailings—has grown substantially. Tailings are fine-grained waste materials generated during ore beneficiation, often mixed with water or chemicals to form slurry-like suspensions that require secure handling and storage. In 2010 alone, global tailings production was estimated at approximately 14 billion tonnes. The most common method for managing tailings is storage in engineered structures known as tailings storage facilities or tailings dams. These dams are the primary means of isolating tailings to prevent environmental contamination. However, their construction, operation, and long-term stability are increasingly concerning, especially as mining activities become larger in scale and intensity. Although mining remains economically vital for many countries and regions, tailings storage poses serious risks. When tailings dams fail, they can release millions of cubic meters of toxic materials into surrounding ecosystems, often containing heavy metals and hazardous substances. This may lead to severe land degradation, water contamination, ecosystem disruption, and direct threats to communities that depend on local natural resources for their livelihoods. In coastal areas, tailings can accumulate and cause long-term contamination, resulting in extremely high environmental recovery costs. Major failures have occurred in Bolivia, Spain, South Africa, Italy, Romania, and Brazil, leading to both environmental devastation and significant social and economic consequences. These repeated incidents have intensified global concern over the safety and regulatory oversight of tailings storage facilities. The frequency and scale of these disasters highlight the urgent need for improved monitoring, stronger design standards, and more rigorous regulatory frameworks to ensure the long-term stability of these structures(L. A. DA Silva Junior and Santos 2023; A. P. V. da Silva et al. 2022; Gomes et al. 2017; Camêlo et al. 2024; Czajkowski et al. 2023; Aires et al. 2018; Bonecker et al. 2022; C. A. da Silva Junior et al. 2018; Lyra 2019; C. C. Pereira et al. 2024; Nascimento et al. 2022; dos Santos Vergilio et al. 2021) .

Mining has played a central role in Brazil's economic and territorial development since the 17th century. In modern times, iron ore has become Brazil's most valuable mineral resource. The Mariana and Ouro Preto regions are central to iron ore production, continuing a long-standing tradition of mineral exploitation (Nogueira et al. 2021) .

Brazil is currently the world's second-largest iron ore producer. In 2020, iron ore accounted for 82% of Brazil's mining exports and 9.3% of the country's total exports. The mining sector also generates substantial employment. In 2019, Brazil recorded the highest percentage of direct mining jobs, with Minas Gerais accounting for 31.6% of all such positions—3.5 times more than in mineral processing and nearly 11 times more than in the broader mineral supply chain. These figures highlight the sector's economic importance and its role in sustaining local livelihoods. However, the growth of the mining industry—especially in iron ore—has also brought serious socio-environmental challenges, particularly related to tailings dam safety. This risk has been highlighted by recent failures in historically significant mining areas (Frachini et al. 2021; Motta and Borges 2021; Cardoso et al. 2022).

One of the most catastrophic failures was the Fundão Dam disaster. While numerous studies have examined its impacts, most focus on specific aspects such as environmental contamination or isolated economic and social losses. Few studies have adopted a multi-dimensional sustainability approach that integrates the full range of impacts (Marta-Almeida et al. 2016; Carmo et al. 2017; Gomes et al. 2017; D. de C. Silva et al. 2018; C. A. da Silva Junior et al. 2018; Aguiar et al. 2020;

Dadalto et al. 2020; Henrique de Moura, Bruno Rocha e Cruz, and De Genaro Chiroli 2020; Matsunaga 2020; K. I. C. Vieira et al. 2020; Nogueira et al. 2021; H. A. Almeida et al. 2022a; Bonecker et al. 2022; Cardoso et al. 2022; Daros et al. 2022; Euclydes, Pereira, and Pintodafonseca 2022; Evangelista et al. 2022; Merçon et al. 2022; Scarpelin et al. 2022; Miranda et al. 2024; Palma et al. 2024; L. Fernandes et al. 2022).

This gap highlights the need for holistic frameworks that can capture the full spectrum of consequences from large-scale tailings dam failures like Fundão. In response to the absence of an integrated framework capable of organizing all available data and clarifying which impact areas are most affected or understudied, this study applies the comprehensive impact assessment framework to the Fundão case. The framework builds on the model introduced in Chapter 2 and incorporates the complete range of sustainability dimensions—environmental, social, and economic.

As part of this study, the proposed framework was applied and validated using data from the Fundão disaster, marking the first comprehensive assessment model adapted to a large-scale tailings dam failure. By systematically organizing and evaluating the disaster's impacts, the framework aims to provide a holistic view, identify knowledge gaps, prioritize research needs, and support a more complete understanding of the event's aftermath.

Ultimately, this work lays the foundation for developing a full impact framework for the Fundão case. It offers actionable insights for policymakers and stakeholders, supporting the creation of more effective public policies and contributing to the design of integrated risk management strategies for tailings dams in Brazil and beyond.

3.2. METHODOLOGY

3.2.1 CASE STUDY

The Rio Doce Basin is the fifth-largest hydrographic basin in Brazil, covering an area of 83,400 km² across the southeastern states of Minas Gerais and Espírito Santo. Minas Gerais accounts for 86% of the basin's drainage area. The basin is bordered by the Paraíba do Sul basin and Espírito Santo's southern coastal basins to the south, the Rio Grande basin to the southwest, the São Francisco basin to the west, the Jequitinhonha basin to the north and northwest, and Espírito Santo's northern coastal basins to the northeast. Within Minas Gerais, the basin is divided into six water resource management units, corresponding to the sub-basins of the Piranga, Piracicaba, Santo Antônio, Suaçuí, Caratinga, and Manhuaçu rivers, each with its own River Basin Committee. The basin is vital to the region, providing water for domestic, industrial, agricultural, and energy production uses. It spans 230 municipalities with a population of 3.5 million people, of which 209 rely exclusively on surface water—eight drawing directly from the Doce River (Lactec 2020a; Alkimin De Lacerda, Bastos, and Graf De Miranda 2017) .

Population density is highest in municipalities such as Ipatinga, Governador Valadares, Aimorés, Colatina, and Linhares. The region also hosts a major mining complex, including three reservoirs related to iron ore processing: the Fundão and Germano dams for tailings storage, and the Santarém Dam, which serves both as a water reservoir for industrial use and as a secondary containment system for overflow from the tailings dams (Lactec 2020a; Alkimin De Lacerda, Bastos, and Graf De Miranda 2017).

The basin generally experiences high temperatures year-round. While the Doce River is significantly affected by droughts, the coastal region of Espírito Santo receives significant rainfall. However, the basin is also prone to flooding, especially in low-lying urban areas during intense rainy seasons. Irregular land occupation and reduced vegetation cover—98% of the basin lies within the critically endangered Atlantic Forest biome—further contribute to its vulnerability (Alkimin De Lacerda, Bastos, and Graf De Miranda 2017).

The region supports a wide range of economic activities, including agriculture (notably coffee, sugar cane, and livestock), agroindustry (sugar and ethanol production), and the timber industry (pulp and paper, reforestation). Trade and services have developed to support local industrial and energy sectors. The basin contains 10 hydroelectric power plants and hosts Latin America’s largest steel complex. On the Espírito Santo coast, 18 ports facilitate trade, supported by major highways and the Vitória-Minas Railway, which connects Belo Horizonte to Vitória and is one of the few Brazilian railways that also transport passengers (Alkimin De Lacerda, Bastos, and Graf De Miranda 2017).

On November 5, 2015, the Fundão tailings dam, operated by Samarco Minerações S.A., collapsed catastrophically. Approximately 44 million cubic meters of mining waste were released, initially contaminating the Fundão and Santarém streams, then flowing into the Gualaxo do Norte, Carmo, and Doce rivers. Over the course of 17 days, the waste traveled more than 650 km from Minas Gerais to the Atlantic Ocean, depositing sediment along the way and resulting in the deaths of 19 people. The disaster is considered one of Brazil’s worst environmental and social tragedies, affecting an estimated 1.4 million people across multiple municipalities. Due to its scale and impact, it has been classified as a "very large-scale disaster," with extensive and long-lasting consequences (Lactec 2020b). Figure 5 presents the geographic location of the Fundão Dam within the surrounding region.

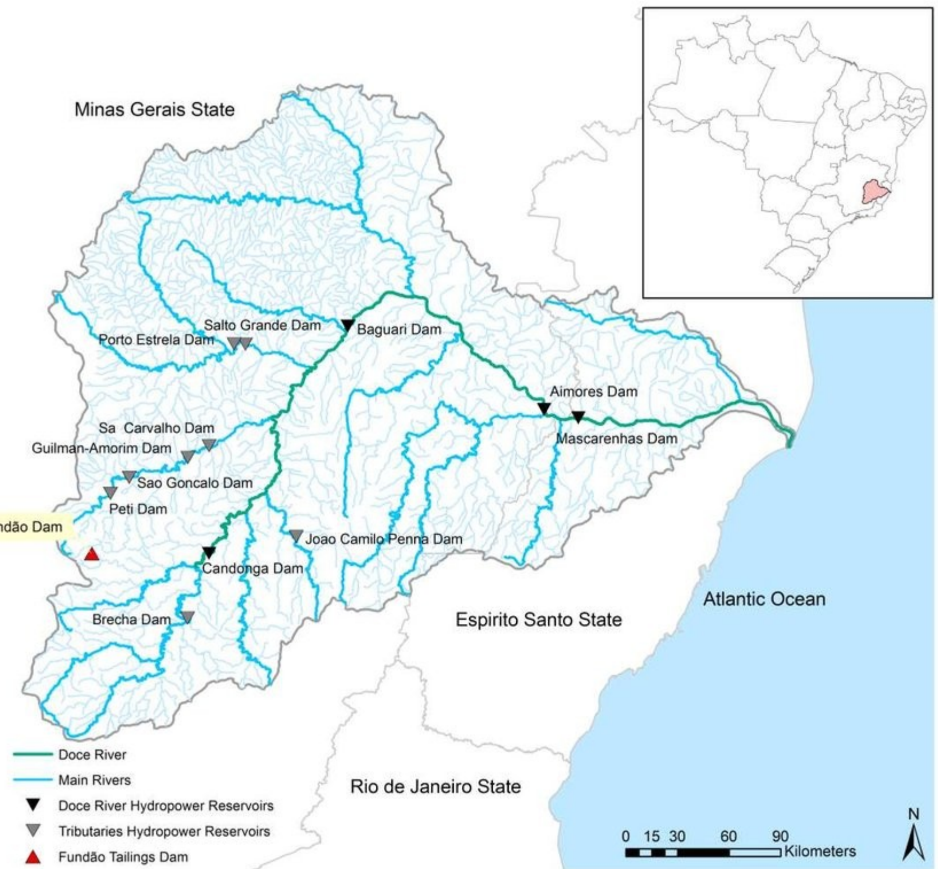

Figure 5 Rio Doce Basin and the location of Fundao dam (Palú 2019)

3.2.2 METHODOLOGICAL APPROACH

A dam failure impact framework—detailing classes, indices, and indicators—was introduced in Chapter Two to systematically categorize the consequences of dam failures. This framework organizes impacts into short-term and long-term temporal phases, each encompassing three core categories: environmental, social, and economic. Within each category, various classes are defined, grouping related indices and indicators. To apply the proposed framework to the Fundão Dam failure, post-disaster reports were used as primary sources of impact data. These reports provided structured evaluations of the disaster's socio-environmental and economic consequences (Alkimin De Lacerda, Bastos, and Graf De Miranda 2017; Bastos et al. 2017; Lactec 2017; 2018;

2020a; 2020b; 2020c; 2020d; 2020e; 2020f; n.d.; Alkimin De Lacerda 2021; Bastos and Horizonte -Mg 2021b).

Lactec, one of Brazil's leading research and innovation centers, conducted the impact assessments under the Preliminary Adjustment Agreement signed by the Federal Public Prosecutor's Office (MPF), Samarco Mineração S.A., Vale S.A., and BHP Billiton Brasil Ltda. Lactec was tasked with diagnosing socio-environmental damages from the Fundão Dam collapse, particularly within the Doce River Basin and surrounding coastal zone (Lactec 2020b).

A total of thirteen reports were analyzed:

- Three Baseline Reports (Bastos et al. 2017; Alkimin De Lacerda, Bastos, and Graf De Miranda 2017; Lactec 2017)
- Three Economic Impact Assessment Reports (Lactec 2020a; 2018; Alkimin De Lacerda 2021)
- Seven Socio-Environmental Impact Assessment Reports (Lactec 2020b; 2020d; 2020c; 2020e; 2020f; Bastos and Horizonte -Mg 2021b; Lactec Institutes 2020)

The socio-environmental reports examined impacts on terrestrial and aquatic ecosystems, marine environments, and cultural heritage (Lactec 2020b). Economic reports focused on how environmental and social damages translated into broader economic effects on communities, industries, and the regional economy (Alkimin De Lacerda 2021) .

All indicators with available pre- and post-failure data were extracted and assigned to the relevant category, class, and index in the framework. For economic indicators, original Lactec-defined weighted scales were noted, but not adopted. Instead, a new, objective scaling system was developed to quantify the percentage change between pre- and post-failure values. Change is defined as the difference between the value of the indicator before and after the dam failure. This system measured the degree of change in each indicator by comparing its pre-failure and post-failure values, without assigning any judgment regarding the severity of impact. This scale ranges from 1 to 10, based on percentage change:

1 = 0–10% change, 2 = 10–20% change, 3 = 20–30% change, 4 = 30–40% change, 5 = 40–50% change, 6 = 50–60% change, 7 = 60–70% change, 8 = 70–80% change, 9 = 80–90% change, 10 = >90% change

This approach ensured a purely data-driven analysis, without applying qualitative labels (e.g., “severe” or “minor”). The exception was for loss of life, a key social impact, which was scaled according to the Canadian Dam Association CDA (2016a) classification:

1-none, 2-Low potential for multiple loss of life, 3- 10 or fewer, 4-100 or fewer, 5-more than 100

This classification was specifically designed to reflect the loss of life, ensuring consistency with established dam safety guidelines while maintaining compatibility with the broader impact assessment framework.

For long-term impact assessment, the percentage of change scaling used for short-term impacts was deemed insufficient to accurately reflect the extent of change over time. Therefore, a different scaling system was developed, focusing on the estimated recovery time for each indicator. Since short-term impacts after a dam failure are considered within the first five years, long-term impact classifications begin from the fifth year onward. This classification is based on the recommended timeframes for impacts in CDA consequence classifications(CDA 2016b). To better capture all impacts in the medium- and long-term periods and provide more precise scoring, a three-section scale was proposed to assess impacts after the short-term period.

This scaling system is:

1 – Recovery within 5 to 10 years, 2 – Recovery within 10 to 25 years, 3 – Recovery taking more than 25 years.

To enrich the dataset, a literature review was conducted using Google Scholar and ScienceDirect with the search terms "Fundão Dam" and "Impacts of Fundão Dam failure." Articles were reviewed for inclusion based on relevance and whether they contained impact indicators not covered in the Lactec reports. Duplicates, inaccessible files, or studies lacking indicators were excluded. These additional sources contributed further before-and-after data for the framework.

Once all relevant indicators were collected and scaled, normalization was applied to bring all values into a standardized (0,1) range (Gopal, Patro, and Kumar Sahu 2015). Indicators were averaged within each index to produce normalized index scores. These were then averaged within their respective classes, and subsequently within each category to generate final category scores. Equations 1 to 3 illustrate the calculation process used to derive the overall impact score for each category.

Equation 1 $IS_o = Ave\ [IS_{sh}; IS_L]$

Where:

IS_o is overall impact score in a category

IS_{sh} is the short-term impact score

IS_L is the long-term impact score

Equation 2 $IS_{sh} = 1/C \sum_{c=1}^{C} (A_{I_C}(A_{J_I}))$

Equation 3 $IS_L = 1/C \sum_{c=1}^{C} (A_{I_C}(A_{J_I}))$

Where:

A_{J_I} is the average of indicator scores within each index

$A_{I_C}(A_{J_I})$ is the average of index scores within each class

C is total number of classes in the category

c: is the index representing each class in the summation

Equations 2 and 3 follow the same hierarchical structure, with differences only in the temporal scope (short-term vs. long-term).

3.3.RESULTS AND DISCUSSION

A total of 95 academic publications related to the Fundão Dam were initially identified. After applying exclusion criteria (duplicates, inaccessible files, no indicators), 14 articles were selected for inclusion in the study. From these, 31 indicators were extracted, of which 26 were integrated into the framework: 3 as short-term economic, 9 as short-term social, and 14 as short-term environmental indicators.

109 indicators were identified in the Lactec reports: 10 short-term and 6 long-term economic; 9 short-term and 3 long-term social; and 69 short-term and 5 long-term environmental indicators. Of these, 82 were incorporated into the framework. Indicators were excluded if data were missing for either the pre- or post-disaster period, or if they lacked clarity for interpretation. Ultimately, the framework includes 110 indicators:

- **Economic**: 12 short-term and 6 long-term
- **Social**: 27 short-term and 3 long-term
- **Environmental**: 57 short-term and 5 long-term

Figure 6 illustrates this distribution, and Table 2 provides a detailed list of the included articles, the number of indicators used, and their corresponding sections within this study.

Table 2 References added alongside the Fundão LACTEC reports

Articles	Number of indicators	Economic	Social	Environmental
(C. A. da Silva Junior et al., 2018)	1			X
(L. A. DA Silva Junior & Santos, 2023)	2	X		
(Aires et al. 2018)	4			X
(Vieira et al., 2020)	1			X
(G. W. Fernandes et al. 2016)	1		X	
(Matsunaga, 2020)	1		X	
(Nunes et al. 2022)	3			X
(Quadra et al. 2019)	1			X
(Cavalheiro Paulelli et al. 2022)	5		X	
(Motta and Borges 2021)	1		X	
(Coimbra, Alcântara, and de Souza Filho 2020)	1			X
(Almeida et al., 2022)	1	X		
(W. G. Pereira et al. 2024)	1			X
(Quaresma et al. 2020)	1			X
(Lactec 2020b; 2020d; 2020c; 2020e; 2020f; Lactec Institutes 2020; Bastos and Horizonte -Mg 2021a)	69		X	X
Lactec 2020a; 2018; Alkimin De Lacerda, Bastos,	15	X		

and Graf De Miranda 2021)				

In several cases, complete sets of indicators for a given index—as originally defined in the framework—were not fully available for the Fundão case. When only one indicator was accessible for a specific index, that single indicator was used to represent the index in the Fundão framework.

Once the indicators and indices were organized, the Fundão Dam Failure Impact Framework was applied to guide the calculation of average normalized values for broader impact categories. These categories, defined in the original Dam Failure Impact Framework, represent high-level themes that group related indicators and indices across short- and long-term impacts within the social, economic, and environmental domains.

Due to data constraints, not all classes from the original framework are represented in the Fundão case. Only those for which indicator data was available were included. Each classification incorporates all relevant and accessible indices and indicators specific to Fundão.

To standardize results and allow comparison, the framework uses average normalized values for each class by aggregating the normalized scores of all related indicators and indices. These averages offer a consolidated measure of impact severity and help highlight which classes were most affected by the Fundão dam failure.

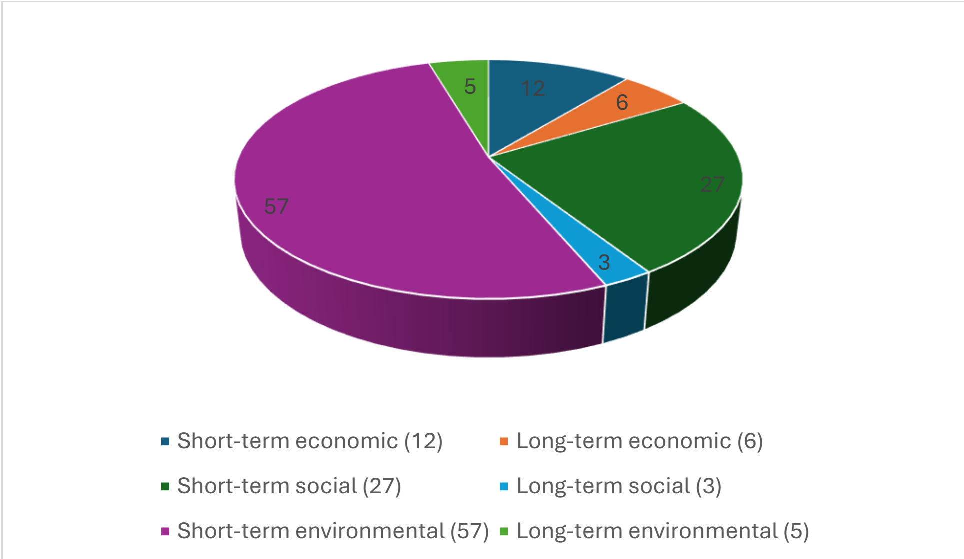

Figure 6 Available Fundão impact indicators data

Table 3 and 4 presents the framework classes for which data was available and not available respectively, in the case of the Fundão dam failure. In the economic short-term impact category, data was available for Classes 1 and 3 of the original framework: (1) Immediate Economic Loss and (3) Secondary Impacts from Environmental and Social Impacts. For the economic long-term category, data was available only for Class 5: Secondary Impacts from Environmental and Social Impacts.

In the social short-term category, data was available for Classes 1, 2, and 3: (1) Immediate Loss, (2) Social Services, and (3) Health and Mental Issues. In the social long-term category, only Class 5 was represented: Secondary Impacts from Environmental and Economic Impacts.

For the environmental domain, both the short-term and long-term categories included data for Classes 1 and 2: (1) Geology and (2) Ecology, as defined in the developed framework in Chapter Two.

Table 3 Classes with available data

Category	Classes with available data
Short-term Economic	1-immediate economic loss, 3-secondary impacts from environment and social impacts
Long-term Economic	5-secondary impacts from environment and social impacts
Short-term Social	1-immediate loss, 2-social service, 3-health impact and mental issues
Long-term Social	5-secondary impacts from env and economic impacts
Short-term Environmental	1-geology, 2-ecology
Long-term Environmental	1-geology, 2-ecology

Table 4 Classes with no data

Category	Classes without data
Short-term Economic	2- emergency response and rehabilitation
Long-term Economic	1- property and infrastructure rehabilitation, 2- adaptation and recovery, 3- research and regulation change, 4- long-term economic trend
Short-term Social	4-secondary impacts from environment and economic impacts
Long-term Social	1-society cohesion, 2-social service, 3-lon-term livelihood, 4-chronic health and mental issues
Short-term Environmental	3-energy use and carbon generation, 4-secondary impacts from social and economic impacts
Long-term Environmental	3-secondary impacts from social and economic impacts

Tables 5 and 6 show the percentage of data availability for each class, the percentage of available indices within each class, the total percentage of available classes, and the total percentage of available indices for the Fundão Dam failure within the framework.

Table 5 % of Classes with available data

Category	% of classes with data
Short-term Economic	66.67
Long-term Economic	20.00
Short-term Social	75.00
Long-term Social	20.00
Short-term Environmental	50.00
Long-term Environmental	66.67
Total % Of Available Classes	46.33

Table 6 % of available indices data

Category	Fundão Classes	% of indices with data
Short-term Economic	1-Immediate economic loss	50.00
	3-Secondary impacts From environmental and social impacts	66.67
Long-term Economic	5-Secondary impacts from environment and social impacts	66.67
Short-term Social	1-Immediate loss	28.57
	2-Social service	100
	3-Health impact and mental issues	100
Long-term Social	5-Secondary impacts from environmental and economic impacts	100
Short-term Environmental	1-Geology	100
	2-Ecology	100
	1-Geology	50.00

Long-term Environmental	2-Ecology	40.00
Total % Of Available Indices	33.53 %	

Following this classification, the average normalized impact values are calculated for each major temporal and thematic category within the overall dam failure impact framework. Table 7 displays the scores for indices, classes, and categories specific to the Fundão case. The complete dataset and detailed tables are provided in Appendix C.

Table 7 Summary of impact scores for Fundão dam failure

Impact list	INDEX SCORE	CLASS SCORE	CATEGORY SCORE
ECONOMIC SHORT TERM			0.46
1-Immediate economic loss		0.24	
Disruption of local businesses index	0		
Property loss and damage index	0.5		
Infrastructure loss and damage index	0.22		
3-Secondary impacts from environment and social impacts		0.63	
Heritage loss and damage index	0.63		
Environmental restoration index	0.62		
ECONOMIC LONG TERM			0.95
5-Secondary impacts from environment and social impacts		0.95	
Long-term environmental damage index	0.90		
Long term heritage loss and damage index	1		

SOCIAL SHORT TERM			0.42
1-Immediate loss		0.49	
Deaths	0.75		
Loss of cultural assets index	0.22		
2-Social service		0.39	
Service supply index	0.39		
3-Health impact and mental issues		0.39	
Mental issues index	0.72		
Social unrest index	0		
Health problems index	0.44		
SOCIAL LONG TERM			1
5-Secondary impacts from env and economic impacts		1	
Loss of cultural assets index	1		
ENV SHORT TERM			0.48
1-Geology		0.52	
Contamination of soils and sediments index	0.65		
Damage to sediments and sediments index	0.28		
Soil environments change index	0.67		
Erosion and displacement impact index	0.67		
Land use/ land cover index	0.37		
2-Ecology		0.43	
Biochemical impact index	0.22		
Flora index	0.37		
Terrestrial fauna index	0.35		
Aquatic fauna index	0.62		
Water quality index	0.83		
Water resource index	0.17		
ENV LONG TERM			0.92
1-Geology		1	
Soil and sediment index	1		
2-Ecology		0.83	
Flora index	0.50		
Aqua fauna index	1		
Terrestrial fauna index	1		

Although some data is available for specific impact classes, significant gaps remain—especially in areas essential for a comprehensive assessment. In the short-term economic impact category, Class 2 (Emergency Response and Dam Rehabilitation) lacks data, limiting insights into immediate economic consequences and recovery efforts. For long-term economic impacts, data is missing in four of the five classes. Only Class 5 (Secondary Impacts from Environmental and Social Changes) contains partial data, while critical areas such as Property and Infrastructure Rehabilitation, Adaptation and Recovery, Research and Regulatory Change, and Long-Term Economic Trends remain unrepresented. These gaps hinder analysis of sustained economic consequences and institutional responses over time.

Short-term social impact data is similarly limited. While some direct impacts are documented, there is no data on secondary social effects resulting from environmental and economic disruptions, making it difficult to capture the broader societal ripple effects. Long-term social impact data is sparse, with only Class 5 (Secondary Impacts from Environmental and Economic Changes) containing limited information. Key classes—such as Long-Term Livelihood and Employment, Community and Social Cohesion, Access to Social Services, and Chronic Health and Mental Health Impacts—lack any data, preventing a full understanding of prolonged social consequences.

In the short-term environmental category, data is missing for key areas such as Energy Use and Carbon Generation, and Secondary Environmental Impacts from Social and Economic Disruption. This restricts evaluation of the disaster's broader environmental footprint. Likewise, in the long-term environmental category, no data was available for Secondary Environmental Impacts from Social and Economic Changes, limiting assessment of how human activity and policy shaped environmental recovery.

Overall, these data limitations highlight the need for improved data collection, standardized reporting, and collaboration among researchers and institutions. In particular, the lower availability of indicators in the social and economic domains—compared to the environmental category—underscores the importance of enhancing data collection efforts in these areas to ensure a more balanced and accurate assessment of dam failure impacts.

3.3.1. DAM FAILURE IMPACTS SCORES

After incorporating the Fundão Dam failure data into the proposed dam failure impact framework, a single aggregated score was calculated for each impact category—environmental, social, and economic. This involved analyzing individual indicators within each category and consolidating them into an overall impact score. Initially, the assessment was conducted without applying any weighting, ensuring an unbiased representation. However, the framework allows for adjustments by introducing weighting factors based on indicator relevance and data availability. Exploring alternative weighting systems is recommended to perform a sensitivity analysis and develop a standardized approach for scoring across all indicators.

Based on the available data, social impacts attained the highest score, followed by environmental and then economic impacts. In this assessment, all indicators and categories were treated with equal importance. The total normalized impact score of the Fundão Dam failure was calculated as 0.70 on a scale from 0 to 1, where 1 represents the maximum possible impact. This score is based on the available data for the case study and reflects the aggregated environmental, social, and economic impacts identified. While the value should be interpreted in light of data availability and potential information gaps, it can serve as a reference point or benchmark for assessing the relative magnitude and distribution of impacts in other dam failure scenarios using the same framework.

Final impact scores are summarized in Tables 8 and 9, with values rounded to two decimal places (see Appendix C).

Table 8 Short-term and long-term impact scores of Fundão dam failure

Category	Normalized Impact Score
Short-term Economic Impact	0.43
Long-term Economic Impact	0.95
Short-term Social Impact	0.42
Long-term Social Impact	1
Short-term Environmental Impact	0.48
Long-term Environmental Impact	0.91

Table 9 Categories impact scores of Fundão dam failure

Category	Normalized Impact Score
Economic Impact	0.69
Social Impact	0.71
Environmental Impact	0.70
Total Failure Impact	0.70

3.4. CONCLUSION AND FUTURE WORK

Building on previous work that developed a comprehensive framework for assessing both immediate and long-term impacts of dam failures, this study applies the framework to the Fundão Dam disaster. The primary goal is to collect, consolidate, and systematically organize all available data related to the Fundão failure within this structured evaluation model. This approach enables a side-by-side comparison of impact indicators across environmental, social, and economic categories, offering a holistic understanding of the disaster's consequences.

This report also demonstrates the functionality of the framework by systematically aggregating impact data, allowing for the identification of data gaps and the distribution of impacts across various dimensions.

In 2015, the mining complex in Mariana, Minas Gerais, Brazil, experienced a catastrophic event when the Fundão Dam collapsed, releasing 33 million cubic meters of mining waste. The waste traveled downstream through the Santarém Dam, contaminating the Gualaxo do Norte and Carmo Rivers, and eventually reaching the Atlantic Ocean. Heavy rainfall further worsened the situation, increasing the total volume of tailings to 44 million cubic meters.

By mapping the available data into the framework, this study assesses the scale and distribution of impacts and identifies critical gaps in information. This process helps determine which categories—whether environmental degradation, social disruption, or economic loss—require further research, targeted data collection, or increased attention from experts and policymakers. In doing so, the study not only evaluates documented impacts but also highlights areas of uncertainty, promoting a more data-driven response to future disasters.

Furthermore, the research underscores the need for a robust and adaptable indicator system that reflects the relative importance of each impact class, and category. Such a system should be tailored to the specific context of the dam, region, or sector, enhancing the framework's utility for comparative analysis, disaster planning, and impact mitigation.

CHAPTER 4: THESIS CONCLUSION

While dams provide significant societal benefits—such as water supply, hydroelectric power, flood control, and irrigation—they also pose serious risks when not properly designed, maintained, or operated. Structural deficiencies, poor maintenance, human error, and the growing influence of climate change all contribute to the potential for dam failures. When such failures occur, the consequences can be catastrophic, including loss of life, extensive environmental damage, and severe economic disruption.

To mitigate these risks, it is essential to enforce robust policies and regulations for inspection, maintenance, and emergency planning. Despite ongoing efforts by scientists, engineers, and policymakers to enhance dam safety and promote best practices, dam failures continue to happen worldwide. A key challenge remains: understanding the full scope of potential impacts and their interconnections to support more effective risk assessments and policy development.

Although numerous studies have examined the consequences of individual dam failures, there has been a lack of a unified, systematic framework to comprehensively assess these impacts—particularly from a sustainability perspective that considers environmental, social, and economic dimensions. This thesis addresses that gap by proposing an integrated impact assessment framework for dam failure events. The framework compiles and organizes indicators from existing literature into a cohesive structure to support broader understanding and informed decision-making. Designed to be both adaptable and expandable, the framework allows researchers and practitioners to tailor it to different contexts and incorporate additional indicators. By offering a more complete picture of dam failure consequences, the framework aims to improve planning, risk mitigation, and policy development to help prevent future disasters.

Recognizing the increasing role of artificial intelligence (AI) in research, this study also explores how AI can support dam failure analysis. AI tools were used to streamline data collection, classification, and indicator extraction, enhancing the overall efficiency of framework development. To validate its real-world applicability, the framework was applied to the 2015 Fundão Dam failure in Brazil, one of the most devastating such events in history. This case study demonstrated the framework's ability to capture and organize diverse impacts and underscored its potential for broader application in risk assessment and policy-making.

Applying the framework also highlighted data gaps and areas requiring further research. By systematically mapping the impacts, the framework helps identify underrepresented dimensions and informs future data collection, policy development, and research priorities.

It is important to acknowledge that different failure scenarios can result in varying impact profiles. The failure mode of a dam is a critical factor influencing the type and extent of post-failure impacts. Similarly, the available response time following a failure plays a significant role in shaping the severity and scope of those impacts. Although these factors are not explicitly included within the framework, they are closely related to the magnitude and distribution of impacts observed after a dam failure, and the impacts under different failure modes can be compared by using the framework.

Despite its contributions, the study has several limitations. First, while AI tools improved efficiency, their use carries a risk of misclassification, omission, or incomplete data due to inherent limitations in automated extraction. Second, methods for calculating impact indicators vary in geographic scope, assumptions, and measurement techniques, which can affect comparability across studies. Additionally, in cases with multiple data sources, only one dataset was used for each indicator, potentially introducing bias. Uneven data availability across the environmental, social, and economic dimensions also complicates cross-category comparisons and may lead to misleading conclusions.

To address these limitations, future research should focus on developing standardized weighting methods to reflect the relative importance of indicators based on context and stakeholder needs. Incorporating multiple data sources per indicator would improve reliability, while regular updates and classification refinements would ensure the framework remains current and relevant as new insights emerge.

4.1. DECLARATION

The ChatGPT AI tool was employed for reviewing the text on this paper.

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APPENDIX A

The following tables present all dam failure impact indicators, including influencing factors, and any associated units of measurement.

- Blue highlight means author added to the list based on understanding from literature
- Red statement means author added to the list

- First column showing the indicator number representing the reference

- D represent direct and I represent indirect and referred to the direct indicator derived from by" I from."

- Same color sections mean the group of one index

*Some of indicators include two or more words, but to prevent duplication of indicator in different indices and classifications, each indicator is classified in one group, for example an indicator is "fatalities and casualties, only it is considered in fatalities index.

* Some indicators are in both short term and long-term classifications.

1- Economic Impact Indicators:

Indicator no	Direct or indirect	indicator name	Subcategory (how the indicator can be calculated or due to)	unit
Short term (up to 5 years)				
1-IMMEDIATE ECONOMIC LOSS				
Service Disruptions INDEX				
736	**D**	**Electricity Supply Loss**	-Loss of megawatts	$
194	**D**	**water supply loss**	Water quality	$
666	**D**	**Lost irrigation water supply**		Water supply: acre-feet/$
15	**D**	**Economic loss due to disruption in water supply and other water uses**		$
395,345	**D**	**Ecosystem service loss**		$
667	**D**	**Lost municipal & industrial water supply**		acre-feet/$
668	**D**	**Lost hydropower generation**		MWh (megawatt hours) and $
756,581,780	**D**	**Disruption to transport service**		
DISRUPTION OF LOCAL BUSINESSES INDEX				
32,282	**D**	**Disruption of local businesses**		$
72	**D**	**Business closures**		$
241,289,523	**D**	**Business interruption**	241- due to downtime of mining and processing operations 523- Loss of Economic Activity,revenue loss	$
606	**D**	**Decrease in local business revenues**		$
663	**D**	**Initial changes in industry value due to alterations in final demand.**		$
303	**D**	**Economic loss in local agriculture**	due to flooding of farmland, leading to loss of livelihood (measured in currency based on agricultural outputs	$
12o,95,633,347	**D**	**Impacts on local fisheries and agriculture**	120-access and output losses 95- Reduction in fish biomass 347- Environmental Impacts affecting fish populations and water quality	$
323,788,531, 512,564	**D**	**Loss of agricultural productivity**	323-Economic dependency on agriculture (e.g., percentage of income derived from farming 565- crop yield loss	$
81,442,802,374	**D**	**Loss of income from fishing and recreation**	81-LOSS OF INFRASTRUCTURE AND FACILITIES	$
128	**D**	**Local revenue loss from tourism, fishing, and agriculture**		$
733	**D**	**Variations in governmental revenue from oil production**	Closure of oil ports and disruption of local economies	$
270	**D**	**Loss of Revenue**		**$**
688	**D**	**monthly sales, monthly customers, LOSS**		$

41	**D**	**capital loss of production**		$
40	**D**	**labor reduction**		$/NUMBER
359	**D**	**Effects on fisheries and commercial activities linked to changes in biodiversity and fish stock dynamics.**		$
290	**I from Disruption of local businesses index**	**Local Tax Revenue Loss**	Decrease in tax collections due to property damage and business closures	
741	**I from Disruption of local businesses index**	**Debt Repayment Issues**		
ECONOMIC DOWNTURN INDEX IN AFFECTED AREAS				
419	**D**	**Economic downturn in affected areas (e.g., unemployment rates)**		
297	**D**	**Interruption Economic Activities**		$
25	**D**	Economic value loss		$
255	**D**	loss of resources		$
629		Economic downtime due to infrastructure damage		
172,566,417	**D**	**Economic downturn in local industries**		$
BENEFIT LOSSES INDEX				
661	**D**	**Benefit Losses: The loss of future benefits**	-Lost flood control benefits ($) -Reductions in tourism (%) -Changes in employment (number of jobs)	Lost benefits: $ (dollars) Recreation visits: number of visits
39	**D**	**Dam benefit losses (agriculture, recreation)**		
PROPERTY LOSS AND DAMAGE INDEX				
12,68,782,228,305,354,387,416,539, 669,676,702, 38,628,280,497	**D**	**property destruction/damage**		NUMBER OR PERCENT
157,182,703, 555, 580,	**D**	**Property loss/destroyed**		
721	**D**	**Damage to Residential and Basic Security Facilities**		
766	**D**	**Property damage incurred due to floods and debris flows**		
100	**D**	**Impact on properties,**		
522	**D**	**Damage to public facilities and homes.**		
770	**D**	**recovery costs for affected properties**		

499,812	**D**	**Changes in local property values**		
44	**I from Property loss and damage INDEX**	**Increased costs of living**		
INFRASTRUCTURE LOSS AND DAMAGE INDEX				
675,623,731	**D**	**impacts on infrastructure**	731-Damage to roads, bridges, and communication networks.disruption of electricity and communication lines	
727	**D**	**impacts on roads, buildings, and essential services**		
23,50,153, 262,284,322, 355,424,500, 511,769,642, 704,724,778, 63,103,159,2 03,486,554,5 77,73,508	**D**	**Infrastructure damage**	724-Flood wave height: Measurement of flood intensity (e.g., maximum height of flood waves). Inundation area: Geographic area inundated by flood waters.,Flow progression over time,Water depth and extent of flooding,Water depth and extent of flooding,Time of wave arrival at key cities 778- Measured in terms of length of roads and railways washed out, and the number of bridges destroyed. 577- Flood Inundation Depth,Flood Inundation Area	724- Flood Wave Height: Meters (m). Inundation Area: Square kilometers (km²). Initial Lake Level: Meters (m) 778- LENGTH AND NUMBER 159-number ,%
189,737,762, 809,396	**D**	**Infrastructure loss**		
648	**D**	**Damage to roads, railways, utilities**		
614	**D**	**damage to infrastructure (roads, accommodation)**	Area of production facilities affected, Area of inundated land (e.g., farmland, infrastructure),Flow rate of released water, volume of tailings released.	Area (square metres), flow rate released water (cubic meter per second), damaged area (square meters), no. of affected population (count), saturation line depth (meter), pressure distribution (pascal)
719	**D**	**Damage to Infrastructure (including road, traffic, and communication facilities)**		
183	**D**	**important facilities affected**		
650	**D**	**Damage to commercial areas**		
619	**D**	**Costs associated with infrastructure repair and loss of productivity**		$
48	**I from Infrastructure loss and damage INDEX**	**Production cost change**		
2-EMERGENCY RESPONSE AND REHABILITATION				
IMPLICATIONS OF MAINTENANCE AND RESTORATION INDEX				
686,380,161	**D**	**Cost of repair or replacement**	686-number of months closed	
604	**D**	**Immediate repair costs**		
755	**D**	**restoration or compensation efforts except environment and social**		$
ALTERNATIVE SUPPLY INDEX				

207	**D**	alternative water supply methods (e.g., water tank trucks		$
196	**D**	Temporary water treatment		
	D	alternative services		
EVACUATIONS AND OTHER DISASTER RESPONSE INDEX				
195,268,478, 498,530,634, 672,814	**D**	**emergency responses**		$
726,154,712,	**D**	**Cost of potential evacuations/ Emergency evacuations**		People NUMBER
391		**Community displacement and health-related costs**		
288,190,810, 423	**D**	**Insurance Claims**	Total value claimed by affected property owners	$
46	**D**	**temporary classroom setup**		$
671 698	**D**	**Temporary structures**		$
3-SECONDARY IMPACTS FROM ENVIRONMENT AND SOCIAL IMPACTS				
HERITAGE LOSS AND DAMAGE INDEX				
78	**D**	**Damages to heritage sites along the Doce River**		COUNTS
79	**D**	**Losses related to local cultural assets**		COUNTS
740	**D**	**Food Shortages**	-percentage reduction in agricultural output Or % increasing of the price	$
420	**I from Food Shortages**	Increased costs of living due to resource scarcity		
ENVIRONMENTAL RESTORATION				
670	**D**	**Environmental restoration**		$
52	**D**	**Economic losses associated with environmental pollution**		
43,163,302,5 69,586,638,7 84,242	**D**	**Cleaning-up costs**	586-Land price, clean up budget	
47	**D**	**Health costs(**post-disaster disease costs, and psychological impact-related workdays lost)		$
ECONOMIC CONSEQUENCES FOR LOCAL AGRICULTURE AND FISHING INDUSTRIES				
572	**D**	**Economic consequences for local agriculture and fishing industries due to contaminated resources**		
592	**D**	**potential crop yield losses DUE TO Changes in agricultural soil quality**		$

359	D	Effects on fisheries and commercial activities linked to changes in biodiversity and fish stock dynamics.		$
655	D	commercial fishery yields due to impacts on fish populations.		

Indicator no	Direct or indirect	Indicator name	Subcategory (how the indicator can be calculated or due to)	unit
Long term (more than 5 years)				
1-PROPERTY AND INFRASTRUCTURE REHABILITATION				
PROPERTY LOSS AND DAMAGE INDEX				
12,68,782,228,305,354,387,416,539, 669,676,702,38,628,280,497,	D	Property destruction /damage		NUMBER OR PERCENT
157,182,703,555, 580,	D	Property loss/destroyed		
721	D	Damage to Residential and Basic Security Facilities		
766	D	Property damage incurred due to floods and debris flows		
100	D	Impact on properties,		
522	D	Damage to public facilities and homes.		
770	D	recovery costs for affected properties		
709,499,771,812	D	Changes in local property values		$
INFRASTRUCTURE LOSS AND DAMAGE INDEX				
675,623, 731	D	impacts on infrastructure	731-Damage to roads, bridges, and communication networks.disruption of electricity and communication lines	
727	D	impacts on roads, buildings, and essential services		
23,50,153, 262,284,	D	Infrastructure damage	724-Flood wave height: Measurement of flood intensity (e.g., maximum height of flood waves).	724- Flood Wave Height: Meters (m). Inundation Area: Square kilometers (km^2).

322,355, 424,500, 511,769, 642,704, 724,778, 63,103,1 59,203,4 86,554,5 77,73,50 8			Inundation area: Geographic area inundated by flood waters.,Flow progression over time,Water depth and extent of flooding,Water depth and extent of flooding,Time of wave arrival at key cities 778- Measured in terms of length of roads and railways washed out, and the number of bridges destroyed. 577- Flood Inundation Depth,Flood Inundation Area	Initial Lake Level: Meters (m) 778- LENGTH AND NUMBER 159-number ,%
189,737, 762,809, 396	**D**	**Infrastructure loss**		
648	**D**	**Damage to roads, railways, utilities**		
614	**D**	**damage to infrastructure (roads, accommodation)**	Area of production facilities affected, Area of inundated land (e.g., farmland, infrastructure),Flow rate of released water, volume of tailings released.	Area (square metres), flow rate released water (cubic meter per second), damaged area (square meters), no. of affected population (count), saturation line depth (meter), pressure distribution (pascal)
719	**D**	**Damage to Infrastructure (including road, traffic, and communication facilities)**		
183	**D**	**important facilities affected**		
650	**D**	**Damage to commercial areas**		
619	**D**	**Costs associated with infrastructure repair and loss of productivity**		$
2-ADAPTATION AND RECOVERY				
SOCIETY ADAPTATION				
325	**D**	**Welfare(**Effects on local communities and welfare)		$
605	**D**	**Compensation paid to victims**		$
692	**D**	**Worker's migration**		NUMBER /cost
	I from Worker's migration	increasing wages and products costs		
RESTORATION AND ECONOMIC RECOVERY INDEX				
574 746 710 139 540 13 389 557 261	**D**	**Restoration and economic recovery except for environmental and social in long term**	746-years to rebuild infrastructure) 139-Financial estimates for ecosystem recovery.	$

591	D	**Costs of remediation and potential fines related to failure**		
673 651	D	**Dam repair/replacement**		$
3-RESEARCH AND REGULATION CHANGE				
344,585	D	**Remediation study and research(**financial feasibility and cost estimation of remediation efforts)		. *$
200	D	**Adaptation strategies cost**		$
4-LONG TERM ECONOMIC TREND				
ECONOMIC TREND index				
33 250 544	D	**Long-term economic decline**		$
432	D	**Alteration of economic flow**		
811	D	**Long-term Economic Loss in Affected Areas**		
664	D	**Changes in regional economic output**		
425,122,164	D	**Changes in local economic activity**	164-due to water contamination	
256,556	D	**impacts on local industries and business**		
130	D	**Long-term market value decline of local resources**		$
747	D	**changes in investment levels**		
715,772	D	**insurance costs**		$
5-SECONDARY IMPACTS FROM ENVIRONMENT AND SOCIAL IMPACTS				
LONG-TERM ENVIRONMENTAL DAMAGE INDEX				
247	D	**Long term environmental cleanup and restoration**		$
258	D	**Economic assessments of long-term environmental damage**		
254,597,662	D	**costs associated with remediation**		
670	D	**Environmental restoration costs**		
314	D	**impact local economies reliant on resources**		
196	D	**water treatment**		
LONG-TERM HEALTH IMPCT INDEX				
590	D	**long-term costs associated with HM exposure**		$/number
449, 165	D	**Long term Cost of Health Care**		
LONG TERM HERITAGE LOSS AND DAMAGE INDEX				
78	D	**Damages to heritage sites along the Doce River**		COUNTS

79	**D**	**Losses related to local cultural assets**		COUNTS

2- Social Impact Indicators:

Indicator no	**Direct or Indirect**	**Indicator name**	**Subcategory (how the indicator can be calculated or due to)**	**unit**
Short term (up to 5 years)				
1-IMMEDIATE LOSS				
FATALITIES , LIFE LOSS, DEATHS				
8,158,202,218,317,390,436,594,639,728,757,20,69,98,143,152,173,216,276,277,352,366,404,506,562,621,640,742,774,781,53,60,99,220 233,260,718,295,299,304,536,188,527,418	**D**	**Fatalities** **(**fatalities /missing persons./Loss of life/DEATHS)	594-i<Volume of tailings released (m^3) Distance traveled by tailings (km) 98-I<Population at Risk (PAR): The number of individuals living in flood-prone areas below the dam. Base Fatality Rate (FATBASE): Average fatalities per population at risk. Flood Severity Metrics: Flood depth and velocity at different points of the inundation area, impacting the lethality of the flood. Warning Time 143- I <Understanding of Dam Breach ,Warning Time,Population at Risk 152-I<Population at risk,Evacuation potential (RP, RE, RS),Shelter Rate(The proportion of the un-evacuated population that successfully shelters in buildings.),preparedness rate 216-I<Severity of Dam Break Flood (SF),Population at Risk (PR),Evacuation Conditions (EC),Understanding of Dam Break (UB),Warning Time (TW),Weather During Dam Break (WB),Dam Break Mode (MB),Water Storage (SW),Building Vulnerability (VB),Dam Break Time (TB),Average Distance from Affected Area to Dam (DD) 276-I<Population at Risk (PAR) - The number of people exposed to critical flood depth. Severity Degree (SD) - A measure indicating the destructive impact of the flood on residents and structures. Warning Time (WT) - The time available for residents to evacuate before the flood reaches them. Understanding Degree (UD) - The public's understanding of the flood situation, influencing their ability to respond effectively. 352-I<Flood Severity: This is assessed by looking at the depth of water, velocity, and inundation extent. Warning Time: The effectiveness and timing of the warning systems implemented. Fatality Rates: Based on observational data from previous dam failures, primarily expressed in fatalities per number of people at risk.Public Awareness and Understanding of Flood Severity: Gauges how well the population comprehends the risks and severity of flooding. Evacuation Rates: Derived from the effectiveness of warning systems and preparedness of people in risky zones. Flood depth and velocity Road network data Building locations/types Population distribution data 366-I<Hydraulic conditions Building characteristics	numbers NUMBER, METER, HOURS Fatality rates: Fraction (no unit) Warning time: Minutes Flood depth: Meters (m) Flood velocity: Meters per second (m/s) Depth x velocity (DV): Square meters per second (m^2/s) Population: Number of people (no unit) Dam height: Meters (m) or Feet (ft) Water volume: Cubic meters (m^3) or Acre feet Depth: Meters (explicitly stated). Velocity: Meters/second (explicitly stated). -Population at Risk - Individuals (unit explicitly stated). Flood Severity Degree - m^2/s (square meters per second) for flood dynamics. Warning Time - Seconds (s). Public Comprehension Degree - A qualitative scale (not explicitly quantified). Water Depth - Meters (m). Flow Velocity - Meters per second (m/s) mortality rate , flood severity (scale), property damage (usd),

			Temporal variables Population dynamics, population at risk, warning time, and flood severity.population distribution, human behavior, and demographic characteristics (age, gender) are considered indirect indicators influencing the direct impact of dam failure. 506-I<Population at Risk,Annual Probability of Dam Failure,Dam Height(M), Social vulnerability parameters 640-I< floodwater depth and velocity conditions,Population at Risk 781-I< flow depth, velocity of mudflow 99- I<Warning Time: The duration residents could potentially receive a warning before flooding occurs. Demographic Data: Population density and characteristics of the affected area. 233-I<Population at risk downstream 295-I<Population at Risk - Number of individuals at risk due to dam failure. Flood Severity Degree - Assessed through flood metrics like flow velocity and water depth. Warning Time - Duration before the event that the population is notified. Public Comprehension of Risks - Understanding level of the population regarding threats from dam failure. 299-I<Depth and velocity of mudflow (measured in meters and meters/second respectively), Extent of pollutant dispersion downstream, 304-I<Evacuation Condition (EC): Measures how well the population can evacuate before floodwaters arrive. Warning Time (TW): The amount of advance notice provided to communities at risk. Population at Risk (PR): The number of individuals living in areas that may be affected by the dam break Flood Severity (SF),Flood Depth (FD) Flood Velocity (FV) Understanding of Dam Break (UB) Building Vulnerability (VB) Height of dam (HD) - meters Severity of dam-break flood (SF) - m2/s Dam break mode (MB) - qualitative Water storage (SW) - 104 m3 Exposure factors: Dam breach time (TB) - qualitative (day/night) Weather at breach (WB) - qualitative Building vulnerability (VB) - qualitative Average distance from affected area to dam (DD) - km Population-related factors: Population at risk (PR) - number of people Understanding of dam break (UB) - qualitative Rescue capability factors: Warning time (TW) - minutes Evacuation condition (EC) - qualitative 536-I<flood severity, warning time, understanding of dam failure, and building vulnerability, 188-I<population density, warning time, and understanding of risks	
CASUALTIES				
813 786 170 298 507 230 278 729	**D**	**Casualties**		number

300 608 382				
LOSS OF LIVELIHOODS index				
392 24 412 560 785 406 320	**D**	**Disruption of livelihoods**	412- related to fishing and water supply 785-Economic loss in local agriculture Affected communities face -loss of income due to displacement and regional instability.	$ **$ NUMBER
6,174	**D**	**Quality of life changes**		
96	**D**	**community livelihoods**	Changes in local fisheries	
743	**D**	**Impact on Livelihoods:**	Affected communities face loss of income due to displacement and regional instability.	
123	**D**	**Changes in livelihood security metrics**		
267	**D**	**loss of livelihood observed after displacement.**		
336	**D**	**Reduced working capital among community members**		
760	**D**	**disruptions to local economies and livelihoods**		
299,335	**D**	**lost income**		
LOSS OF CULTURAL ASSETS index				
21 138 410 722 184	**D**	**Heritage loss or damage**	138-Destruction of historical sites and community identity.	number 722-Cultural relics: Dimensionless 0-100 scale
647	**D**	**Impacts on archaeological/cultural sites**		
414	**D**	**Cultural heritage preservation metrics**		
175	**D**	**Loss of cultural relics and art treasures**		
793,446	**D**	**Impacts on Traditional Land Use and resources**		793-Qualitative indicators.
249	**I from Impacts on Traditional Land Use and resources**	**Loss of livelihoods linked to agriculture and fishing**		
296	**D**	**Interruption of Social activities**		
450	**D**	**Shifts in cultural practices**		
PEOPLE DISPLACEMENTS				
16 22 70 131 219 248 263 283 306 319 332 370 377	**D**	**People displacement(**People displacement/ * Number of evacuations/Number of people affected/evacuated)	-Number of individuals evacuated 306-The number of individuals forced to relocate due to dam failure. 723- <Population exposed to different flood depths (number of people) 201-water supply disruptions	number

407 417 470 487 494 509 524 558 582 595 617 632 677 730 723 779 805 166 201 711 264 54 541 773 630 790 683 759 501				
714	**D**	**Changes in population density in impacted areas**		number
45	**I from People displacement**	**missing school days**		Days Or % of children miss school
31,776	**I from People displacement**	**Loss of educational opportunities**		% of children miss education
LOSS OF OPPORTUNITIES				
129 331 397 565 665 291	**D**	**employment rates**		129-% -number
607,18,687	**D**	**Job losses in affected regions**		%/number
682 5 641	**D**	**Loss of recreational opportunities**	5-electricity loss	-$
656	**D**	**loss of recreational fishing activities.**		
438 795	**D**	**Alteration of Fishing Practices**	438-Direct measures would be the reported decrease in traditional fishing practices. - *348-Community reliance on healthy aquatic systems	795-Frequency changes (number of participants).
376	**D**	**Loss of Tourism Revenue**		
COMMUNITY RESILIENCE INDEX				
137 292 415 758 815	**D**	**Community Resilience capacity** **(**Community Resilience Metrics and capacity to recover/ Changes in community	137-community capacity to recover post-disaster. 292-Measures of community preparedness and recovery post-disaster.	231-TIME NEED FOR RECOVERY

231 324 341 369 532 474		preparedness and emergency response capacity)		
645	**D**	**Public resistance to rebuilding efforts**		
660	**D**	**Governance Consequences**		
775		**Changes in community preparedness and emergency response capacity**		
80	**D**	**Preparedness Funding(**willingness to pay (usd) to prevent future incidents)		
2-SOCIAL SERVICE				
SERVICE SUPPLY INDEX				
409 649 433	**D**	**Disruption of water supply**		
132,4,198,4 13,118	**D**	**Access to clean water and sanitation facility counts**	198- water supply disruptions	Number 4-number of livelihoods dependent on water.
281	**D**	**<Power**	Time duration for power is interrupts	NUMBER OF FAMILIES AFFECTED
571	**D**	**Limitations on local populations accessing river water for consumption and agriculture**		
285	**D**	**Utility Service Disruption Duration**		hours
471,485,34 2,140	**D**	**ecosystem services**	140-Evaluations of lost services like water purification and habitat provision.	
513 690	**D**	**Losses in services**		
735	**D**	**Access to medical facilities**		
333	**D**	**Access to services post-disaster (e.g., clean water, health services)**		number
716,525	**D**	**Loss of community services**		
576	**D**	**Disruption of Transportation Networks**	-Flood Inundation Depth(m), -Flood Inundation Area(km²)	
458,135	**D**	**Loss of access to fisheries resources (Potential implications on local fisheries and ecosystem services, / Loss of access to fisheries resources)**	458-health status of fish communities 135-number	-number
464,680,62 4	**D**	**Impact on fisheries**		
550 362 439	**D**	**availability of food and income for local communities/food security**	550-Reduced fish populations 439-environmental degradation	550-Trophic Position Units Inference: May need to be inferred from ecological studies.

				Species Diversity Units: Count (number of species). Stable Isotope Ratios: Units: δ13C and δ15N (per mil, ‰).
796	**D**	**Access to Traditional Food Sources: Reflects stress on dietary practices**	796-environmental degradation	
734	**D**	**The extent of shelter availability and access to basic necessities.**		number
533	**D**	**Access to Recovery Services**		Measured by the percentage of affected population receiving aid
505,631	**D**	**Access to emergency services**		
446	**D**	**loss of access to traditional land use and resources**		
3-HEALTH IMPACT AND MENTAL ISSUES				
MENTAL ISSUES INDEX				
167 293 421 610 232 543 400 293	**D**	**Mental health impacts/issues**	-qualitative measures like interviews that assess perceived stress related to the incident.	NUMBER)
30	**D**	**Health impacts due to displacement**	Due to displacement	
791	**D**	**psychological effects due to fatalities**		
437 794	**D**	**Emotional Stress Level**	qualitative measures like interviews that assess perceived stress related to the incident.	
561	**D**	**psychological distress among affected populations**		number
371 659 816 510 713	**D**	**psychological impacts**		
	D	**Mental Health impacts from injuries**		number
575	**D**	**public perception and fear regarding the safety of local resources**		number
658	**D**	**emotional impacts relative to loss of fishing livelihoods.**		
720	**D**	**Social Unrest and Turmoil (triggered by panic and loss of life)**		
36	**D**	**Social morale decline**	-due to displacement and loss of life	
PHYSICAL HEALTH PROBLEMS index				
252	**D**	**Public health outcomes linked to contamination events**		

37 488	D	**Community well-being**		
		4-SECONDARY IMPACTS FROM ENV AND ECONOMIC IMPACTS		
361	D	**Impacts on community health related to environmental degradation**		number
405	D	**The toxicity level of mud impacting local communities**		
434	D	**Health problems arising from tailings exposure./**	-WATER QUALITY -Disability-Adjusted Life Years (DALY), -Measured for As (Arsenic), Cd (Cadmium), and Pb (Lead) immediately post-failure -Loss of access to clean water resources - exposure to toxic metals (Aluminum, Arsenic, Mercury, Nickel). -Blood metal concentrations of toxic elements (Al, As, Hg, Ni) in participants' blood samples, -Dietary habits and sources of water as factors contributing to exposure risks, -Source of food (e.g., seafood consumption linked to metal exposure). -Water source as a potential source of contamination, -Community demographics and lifestyle. Previous health status linked to exposure. -Aluminum (Al), Arsenic (As), Cadmium (Cd), Cobalt (Co), Copper (Cu), Mercury (Hg), Manganese (Mn), Nickel (Ni), Lead (Pb), Selenium (Se), and Zinc (Zn) ,smoking habits, -Health conditions reported by participants: Mental disorders, malaise, skin lesions, gastrointestinal disorders, and bone diseases were documented.	-number -cases per population -PEOPLE NUMBER
315	D	**Health risks: Accumulation of metals in the human body.**		
789 7	D	**.health issues from pollution exposure**	7- Loss of access to clean water resources	
584	D	**health risks from heavy metal (HM) exposure.**	Disability-Adjusted Life Years (DALY),Measured for As (Arsenic), Cd (Cadmium), and Pb (Lead) immediately post-failure	
224 364 191 199 365 748 55 495 559	D	**Health impact**	364-exposure to toxic metals (Aluminum, Arsenic, Mercury, Nickel).Blood metal concentrations of toxic elements (Al, As, Hg, Ni) in participants' blood samples,Dietary habits and sources of water as factors contributing to exposure risks,Source of food (e.g., seafood consumption linked to metal exposure).Water source as a potential source of contamination,Community demographics and lifestyle.Previous health status linked to exposure.Aluminum (Al), Arsenic (As), Cadmium (Cd), Cobalt (Co), Copper (Cu), Mercury (Hg), Manganese (Mn), Nickel (Ni), Lead (Pb), Selenium (Se), and Zinc (Zn) ,smoking habits,Health conditions reported by participants: Mental	364-(ug/l) 191-number 365-ng/mL

			disorders, malaise, skin lesions, gastrointestinal disorders, and bone diseases were documented. 199-lowered water quality. 365-urinary levels of toxic metals/metalloids and oxidative stress indicators (specifically, DNA damage),Toxic Metal Levels: Urinary concentrations of metals/metalloids such as arsenic (As), cadmium (Cd), mercury (Hg), nickel (Ni), and lead (Pb).Oxidative Stress Biomarker: Levels of 8-hydroxy-2'-deoxyguanosine (8OHdG). 55-TAILINGS RELEASE,	
657	**D**	**Public health risks linked to contaminated water sources previously used for drinking**		
464 151 466	**D**	**Humanistic Ecological Environment**		
447	**D**	**health risks associated with the contamination of water and fish,**		
568	**D**	**Potential health implications for local populations due to contaminated water and soil.**		cases per population
732	**D**	**waterborne diseases due to contaminated water sources and fish**	The prevalence of stagnant water as vectors for disease spread	
(Shandro 2017)	**D**	**Difficult access to safe water due to deterioration of water quality**		

Indicator no	**Direct or Indirect**	**indicator name**	**Subcategory (how the indicator can be calculated or due to)**	**unit**
Long term (more than 5 years)				
1-SOCIETY COHESION				
441, 797 691	**D**	**administrative burdens on community leadership**		
689	**D**	**changes in community leadership, and migration of workers**		
294 17 301 422 443 609 29 334 399 475 542	**D**	**Community Cohesion**	294-Changes in community dynamics and relationships post-event -crime rates, poverty levels 787,301-Due to Public perception and fear related to mining and dam infrastructure, 443-Inter-community tensions -Community Displacement/	-number

787			-Casualties	
429,519,616,266,496,356	D	**Social disruption**	356- Community Displacement/Casualties	
124	D	**Social capital CHANGE in affected communities**		
192	D	**long-term community fragmentation**	displacement	
803	D	**social coherence impacts**	Intra-community and Inter-community Tension	
489	D	**Increased vulnerability and loss of community cohesion**		
801 444	D	**competition for fishing resources**		
641	D	**Social Value and Recreational Loss**	-Economic losses from damage to properties, public utilities, and other critical facilities	
238	D	**Changes in public perception and values**		
761 426 251	D	**Changes in community demographics**	251-DUE TO MIGRATION	-number -%
660	D	**Governance Consequences**		
749		**Social stability**	crime rates, poverty levels)	
168	D	**Population decreases or migration trends**		number
2-SOCIAL SERVICE				
571	D	**Limitations on local populations accessing river water for consumption and agriculture**		
409 649 433	D	**Disruption of water supply**		
132,4,198,413,118	D	**Access to clean water and sanitation facility counts**	198- water supply disruptions	Number 4-number of livelihoods dependent on water.
471,485,342,140	D	**ecosystem services**	140-Evaluations of lost services like water purification and habitat provision.	
513 690	D	**Losses in services**		
716,525	D	**Loss of community services**		
296	D	**Interruption of Social activities**		
576	D	**Disruption of Transportation Networks**	-Flood Inundation Depth(m), -Flood Inundation Area(km²)	
458,135	D	**Loss of access to fisheries resources (Potential implications on local fisheries and ecosystem services, / Loss of access to fisheries resources)**	458-health status of fish communities 135-number	-number
550 362 439	D	**availability of food and income for local communities/food security**	550-Reduced fish populations 439-environmental degradation	550-Trophic Position Units Inference: May need to be inferred from ecological studies. Species Diversity

				Units: Count (number of species). Stable Isotope Ratios: Units: δ13C and δ15N (per mil, ‰).
796	**D**	**Access to Traditional Food Sources: Reflects stress on dietary practices**	796-environmental degradation	
446	**D**	**loss of access to traditional land use and resources**		
3-LON-TERM LIVELIHOOD				
618	**D**	**long-term housing insecurity**		
321	**D**	**Increased poverty**		$
611 253 545	**D**	**Long-term employment rate and increased unemployment**		NUMBER, %
4-CHRONIC HEALTH AND MENTAL ISSUES				
440	**D**	**Changes in Dietary Patterns**		
502	**D**	**Long-term psychological effects**		
445	**D**	**Emotional trauma related to perceived threats to salmon health**		
252	**D**	**Public health outcomes linked to contamination events**		
584	**D**	**health risks from heavy metal (HM) exposure.**	Disability-Adjusted Life Years (DALY),Measured for As (Arsenic), Cd (Cadmium), and Pb (Lead) immediately post-failure	
589,600,71, 215,162	**D**	**long-term health impacts**	71- displacement and loss of life 215-WATER CONTAMINATION 162-derived from toxic element exposure	number
134	**I from : long-term health impacts, Changes in Dietary Patterns , Long-term psychological effects**	**Changes in social well-being scales**		number
5-SECONDARY IMPACTS FROM ENV AND ECONOMIC IMPACTS				
732	**D**	**waterborne diseases due to contaminated water sources and fish**	The prevalence of stagnant water as vectors for disease spread	
434	**D**	**Health problems arising from tailings exposure.**	-WATER QUALITY -Disability-Adjusted Life Years (DALY), -Measured for As (Arsenic), Cd (Cadmium), and Pb (Lead) immediately post-failure -Loss of access to clean water resources - exposure to toxic metals (Aluminum, Arsenic, Mercury, Nickel).	-number -cases per population -PEOPLE NUMBER

			-Blood metal concentrations of toxic elements (Al, As, Hg, Ni) in participants' blood samples, -Dietary habits and sources of water as factors contributing to exposure risks, -Source of food (e.g., seafood consumption linked to metal exposure). -Water source as a potential source of contamination, -Community demographics and lifestyle. Previous health status linked to exposure. -Aluminum (Al), Arsenic (As), Cadmium (Cd), Cobalt (Co), Copper (Cu), Mercury (Hg), Manganese (Mn), Nickel (Ni), Lead (Pb), Selenium (Se), and Zinc (Zn) ,smoking habits, -Health conditions reported by participants: Mental disorders, malaise, skin lesions, gastrointestinal disorders, and bone diseases were documented.	
789 7	**D**	**.health issues from pollution exposure**	7- Loss of access to clean water resources	
657,133	**D**	**Public health risks linked to contaminated water sources previously used for drinking**		
568	**D**	**Potential health implications for local populations due to contaminated water and soil.**		cases per population
315	**D**	**Health risks: Accumulation of metals in the human body.**		
361	**D**	**Impacts on community health related to environmental degradation**		number
447	**D**	**health risks associated with the contamination of water and fish,**		
464 151 466	**D**	**Humanistic Ecological Environment**		
(Shandro 2017)	**D**	**Difficult access to safe water due to deterioration of water quality**		
Fundao damfailure, LACTAC report	**D**	**LOSS OF CULTURAL ASSETS index**		

3- Environmental Impact Indicators:

Indicator no	Direct or Indirect	indicator name	Subcategory (how the indicator can be calculated or due to)	unit
Short term (up to 5 years)				
1-GEOLOGY				
1-1-SOIL AND SEDIMENT INDEX				
240 209 567 461	D	**Contamination of soils and sediments**	209-Iron,Arsenic,Mercury 567-Measurements of elements like Iron (Fe), Aluminum (Al), and Manganese (Mn) in water, sediment, and soil samples.Concentrations of heavy metals and minerals in sediment and soil samples downstream of the dam failure.	240-(mg/kg) 209-mg/kg ; ug/l 567-water conc(micrograms per liter), sediment and soil conc. (%)
91,210	D	**sediment quality**	91-(e.g., turbidity and sediment load). 210-rate of waste discharge,Fe, As, Hg	91-mg/L 210-mg/kg ; ug/l
236	D	**sediment toxicity**		
67,350	D	**Metals and Arsenic Concentration in sediment**		mg/kg 350-mg/kg
208	D	**Suspended Sediment Loads**		mg/kg ; ug/l
82	D	**Injuries to sediments, watercourse opacity, and oxygenation**	$ per m3 of tailings released	
205	D	**Alterations in bottom sediments**		µg/L or mg/L
259 588	D	**soil contamination levels**		(mg/kg)
104,88	D	**SEDIMENT Metal Concentrations: Measured in dissolved,**	Chromium (Cr), Nickel (Ni), Cadmium (Cd), and Mercury (Hg)	(mg-kg)
378	D	**Channel erosion and sediment yield.**	Flood Frequency: Events per specified time.	channel erosion (meters), sediment yeild (percentage)
147,461	D	**Soil environment change**		
312	D	**sediment contamination**	-Fine sand, coarse sand, very fine sand, manganese (Mn), and iron (Fe) fractions. -Distance from B1 dam: Used to understand the spread and distribution of tailings. -Redox potential: Influencing the release of metals like manganese. -Hydraulic features: Such as the presence of the Igarapé -thermoelectric plant weir, which acts as a barrier to tailings migration. -Historical mining activities and agricultural practices	Chlorophyll-a: mg/L Flow rate: m³/s Total arsenic: mg/L Dissolved manganese: mg/L Total calcium: mg/L Fine sand, coarse sand, very fine sand: g/kg Mn, Fe fractions: mg/kg NDVI: Index value (normalizednormalized)
428	D	**Suppressed stocks in the mud passage and deposition areas (MPDA)**		
765	D	**Magnitude of mud and debris flows**	Peak Outflow Rates: m³/s (cubic meters per second) Flood Volume Released: m³ (cubic meters) Erosion Rate: m/year (meters per year),Rainfall Intensity	
121,338,477	D	**Erosion and sedimentation rates**	338-Volume of dam outwash material released (M m³), Sedimentation depth in impacted water bodies (m)	121-% 338-(M m³)
767	D	**Volume of sediment mobilized into nearby water bodies**	Peak Outflow Rates: m³/s (cubic meters per second) Flood Volume Released: m³ (cubic meters) Erosion Rate: m/year (meters per year),Rainfall Intensity	
697	D	**sedimentation,**		
57,61,265,492, 529,695,708,75 0,808	D	**Soil erosion impact**	750-Peak discharge (m3/s) Flow depths (m) Flow velocities (m/s) Depth-velocity product (m2/s)	57,61-M2 265-meters/year 529-m/y, 695-meters per year

			Inundation extent (mapped) Tailings deposition extent (m)	
66,136,503,553 ,751,379	**D**	**sediment displacement**	751-Peak discharge (m3/s) Flow depths (m) Flow velocities (m/s) Depth-velocity product (m2/s) Inundation extent (mapped) Tailings deposition extent (m)	M2
427	**D**	**sediment dynamics in the landscape**	427-Hydraulic parameters including flow, stage, shear stress, stream power. Peak discharge value (13,000 m³/s) ,Historical context of sediment connectivity before the dam failure, considering landform changes and sediment deposition patterns.Morphometric analysis of landforms, including gravel bars, sand beds, and plunge pools.Sediment source and yield relationships, historical patterns of sediment connectivity, and effects on underlying geological structures.	427-PEAK FLOW M^3/S, FLOW DEPTH (METRES), flow velocity (m/s), bedrock channel erosion depth (m), plunge pool area (m^2), sediment volume (m^30, sediment deposit thickness (cm)
777	**D**	**changes in creek flow characteristics, sediment entrainment, and debris flow dynamics.**		
372	**D**	**changes in sediment dynamics in coastal marine environments**	Suspended Particulate Matter (SPM) Concentration,Changes in sediment grain size, Sediment Bulk Density,Local wind and wave conditions affecting sediment dispersal mechanisms.Turbidity	PEAK FLOW M^3/S, FLOW DEPTH (METRES), flow velocity (m/s), bedrock channel erosion depth (m), plunge pool area (m^2), sediment volume (m^30, sediment deposit thickness (cm)
86 516	**I from contamination of sediment and soil**	**microbial communities CHANGE**	86-tailings contamination(Heavy Metal Concentrations)	86-(ppm) or milligrams per liter (mg/L 516- Microbial Diversity Indices: Typically measured in indices such as Shannon or Simpson index (normalized).
515	**I from contamination of sediment and soil**	**Bacterial and Archaeal Taxa Abundance**	heavy metal contamination in sediments	%, mg/kg
62	**I from sediment quality, sediment displacement, erosion**	**potential changes in river geometry**		
83	**I from sediment quality, sediment displacement, erosion**	**Changes in riparian morphology**		
145,176,459	**I from sediment quality, sediment displacement, erosion**	**River Morphology**		176-meter
206	**I from sediment quality, sediment displacement, erosion**	**Changes in fluvial dynamics**		
385,479,752	**I from sediment quality, sediment displacement, erosion**	**geomorphological consequences**		479- erosion potential (m)
768	**I from sediment quality, sediment displacement, erosion**	**Changes in watershed hydrology**		
102,211,373,70 0	**I from sediment quality, sediment displacement, erosion**	**hydrological and geomorphological changes**		
456	**I from sediment quality, sediment displacement, erosion**	**Morphological damage**		
1-2-LAND USE/ LAND COVER INDEX				

1 316 368 403 430 538 520	**D**	**land use and land cover change**	316- river, forest, clear water, agricultural land, built-up areas, grassland, and mine/tailings. 403-Normalized Difference Vegetation Index (NDVI) -Emergy accounting 430-Emergy accounting	1-km^2 316-Area Affected: Hectares (ha) 403-NDVI: Dimensionless index (no explicit units stated). 430-emergy accounting (solar energy), total emergy-based dollar value - acres
705	**D**	**Land destruction due to debris flows**		hectares or acres
329	**D**	**Land degradation**		ha
678,701	**D**	**Negative impacts to wetland systems**		
578	**D**	**Impact on Agricultural Land**	Flood Inundation Depth,Flood Inundation Area	
699	**I from land use /land cover index**	**changes in land development patterns**		

2-ECOLOGY

2-1-BIOCHEMICAL INDEX

517 105 126 340	**D**	**Effects on Biogeochemical Cycles and biology**	517-Changes in microbial communities that could impact organic matter recycling and nutrient cycling 105- Assessed through cytotoxic, genotoxic, 340-Changes in fish populations (e.g., Rainbow Trout) Habitat availability for spawning species, Benthic organism community composition over time Plant test species growth metrics post-incident	105-% 340-number
106	**D**	**mutagenic effects in various organisms and changes in the mitotic index.**		
93	**D**	**loss of genetic variability and biomass reduction**		
273,360,798,547,185,222	**I from ECOLOGY**	**ecological consequences**		185-AREA
455	**I from ECOLOGY**	**Trophic diversity change**		

2-2-FLORA

3 142 156 212 739 472	**D**	**Vegetation loss/mortality**	156-quantitative assessment of vegetation	3-km^2 or % 142-ha 739-Number of species 472-number
764,77	**D**	**Changes to riparian vegetation**		ha
148, 42, 462	**D**	**Vegetation Cover change**		M2
481	**D**	**Plant Biomass Loss (PB)**	Plant Height, Timing of Flood, and Other Factors ,Flood depth, velocity, and duration,Flood timing	plant biomass loss (kg/ha)

313	**D**	**the vigor of riparian forests**	<Normalized Difference Vegetation Index (NDVI). Distance from B1 dam: Used to understand the spread and distribution of tailings. Redox potential: Influencing the release of metals like manganese. Hydraulic features: Such as the presence of the Igarapé thermoelectric plant weir, which acts as a barrier to tailings migration.	Chlorophyll-a: mg/L Flow rate: m³/s Total arsenic: mg/L Dissolved manganese: mg/L Total calcium: mg/L Fine sand, coarse sand, very fine sand: g/kg Mn, Fe fractions: mg/kg NDVI: Index value (normalized)
101	**D**	**Impact on plantations**		
2-3-FAUNA				
2-3-1-TERRESTRIAL FAUNA				
739	**D**	**Terrestrial fauna loss**	739- Immediate impact on wildlife, such as crocodiles, hippos, and fish due to water changes. Water flow and volume (cubic meters)	739- NUMBER OF species
28 286 271 116 694 583	**D**	**Wildlife habitat loss**		Number 694-hectars
643	**D**	**Loss or deterioration of habitats, specifically for species listed as blue-listed or red-listed**		number
58	**D**	**Terrestrial ecosystem impact index**	Pollution	
35 115 141 226 330 394 482 807 92 275 521 548 149 463 535 551 598	**D**	**Biodiversity loss**	141-<Assessments of species richness and population stability 482-Species Richness, Survival Time of Animals, and Other Factors ,Flood depth, velocity, and duration,Migration ability of animals 274-Changes in species composition and diversity due to environmental disturbances 521- due to flooding 524-Measurements of diversity indices (e.g., Shannon-Wiener diversity index). Environmental Quality Parameters: Evaluation of affected water and habitat characteristics impacting fish health and populations.,Long-term changes in ecosystem health	Number 482-species richness (count)
84	**D**	**Changes in the wildlife food chain**		
603	**D**	**Changes in local wildlife populations**		
245	**D**	**Disruption of ecosystems and habitats**		
75	**D**	**Terrestrial wildlife impact**		COUNTS,Estimates for recovery times for injured species and ecosystems
754	**D**	**Changes in habitat quality**		
127	**D**	**cumulative effects on species**		number
186, 563	**D**	**habitat destruction**		number

622 625 685 817 707				
97	**D**	**Genetic diversity indices (number of alleles, allelic richness, observed and expected heterozygosity)**	(number of alleles, allelic richness, observed and expected heterozygosity)Inbreeding coefficient (Fis) M-ratio (indicator of population bottlenecks) Population differentiation (Jost's D index) Genetic structure (STRUCTURE and DAPC analyses)	COUNT AND RATIO
76	**D**	**Birds**		COUNTS,Estimates for recovery times for injured species and ecosystems
2-3-2-AQUATIC FAUNA				
74	**D**	**Aquatic fauna loss**		COUNTS,Estimates for recovery times for injured species and ecosystems
635	**D**	**temporary loss of fish habitats**		
127	**D**	**cumulative effects on species**		number
90	**D**	**Histopathological damage in aquatic organisms,**	metal bioaccumulation.((disease prevalence, tissue damage)	
337	**D**	**marine benthic macrofauna affected by the tailings mud**	337-Iron Mineralogical Set (IMS) Index, Species Abundance, Richness, and Diversity,Sediment Characteristics: Such as grain size and composition, which influence macrofauna composition. Concentration of Metal(oid)s: Observed with the presence of contaminants (V, Al, Ba, etc.) from the tailings mud. IMS Index: Used to trace the presence of Fundão dam tailings mud. Sediment Variables: Including granulometry (average grain size), total organic matter (TOM), total organic carbon (TOC), total nitrogen (TN), and calcium carbonate ($CaCO_3$). Metal(oid)s Concentrations: Including iron (Fe), aluminum (Al), manganese (Mn), arsenic (As), silver (Ag), barium (Ba), cadmium (Cd), cobalt (Co), chromium (Cr), copper (Cu), nickel (Ni), lead (Pb), and vanadium (V). Organic Pollutants: Including DDTs, PCBs, PAHs, and sterols.	
452 453 14	**D**	**Ecotoxicological impacts on fish health**	452-DNA damage Lipid peroxidation (LPO) Protein carbonyls (PCO) Histological damage in gills and liver Metallothioneins concentration Activity of superoxide dismutase, Seasonal variations in metal concentrations in the water and sediments Trophic levels of fish communities Environmental conditions (rainy vs. dry seasons),Integrated Biomarker Response (IBR) index Integrated Metal Bioaccumulation (IMB) index,Changes in community structure (e.g., microbial community) Changes in zooplankton diversity 453-heavy metal concentration 14-due to increased turbidity and contamination by heavy metals.	Heavy Metal Concentrations: mg/kg Lipid Peroxidation: nmol/mg protein DNA damage: quantified through comet assays or similar measures (exact units not specified) Other biochemical indicators: often expressed as activity units (e.g., U/mg protein)
679, 652,85	**D**	**Potential mortality of mussel and fish populations**	652-Growth and survival rates of aquatic organisms like freshwater scuds and mayfly larvae, Changes in food web dynamics due to the decline in populations of key species	85-number
457,799	**D**	**health status of fish communities**	457-physiological alterations due to metal exposure and seasonal variations in bioaccumulation.	

			799-esions and other indicators of contamination.	
753	**D**	**loss or deterioration of critical fish or wildlife habitat**		
125,171,349,375,411,	**D**	**Changes in fish populations**		number
357	**D**	**macrobenthic crustacean diversity and abundance**	Species Richness: Number of different species recorded. Species Abundance: Total number of individuals observed within a species. Environmental Variables: Parameters such as turbidity and pH levels that are directly correlated to species composition. species richness (number), abundance(no. of individuals), shannon wiener index (no dimension), turbidity (NTU), ph , temperature, salinity	
59 546 637 279 725	**D**	**Aquatic ecosystem impact**	59-POLUTION 546-changes in fish populations:trophic structure of fish communities,Habitat Alteration,Changes in water quality and habitat structure 279-Measures such as fish populations and plant health 725-Flood wave height: Measurement of flood intensity (e.g., maximum height of flood waves). Inundation area: Geographic area inundated by flood waters.,Flow progression over time,Water depth and extent of flooding,Water depth and extent of flooding,Time of wave arrival at key cities	546-Trophic Position Units: Not explicitly stated in the summary. Inference: May need to be inferred from ecological studies. Species Diversity Units: Count (number of species). Stable Isotope Ratios: Units: δ13C and δ15N (per mil, ‰). 725-Flood Wave Height: Meters (m). Inundation Area: Square kilometers (km²). Initial Lake Level: Meters (m)
65	**D**	**CHANGE aquatic ecosystems (freshwater, marine, and coastal)**	HEAVY METAL AND arsenic INCREASE	
2-4-WATER				
2-4-1- WATER QUALITY INDEX				
26 2 56 94 108 113 117 187 193 204 225 269 272 311 328 343 358 401 451 467 468 504 528 537 552	**D**	**Water quality degradation**	94- turbidity, -CONTAMINTATION 108-suspended particulate matter (SPM), 113A-lkalinity -Conductivity -Chloride content, -Total phosphorus -Total solids -Biochemical oxygen demand (BOD) -Escherichia coli -Nitrate -Ph 117-HEAVY METAL 187- pollutant levels and sedimentation 193- alterations in solids, metals, and metalloids' concentration,water pH levels ,204- solids, metals, metalloids 225- pollutant concentration 272- due to increased pH, metal concentrations(As, Ba, Cd, Cr, Cu, Fe, Mn, Ni, Pb, Zn) and turbidity,suspended solids, and electrical conductivity,Coliform levels,Factors associated with anthropogenic influences ,dissolved oxygen	2,108-NTU 94- mg/L 113-conductivity (uS/cm, micrisiemmens per cm), -pH (ph units), -dissolved oxygen (mg/l) -mg/L -us/cm mg/l) - µg/L or mg/L -mg/kg ; ug/l pH: no units 117,187- mg/l 193-204,- µg/L or mg/L 272- mg/L pH: no units Electrical conductivity: µS/cm (inferred) Turbidity: NTU Total suspended solids: mg/L

573 579 339 626 653 706 744 783 792 800 804 111			311- Chlorophyll-a, flow rate, total arsenic, dissolved manganese, and total calcium. Distance from B1 dam: Used to understand the spread and distribution of tailings. Redox potential: Influencing the release of metals like manganese. Hydraulic features: Such as the presence of the Igarapé thermoelectric plant weir, which acts as a barrier to tailings migration. Historical mining activities and agricultural practices 343- Comparison of pre- and post-event turbidity levels (NTU), Plankton community structure metrics,copper levels, turbidity) Fish mortality rates 401- Suspended Particulate Matter (SPM): mg/L 451- Water turbidity (measured in NTU) Iron levels (measured in µg/L or mg/L) Mortality rates of zebrafish embryos (expressed as percentages),Microbial colony-forming units (CFU) Rates of potential pathogenic microbial growth Dissolved Metals: Concentrations of metals like iron and mercury were measured, with iron levels increasing significantly downstream. Microbial Abundance: 467- Flood Velocity: Calculated through numerical simulations. Flood Depth: Obtained from simulations,COD(Chemical Oxygen Demand), TP(Total Phosphorus), TN(Total Nitrogen), and pH levels in monitoring sites,Pollutant Concentration 468- Flood Duration,Velocity Changes 528- pH, turbidity 537- turbidity, chemical pollutants 573- turbidity, pH, total dissolved solids, and dissolved oxygen, metal concentration 653-Concentrations of heavy metals ,Toxicity levels of copper 339- Metal concentrations in various media (mg/L or µg/L) Toxicity testing results on sediment and water (general toxicity scale) 744&783- Extent of pollutant dispersion downstream 792- concentrations of metals like manganese,aluminum, phosphorus,Chlorophyll-a, flow rate, total arsenic, and total calcium. Sediment Quality Indicators: Fine sand, coarse sand, very fine sand, manganese (Mn), and iron (Fe) fractions. and changes in the riparian vegetation index (NDVI) 111-Chloride Content,	Dissolved oxygen: mg/L Nutrients: mg/L Contamination factor: no units 311- Chlorophyll-a: mg/L Flow rate: m³/s Total arsenic: mg/L Dissolved manganese: mg/L Total calcium: mg/L Fine sand, coarse sand, very fine sand: g/kg Mn, Fe fractions: mg/kg NDVI: Index value (normalized) 343- mg/L for metal concentrations and NTU for turbidity. 451- turbidity (ntu), dissolved metals (mg/l), microbial colony units (cfu/ml), zebrafish mortality (%) 467- H: No unit; dimensionless. COD: mg/L (milligrams per liter). TP (Total Phosphorus): mg/L. TN (Total Nitrogen): mg/L. ,468,537,552,706- mg/L 792- Chlorophyll-a: mg/L Flow rate: m³/s Total arsenic: mg/L Dissolved manganese: mg/L Total calcium: mg/L Fine sand, coarse sand, very fine sand: g/kg Mn, Fe fractions: mg/kg NDVI: Index value (normalized) 111-mg/l)
87,112	**D**	Turbidity		87- NTU
107	**D**	**suspended particulate matter (SPM)**		
109	**D**	**Alkalinity,**		(mg/l)
110	**D**	**Conductivity,**		us/cm
217,353,480,60 1,693,150,114, 636,383,239,64	**D**	**water pollution**	217-Gray Water Footprint (WF) 480-Point Source (PS) and Non-Point Source (NPS) pollution,Flood depth, velocity, and duration 601-Concentration of heavy metals in water (mg/L)	217-cubic mters 480-mg/L 693-ppm for contaminants 114-mg/l, m³ for volume

,599,388,214,1 55,11			114-(e.g., heavy metals in water and sediment), TAILING RELEASE 239-concentrations of toxic metals like As, Cu, Pb, Zn 64-Cd, Cu, Cr, Fe, Hg, Mn, Pb, Zn, and arsenic) 214-Concentration of Toxic Metals 11- km2 155-heavy metals, cyanide concentrations	239&64&388-mg/l 214-mg/kg ; ug/l 155- mg/dm^3
476	**D**	**Maximum Water Surface Elevation**		
351	**D**	**Dissolved oxygen**	milligrams per liter (mg/L)	
408		**Biophysical impacts on the river system**	water quality, freshwater and saltwater biota, fish community analysis, Historical land use data (e.g., deforestation rates) Climate change models ,habitat disruption	
460,146	**D**	**Water Environment**		
246	**D**	**Transboundary migration of effluent in rivers**		
34	**D**	**Contamination of water bodies**		Km2
89	**D**	**Change Water quality parameters (temperature, conductivity, pH, dissolved oxygen)**		water temperatute (degree celsius), electrical conductivity (uS/cm, micrisiemmens per cm), pH (ph units), dissolved oxygen (mg/l) ,
86 516	**I from contamination of water**	**microbial communities CHANGE**	86-tailings contamination(Heavy Metal Concentrations)	86-(ppm) or milligrams per liter (mg/L 516- Microbial Diversity Indices: Typically measured in indices such as Shannon or Simpson index (normalized).
2-4-2-WATER RESOURCE INDEX				
9 326	**D**	**Changes in water resources**		9-km²
169	**D**	**Groundwater damage**	toxic elements	-mg/dm^3
244	**D**	**Subsequent groundwater contamination**		mg/l
3-ENERGY USE AND CARBON GENERATION INDICATORS				
307	**D**	**on-site fuel combustion**	-Specific activities that had a high contribution include demolition and the chemical sector	fossils: kg Sb eq
308	**D**	**purchased electricity**	-Specific activities that had a high contribution include demolition and the chemical sector	$
310	**I from on-site fuel combustion**	**climate change Ozone depletion Human toxicity Acidification Eutrophication Resource depletion metrics**		
4-SECONDARY IMPACTS FROM SOCIAL AND ECONOMIC IMPACTS				
-(Fernandes 2016		**environmental pollution due to no maintenance**	-limited access to and maintenance of fisheries in the affected area	
435		**Physical conversion of land due to population displacement**		

Long term (more than 5 years)				
1-GEOLOGY				
1-1-SOIL AND SEDIMENT				
Indicator no	**Direct or indirect**	**Indicator or index name**	**Subcategory (how the indicator can be calculated or due to)**	**unit**
240 209 567 461	**D**	**Contamination of soils and sediments**	209-Iron,Arsenic,Mercury 567-Measurements of elements like Iron (Fe), Aluminum (Al), and Manganese (Mn) in water, sediment, and soil samples.Concentrations of heavy metals and minerals in sediment and soil samples downstream of the dam failure.	240-(mg/kg) 209-mg/kg ; ug/l 567-water conc(micrograms per liter), sediment and soil conc. (%)
91,210	**D**	**sediment quality**	91-(e.g., turbidity and sediment load). 210-rate of waste discharge,Fe, As, Hg	91-mg/L 210-mg/kg ; ug/l
236	**D**	**sediment toxicity**		
67,350	**D**	**Metals and Arsenic Concentration in sediment**		mg/kg 350-mg/kg
208	**D**	**Suspended Sediment Loads**		mg/kg ; ug/l
82	**D**	**Injuries to sediments, watercourse opacity, and oxygenation**	$ per m3 of tailings released	
205	**D**	**Alterations in bottom sediments**		µg/L or mg/L
259 588	**D**	**soil contamination levels**		(mg/kg)
104	**D**	**SEDIMENT Metal Concentrations: Measured in dissolved,**	Chromium (Cr), Nickel (Ni), Cadmium (Cd), and Mercury (Hg)	(mg-kg)
378	**D**	**Channel erosion and sediment yield.**	Flood Frequency: Events per specified time.	channel erosion (meters), sediment yeild (percentage)
405	**D**	**The toxicity level of mud impacting local communities**		
147,461	**D**	**Soil environment change**		
312	**D**	**sediment contamination**	-Fine sand, coarse sand, very fine sand, manganese (Mn), and iron (Fe) fractions. -Distance from B1 dam: Used to understand the spread and distribution of tailings. -Redox potential: Influencing the release of metals like manganese. -Hydraulic features: Such as the presence of the Igarapé -thermoelectric plant weir, which acts as a barrier to tailings migration. -Historical mining activities and agricultural practices	Chlorophyll-a: mg/L Flow rate: m^3/s Total arsenic: mg/L Dissolved manganese: mg/L alcium: mg/L Fine sand, coarse sand, very fine sand: g/kg Mn, Fe fractions: mg/kg NDVI: Index value (normalized)
428	**D**	**Suppressed stocks in the mud passage and deposition areas (MPDA)**		
765	**D**	**Magnitude of mud and debris flows**	Peak Outflow Rates: m^3/s (cubic meters per second) Flood Volume Released: m^3 (cubic meters) Erosion Rate: m/year (meters per year),Rainfall Intensity	
121,338,477	**D**	**Erosion and sedimentation rates**	338-Volume of dam outwash material released (M m^3), Sedimentation depth in impacted water bodies (m)	121-% 338-(M m^3)
767	**D**	**Volume of sediment mobilized into nearby water bodies**	Peak Outflow Rates: m^3/s (cubic meters per second) Flood Volume Released: m^3 (cubic meters) Erosion Rate: m/year (meters per year),Rainfall Intensity	
697	**D**	**sedimentation,**		
57,61,265,492, 529,695,708,75 0,808	**D**	**Soil erosion impact**	750-Peak discharge (m3/s) Flow depths (m) Flow velocities (m/s) Depth-velocity product (m2/s) Inundation extent (mapped) Tailings deposition extent (m)	57,61-M2 265-meters/year 529-m/y, 695-meters per year

66,136,503,553,751,379	**D**	**sediment displacement**	751-Peak discharge (m3/s) Flow depths (m) Flow velocities (m/s) Depth-velocity product (m2/s) Inundation extent (mapped) Tailings deposition extent (m)	M2
427	**D**	**sediment dynamics in the landscape**	427-Hydraulic parameters including flow, stage, shear stress, stream power. Peak discharge value (13,000 m³/s) ,Historical context of sediment connectivity before the dam failure, considering landform changes and sediment deposition patterns.Morphometric analysis of landforms, including gravel bars, sand beds, and plunge pools.Sediment source and yield relationships, historical patterns of sediment connectivity, and effects on underlying geological structures.	427-PEAK FLOW M^3/S, FLOW DEPTH (METRES), flow velocity (m/s), bedrock channel erosion depth (m), plunge pool area (m^2), sediment volume (m^30, sediment deposit thickness (cm)
777	**D**	**changes in creek flow characteristics, sediment entrainment, and debris flow dynamics.**		
372	**D**	**changes in sediment dynamics in coastal marine environments**	Suspended Particulate Matter (SPM) Concentration,Changes in sediment grain size, Sediment Bulk Density,Local wind and wave conditions affecting sediment dispersal mechanisms.Turbidity	PEAK FLOW M^3/S, FLOW DEPTH (METRES), flow velocity (m/s), bedrock channel erosion depth (m), plunge pool area (m^2), sediment volume (m^30, sediment deposit thickness (cm)
213		**LONG TERM potential for enhanced erosion and remobilization of contaminated particles due to heavy rainfall**		mg/kg ; ug/l
62	**I from sediment quality, sediment displacement, erosion**	**potential changes in river geometry**		
83	**I from sediment quality, sediment displacement, erosion**	**Changes in riparian morphology**		
145,176,459	**I from sediment quality, sediment displacement, erosion**	**River Morphology**		176-meter
206	**I from sediment quality, sediment displacement, erosion**	**Changes in fluvial dynamics**		
385,479,752	**I from sediment quality, sediment displacement, erosion**	**geomorphological consequences**		479- erosion potential (m)
768	**I from sediment quality, sediment displacement, erosion**	**Changes in watershed hydrology**		

102,211,373,700	I from sediment quality, sediment displacement, erosion	**hydrological and geomorphological changes**		
456	I from sediment quality, sediment displacement, erosion	**Morphological damage**		
86 516	I from contamination of sediment and soil	**microbial communities CHANGE**	86-tailings contamination(Heavy Metal Concentrations)	86-(ppm) or milligrams per liter (mg/L 516- Microbial Diversity Indices: Typically measured in indices such as Shannon or Simpson index (normalized).
515	I from contamination of sediment and soil	**Bacterial and Archaeal Taxa Abundance**	heavy metal contamination in sediments	%, mg/kg
570	I from changes in sediment dynamics, sediment displacement, erosion	**Long-term Geochemical Changes**		
1-2-LAND USE/ LAND COVER				
1 316 368 403 430 538 520	D	**land use and land cover change**	316- river, forest, clear water, agricultural land, built-up areas, grassland, and mine/tailings. 403-Normalized Difference Vegetation Index (NDVI) -Emergy accounting 430-Emergy accounting	1-km^2 316-Area Affected: Hectares (ha) 403-NDVI: Dimensionless index (no explicit units stated). 430-emergy accounting (solar energy), total emergy-based dollar value - acres
705	D	**Land destruction due to debris flows**		hectares or acres
329	D	**Land degradation**		ha
678,701	D	**Negative impacts to wetland systems**		
578	D	**Impact on Agricultural Land**	Flood Inundation Depth,Flood Inundation Area	
699	I from land use /land cover index	**changes in land development patterns**		
2-ECOLOGY				
2-1-BIOCHEMICAL				
517 105 126 340	D	**Effects on Biogeochemical Cycles and biology**	517-Changes in microbial communities that could impact organic matter recycling and nutrient cycling 105- Assessed through cytotoxic, genotoxic, 340-Changes in fish populations (e.g., Rainbow Trout) Habitat availability for spawning species, Benthic organism community composition over time Plant test species growth metrics post-incident	105-% 340-number

106	**D**	**mutagenic effects in various organisms and changes in the mitotic index.**		
93	**D**	**loss of genetic variability and biomass reduction**		
273,360,798,547,185,222	**I from ECOLOGY**	**ecological consequences**		185-AREA
455	**I from ECOLOGY**	**Trophic diversity change**		
2-2-FLORA				
3 142 156 212 739 472	D	**Vegetation loss/mortality**	156-quantitative assessment of vegetation	3-km^2 or % 142-ha 739-Number of species 472-number
148, 42, 462	D	**Vegetation Cover change**		M2
481	D	**Plant Biomass Loss (PB)**	Plant Height, Timing of Flood, and Other Factors ,Flood depth, velocity, and duration,Flood timing	plant biomass loss (kg/ha)
764,77	**D**	**Changes to riparian vegetation**		ha
313	**D**	**the vigor of riparian forests**	<Normalized Difference Vegetation Index (NDVI). Distance from B1 dam: Used to understand the spread and distribution of tailings. Redox potential: Influencing the release of metals like manganese. Hydraulic features: Such as the presence of the Igarapé thermoelectric plant weir, which acts as a barrier to tailings migration.	Chlorophyll-a: mg/L Flow rate: m^3/s Total arsenic: mg/L Dissolved manganese: mg/L Total calcium: mg/L Fine sand, coarse sand, very fine sand: g/kg Mn, Fe fractions: mg/kg NDVI: Index value (normalized)
101	**D**	**Impact on plantations**		
2-3-FAUNA				
2-3-1-TERRESTRIAL FAUNA				
739	**D**	**Terrestrial fauna loss**	739- Immediate impact on wildlife, such as crocodiles, hippos, and fish due to water changes. Water flow and volume (cubic meters)	739- NUMBER OF species
28 286 271 116 694 583	**D**	**Wildlife habitat loss**		Number 694-hectars
643	**D**	**Loss or deterioration of habitats, specifically for species listed as blue-listed or red-listed**		number
35 115 141 226 330 394 482 807 92 275 521 548 149 463 535 551	**D**	**Biodiversity loss**	141-<Assessments of species richness and population stability 482-Species Richness, Survival Time of Animals, and Other Factors ,Flood depth, velocity, and duration,Migration ability of animals 274-Changes in species composition and diversity due to environmental disturbances 521- due to flooding 524-Measurements of diversity indices (e.g., Shannon-Wiener diversity index). Environmental Quality Parameters: Evaluation of affected water and habitat characteristics impacting fish health and populations.,Long-term changes in ecosystem health	Number 482-species richness (count)

598 181				
84	D	**Changes in the wildlife food chain**		
603	D	**Changes in local wildlife populations**		
245	D	**Disruption of ecosystems and habitats**		
514		**Long-term degradation of ecosystems and loss of biodiversity.**		
75	D	**Terrestrial wildlife impact**		COUNTS,Estimates for recovery times for injured species and ecosystems
754	D	**Changes in habitat quality**		
127	D	**cumulative effects on species**		number
186, 563 622 625 685 817 707	D	**habitat destruction**		number
97	D	**Genetic diversity indices (number of alleles, allelic richness, observed and expected heterozygosity)**	(number of alleles, allelic richness, observed and expected heterozygosity)Inbreeding coefficient (Fis) M-ratio (indicator of population bottlenecks) Population differentiation (Jost's D index) Genetic structure (STRUCTURE and DAPC analyses)	COUNT AND RATIO
58	D	**Terrestrial ecosystem impact index**	Pollution	
76	D	**Birds**		COUNTS,Estimates for recovery times for injured species and ecosystems
490	D	**Long-lasting effects on biodiversity and ecosystem services**		
2-3-2-AQUATIC FAUNA				
74	D	**Aquatic fauna loss**		COUNTS,Estimates for recovery times for injured species and ecosystems
127	D	**cumulative effects on species**		number
90	D	**Histopathological damage in aquatic organisms,**	metal bioaccumulation.((disease prevalence, tissue damage)	
337	D	**marine benthic macrofauna affected by the tailings mud**	337-Iron Mineralogical Set (IMS) Index, Species Abundance, Richness, and Diversity,Sediment Characteristics: Such as grain size and composition, which influence macrofauna composition. Concentration of Metal(oid)s: Observed with the presence of contaminants (V, Al, Ba, etc.) from the tailings mud. IMS Index: Used to trace the presence of Fundão dam tailings mud. Sediment Variables: Including granulometry (average grain size), total organic matter (TOM), total organic carbon (TOC), total nitrogen (TN), and calcium carbonate ($CaCO_3$). Metal(oid)s Concentrations: Including iron (Fe), aluminum (Al), manganese (Mn), arsenic (As), silver (Ag), barium (Ba), cadmium (Cd), cobalt (Co), chromium (Cr), copper (Cu), nickel (Ni), lead (Pb), and vanadium (V). Organic Pollutants: Including DDTs, PCBs, PAHs, and sterols.	
452 453 14	D	**Ecotoxicological impacts on fish health**	452-DNA damage Lipid peroxidation (LPO) Protein carbonyls (PCO) Histological damage in gills and liver Metallothioneins concentration	Heavy Metal Concentrations: mg/kg Lipid Peroxidation: nmol/mg protein

			Activity of superoxide dismutase, Seasonal variations in metal concentrations in the water and sediments Trophic levels of fish communities Environmental conditions (rainy vs. dry seasons),Integrated Biomarker Response (IBR) index Integrated Metal Bioaccumulation (IMB) index,Changes in community structure (e.g., microbial community) Changes in zooplankton diversity 453-heavy metal concentration 14-due to increased turbidity and contamination by heavy metals.	DNA damage: quantified through comet assays or similar measures (exact units not specified) Other biochemical indicators: often expressed as activity units (e.g., U/mg protein)
679, 652	**D**	**Potential mortality of mussel and fish populations**	652-Growth and survival rates of aquatic organisms like freshwater scuds and mayfly larvae, Changes in food web dynamics due to the decline in populations of key species	
457,799	**D**	**health status of fish communities**	457-physiological alterations due to metal exposure and seasonal variations in bioaccumulation. 799-esions and other indicators of contamination.	
753	**D**	**loss or deterioration of critical fish or wildlife habitat**		
125,171,349,375,411,	**D**	**Changes in fish populations**		number
464,680,624	**D**	**Impact on fisheries**		
357	**D**	**macrobenthic crustacean diversity and abundance**	Species Richness: Number of different species recorded. Species Abundance: Total number of individuals observed within a species. Environmental Variables: Parameters such as turbidity and pH levels that are directly correlated to species composition. species richness (number), abundance(no. of individuals), shannon wiener index (no dimension), turbidity (NTU), ph , temperature, salinity	
59 546 637 279 725	**D**	**Aquatic ecosystem impact**	59-POLUTION 546-changes in fish populations:trophic structure of fish communities,Habitat Alteration,Changes in water quality and habitat structure 279-Measures such as fish populations and plant health 725-Flood wave height: Measurement of flood intensity (e.g., maximum height of flood waves). Inundation area: Geographic area inundated by flood waters.,Flow progression over time,Water depth and extent of flooding,Water depth and extent of flooding,Time of wave arrival at key cities	546-Trophic Position Units: Not explicitly stated in the summary. Inference: May need to be inferred from ecological studies. Species Diversity Units: Count (number of species). Stable Isotope Ratios: Units: δ13C and δ15N (per mil, ‰). 725-Flood Wave Height: Meters (m). Inundation Area: Square kilometers (km²). Initial Lake Level: Meters (m)
65	**D**	**CHANGE aquatic ecosystems (freshwater, marine, and coastal)**	HEAVY METAL AND arsenic INCREASE	
2-4-WATER				
2-4-1- WATER QUALITY				
26 2 56 94 108 113 117 187 193	**D**	**Water quality degradation**	94- turbidity, -CONTAMINTATION 108-suspended particulate matter (SPM), 113A-lkalinity -Conductivity -Chloride content, -Total phosphorus -Total solids -Biochemical oxygen demand (BOD) -Escherichia coli	2,108-NTU 94- mg/L 113-conductivity (uS/cm, micrisiemmens per cm), -pH (ph units), -dissolved oxygen (mg/l) -mg/L -us/cm

204 225 269 272 311 328 343 358 401 451 467 468 504 528 537 552 573 579 339 626 653 706 744 783 792 800 804 111			-Nitrate -Ph 117-HEAVY METAL 187- pollutant levels and sedimentation 193- alterations in solids, metals, and metalloids' concentration,water pH levels ,204- solids, metals, metalloids 225- pollutant concentration 272- due to increased pH, metal concentrations(As, Ba, Cd, Cr, Cu, Fe, Mn, Ni, Pb, Zn) and turbidity,suspended solids, and electrical conductivity,Coliform levels,Factors associated with anthropogenic influences ,dissolved oxygen 311- Chlorophyll-a, flow rate, total arsenic, dissolved manganese, and total calcium. Distance from B1 dam: Used to understand the spread and distribution of tailings. Redox potential: Influencing the release of metals like manganese. Hydraulic features: Such as the presence of the Igarapé thermoelectric plant weir, which acts as a barrier to tailings migration. Historical mining activities and agricultural practices 343- Comparison of pre- and post-event turbidity levels (NTU), Plankton community structure metrics,copper levels, turbidity) Fish mortality rates 401- Suspended Particulate Matter (SPM): mg/L 451- Water turbidity (measured in NTU) Iron levels (measured in µg/L or mg/L) Mortality rates of zebrafish embryos (expressed as percentages),Microbial colony-forming units (CFU) Rates of potential pathogenic microbial growth Dissolved Metals: Concentrations of metals like iron and mercury were measured, with iron levels increasing significantly downstream. Microbial Abundance: 467- Flood Velocity: Calculated through numerical simulations. Flood Depth: Obtained from simulations,COD(Chemical Oxygen Demand), TP(Total Phosphorus), TN(Total Nitrogen), and pH levels in monitoring sites,Pollutant Concentration 468- Flood Duration,Velocity Changes 528- pH, turbidity 537- turbidity, chemical pollutants 573- turbidity, pH, total dissolved solids, and dissolved oxygen, metal concentration 653-Concentrations of heavy metals ,Toxicity levels of copper 339- Metal concentrations in various media (mg/L or µg/L) Toxicity testing results on sediment and water (general toxicity scale) 744&783- Extent of pollutant dispersion downstream 792- concentrations of metals like manganese,aluminum, phosphorus,Chlorophyll-a, flow rate, total arsenic, and total calcium. Sediment Quality Indicators: Fine sand, coarse sand, very fine sand, manganese (Mn), and iron (Fe) fractions. and	mg/l) - µg/L or mg/L -mg/kg ; ug/l pH: no units 117,187- mg/l 193-204,- µg/L or mg/L 272- mg/L pH: no units Electrical conductivity: µS/cm (inferred) Turbidity: NTU Total suspended solids: mg/L Dissolved oxygen: mg/L Nutrients: mg/L Contamination factor: no units 311- Chlorophyll-a: mg/L Flow rate: m^3/s Total arsenic: mg/L Dissolved manganese: mg/L Total calcium: mg/L Fine sand, coarse sand, very fine sand: g/kg Mn, Fe fractions: mg/kg NDVI: Index value (normalized) 343- mg/L for metal concentrations and NTU for turbidity. 451- turbidity (ntu), dissolved metals (mg/l), microbial colony units (cfu/ml), zebrafish mortality (%) 467- H: No unit; dimensionless. COD: mg/L (milligrams per liter). TP (Total Phosphorus): mg/L. TN (Total Nitrogen): mg/L. ,468,537,552,706- mg/L 792- Chlorophyll-a: mg/L Flow rate: m^3/s Total arsenic: mg/L Dissolved manganese: mg/L Total calcium: mg/L Fine sand, coarse sand, very fine sand: g/kg Mn, Fe fractions: mg/kg NDVI: Index value (normalized) 111-mg/l)

			changes in the riparian vegetation index (NDVI) 111-Chloride Content,	
87,112	**D**	Turbidity		87- NTU
107	**D**	**suspended particulate matter (SPM)**		
109	**D**	**Alkalinity,**		(mg/l)
110	**D**	**Conductivity,**		us/cm
217,353,480,601,693,150,114,636,383,239,64,599,388,214,155,11	**D**	**water pollution**	217-Gray Water Footprint (WF) 480-Point Source (PS) and Non-Point Source (NPS) pollution,Flood depth, velocity, and duration 601-Concentration of heavy metals in water (mg/L) 114-(e.g., heavy metals in water and sediment), TAILING RELEASE 239-concentrations of toxic metals like As, Cu, Pb, Zn 64-Cd, Cu, Cr, Fe, Hg, Mn, Pb, Zn, and arsenic) 214-Concentration of Toxic Metals 11- km2 155-heavy metals, cyanide concentrations	217-cubic mters 480-mg/L 693-ppm for contaminants 114-mg/l, m^3 for volume 239&64&388-mg/l 214-mg/kg ; ug/l 155- mg/dm^3
587	**D**	**Long-term water pollution potential**		
476	**D**	**Maximum Water Surface Elevation**		
351	**D**	**Dissolved oxygen**	milligrams per liter (mg/L)	
460,146	**D**	**Water Environment**		
246	**D**	**Transboundary migration of effluent in rivers**		
34	**D**	**Contamination of water bodies**		Km2
408		**Biophysical impacts on the river system**	water quality, freshwater and saltwater biota, fish community analysis, Historical land use data (e.g., deforestation rates) Climate change models ,habitat disruption	
89	**D**	**Change Water quality parameters (temperature, conductivity, pH, dissolved oxygen)**		water temperatute (degree celsius), electrical conductivity (uS/cm, micrisiemmens per cm), pH (ph units), dissolved oxygen (mg/l) ,
613	**D**	**Prolonged persistent contamination of water sources**		(mg/L)
2-4-2-WATER RESOURCE				
9 326	**D**	**Changes in water resources** **Subsequent groundwater contamination**		9-km²
169	**D**	**Groundwater damage**	toxic elements	-mg/dm^3
244	**D**	**Subsequent groundwater contamination**		mg/l
86 516	**I from contamination of water**	**microbial communities CHANGE**	86-tailings contamination(Heavy Metal Concentrations)	86-(ppm) or milligrams per liter (mg/L 516- Microbial Diversity Indices: Typically measured in indices such as Shannon or Simpson index (normalized).
745 627 227 19 620	**I from ECOLOGY**	**Long term Ecological pattern change**		
717	**I from ECOLOGY**	**Long-term environmental degradation**		
644	**I from ECOLOGY**	**Long-term environmental changes from**		

		the loss of recreational and aesthetic aspects of reservoirs.		
534,526,654,612, 602,763,27,393	**I from ECOLOGY**	**Long-term degradation of local ecosystems**		
SECONDARY IMPACTS FROM SOCIAL AND ECONOMIC IMPACTS				
(Fernandes 2016	**D**	**environmental pollution due to no maintenance**	-limited access to and maintenance of fisheries in the affected area	
435		**Physical conversion of land due to population displacement**		

APPENDIX B

The following table lists the references corresponding to the indicator numbers presented in Appendix A.

Indicator number	Reference	NO
222, 226, 225, 227, 220, 230, 229, 231, 224, 232, 228	(Ji et al. 2021)	1
206, 205, 193, 204, 202, 201, 198, 199, 194, 207, 195, 196, 203, 196, 200	(Guimarães et al. 2023)	2
472, 477, 468, 476, 470, 474, 471, 475, 478	(Yi Xiong 2011)	3
236, 238, 235	(Jumani et al. 2023)	4
273, 274,	(Lines et al. 2023)	5
143,	(Ge et al. 2019)	6
113, 112, 109,110,111	(Santos et al. 2023)	7
60,61,62,63	(EL Bilali et al. 2022b)	8
304,305,306	(Mahmoud, Wang, and Jin 2020)	9
514,506,507,509,510,512,508,511,513	(Ge, Qin, et al. 2020)	10
521,535,529,528,520,534,526,534,527,524,532,525,533,519 523,531,530,522	(Pramono Yakti et al. 2019)	11
368,366,370,369,371	(Peng and Zhang 2012)	12
185,176,186,187,181,173,188,174,175,184,191,192,190,183,182,18 9	(Gu et al. 2020)	13
42,28,35,26,34,27,20,24,21,22,31,45,37,30,36,29,39,25,32,40,41,46 ,48,47,43,44,38,23,33	(Aqilah et al. 2024)	14
233	(Jiao, Li, and Ma 2022)	15
365	(Cavalheiro Paulelli et al. 2023)	16
57,56,49,58,59,53,54,55,52,50	(Azam and Li 2010)	17
216	(Huang et al. 2017)	18
156,171,155,169,160,158,170,166,167,168,162,172,161,163,157,15 9,165,164	(Glotov et al. 2018)	19
3,14,2,11,9,1,19,8,6,16,18,4,5,7,17,15,12,13	(Aires et al. 2018)	20
798,799,800,795,796,794,801,797,803,793,802	(Shandro et al. 2016)	21
271,265,269,260,267,263,264,266,270,268,261,262	(Seema Jagtap 2016)	22
807,817,808,804,806,813,805,815,816,814,810,812,809,811	(Limin Zhang 2016)	23
665,660,659,661,666,667,668,671,672,670,663,662,673,669,670,66 4	(US department of Homeland security 2011)	24
126,142,115,141,116,127,125,127,121,136,117,114,123,138,131,12 9,137,132,135,118,140,133,124,134,128,120,139,130,122	(G. W. Fernandes et al. 2016)	25
567,573,570,571,575,568,572,569,574	(L. S. C. da Silva et al. 2024)	26

643,646,644,640,647,645,649,641,650,651,648,642	(Ministry of Forests 2017)	27
652,653,654,656,658,657,655	(Winston Szeto 2022)	28
330,328,326,329,336,320,332,331,335,324,333,334,321,323,322,325	(Manoah Muchanga and Bretha Mzyece 2023)	29
456,452, 457,453, 458	(C. E. D. Vieira et al. 2022)	30
479,481,482,480	(Zhang et al. 2022)	31
83,77,75,76,85,84,74,82,79,80,78,81,152,154,153	(Czajkowski et al. 2023)	32
718,722,720,721,719	(He et al. 2020)	33
678,679,680,682,683,685,686,687,688,689,690,691,692,693,694,695,696,697,698,699,700, 701	(FEMA 2012)	34
548,546, 550,547	(D. R. de Carvalho et al. 2024)	35
636,637,639,638	(Bonnie Gestring 2021)	36
364	(Cavalheiro Paulelli et al. 2022)	37
427	(Santos-González et al. 2021)	38
384,385,394,388,383,393,390,386,382,392,397,400,399,395,391,387,396,389	(Rana et al. 2022)	39
217,218,219	(Islam and Murakami 2021)	40
677,676,675	(Department of Natural Resources 2018)	41
588,587,584,589,592,586,591,585,590	(Xu et al. 2022)	42
728,729,730,735,734,732,733,731	(ACAPS 2023)	43
752,764,754,753,750,751,763,757,760,759,758,761,756,755,762	(Piésold 2017)	44
105,106,106,104,108,107	(dos Santos Vergilio et al. 2021)	45
579,578,583,582,576,581,580,577	(Winarta, Juwono, and Dermawan 2019)	46
725,723,726,727,724	(Andredakis, Probst, and Annunziato 2016)	47
739,739,744,745,742,743,748,749,736,740,741,737,746,747	(The Institute of Risk Management South Africa 2015)	48
272	(Kütter et al. 2023)	49
492,503,504,494,501,505,495,496,502,498,497,499,500	(Ghimire and Schulenberg 2022)	50

408,417,418,419,420,421,422,423,424,425,426,409,410,411,412,413,414,415,416	(Sánchez et al. 2018)	51
464,459,462,463,461,460	(Wu et al. 2019)	52
537,538,536,541,543,542,539,540,544	(Ge 2021)	53
286,279,277,278,283,291,292,285,281,293,293,294,282,289,290,288,280,284	(McCartney 2009)	54
102,101,99,100,103	(de Oliveira et al. 2022)	55
360,357,358,362,361,359	(Oliveira-Filho et al. 2023)	56
483,484,490,487,485,488,489,486	(G. B. Carvalho and Corteletti 2021)	57
257,245,240,259,239,246,244,245,249,248,252,251,253,255,241,242,247,254,258 ,250, 256	(Kossoff et al. 2014)	58
598,603,599,601,613,612,602,594,608,595,607,610,609,600,611,606,604,597,605	(Garcia et al. 2024)	59
299,300,301,303,302, 783,781,786,785,790,791,789,787,788,784,782	(Lumbroso et al. 2021)	60
war	(Ramirez et al. 2022)	61
340,349,338,350,339,343,351,341,348,342,347,345,344	(Wernick WSP Golder Vancouver and McMahen 2016)	62
768,767,777,765,774,773,779,776,775,780,766,771,770,769,778,772	(Tannant and Skermer 2013)	63
295,298,296,297	(IEEE Staff 2009)	64
276	(Liu 2011)	65
353,352,356,354,355	(Faiqa Norkhairi, Thiruchelvam, and Hasini 2018)	66
622,624,625,635,626,627,621,630,632,631,633,634,628,623,629	(David Morhart 2010)	67
145,151,148,149,147,146,150	(Ge, Li, et al. 2020)	68
450,438,446,437,447,441,443,444,440,445,442,449,98	(Shandro et al. 2017)	69
792,313,312,311,315,314	(Mendes et al. 2023)	70
451	(Thompson et al. 2020)	71
620,617,616,618,614,619	(Gao et al. 2024)	72
467	(Wang and Zhou 2010)	73
66,67,64,65,69,70,71,72,73,68	(Costa et al. 2022)	74
707,708,706,705,717,714,711,716,713,712,703,702,709,704,710,715	(“Testalinden Dam (British Columbia, 2010) _ Case Study _ ASDSO Lessons Learned,” n.d.)	75

402,405,401,403,404,406,407	(Silva Rotta et al. 2020)	76
93,92,97,90,91,94,96,95	(De Biasi et al. 2023)	77
373,375,372,377,376,374	(Quaresma et al. 2020)	78
307,308,309,310	(Martinez et al. 2018)	79
211,212,212,213,208,210,209,214,215	(Hatje et al. 2017)	80
337	(Nascimento et al. 2022)	81
563,551,553,552,562,560,558,565,559,561,566,564,555,554,557,556	(Stamou, Politis, and Xanthopoulou 2005)	82
517,515,516	(L. Fernandes et al. 2022)	83
86,88,89,87	(P. I. N. de Almeida et al. 2023)	84
316,317,319	(Moraga, Gurkan, and Sebnem Duzgun 2020)	85
431,428,430,435,436,433,434,429,432	(Scarpelin et al. 2022)	86
98	(Mahmoody Vanolya and Rukundo 2017)	87
152,153,154	(Ge et al. 2022)	88

APPENDIX C

In this table, the framework features and the Fundão Dam failure indicators are presented. The titles for short-term and long-term environmental, economic, and social categories are highlighted in green rows. The class titles are displayed in blue, while the original dam failure impact framework's indices and indicators are shown in yellow. The Fundão indicators, which follow these titles, are placed in white rows.

Table of all Fundão failure impact indicators adjusted into the framework
(references of this table is table 2 and the Lactec resources referred in methodology section of chapter 3)

Indicator	Baseline	Damage/change	% of change	Score	Normalized value	Index score	Class score	Category score
economic short term								
1-immediate economic loss								
disruption of local businesses index								
loss of agricultural productivity								
the bean, maize and crotalaria productivity		No change	0	1	0	**0**		
property loss and damage								
property destruction/damage								
building damage due to mud contact			43	5	0.444444444	**0.5**	**0.240740741**	
building damage due to reconstruction activity			57	6	0.555555556			
infrastructure loss and damage index								
important facilities affected								
damages in mineral extraction processes	146,226.01 ha	34,174.2 ha	23	3	0.222222222	**0.222222222**		
3-secondary impacts from environment and social impacts								
heritage loss and damage index								
losses related to local cultural assets								
archaeological assets (buried)	1,035,410 m^2	703,947 m^2 buried	68	7	0.666666667			**0.433333333**
archaeological assets (sedimentary layers disturbed) m2	925,494	363,774	39.30592743	4	0.333333333	**0.62962963**		
archaeological assets (began to suffer accelerated degradation of archaeological) m2	77,698	67,727	87.16697985	9	0.888888889			
environmental restoration index							**0.625925926**	
tecnosoil impact g m-2	28.127,70 TON	28.127,70 TON	100	10	1			
digging birds(he diagnosis of damage to wildlife,terrestrial fauna) number	30,327	474 reduction	1.56	1	0	**0.622222222**		
ichtyofauna(fish mortality)	1,687,000	1603000 LOSS	95%	10	1			
native vegetation impact (native)			16	2	0.111111111			

marine area>deposition of waste on the ocean floor(fc)			600	10	1			
economic long term								
5-secondary impacts from environment and social impacts								
long-term environmental damage index								
vegetation impact (25 years)				2	0.5			
tecnosoil impact g m-2(loss discounted c), 85 years	28.127,70 TON	307.710,88 TON		3	1			**0.95**
ichtyofauna (163 years)	1,687,000	10.105.769,16		3	1	**0.9**		
marine area(loss of environmental suitability,) m2	2.051.816.010,93 Weighted :1.882.732.595,20m2= 188.273,26 ha	23.534.157.440,00m2=2.353.415,74 ha	163 years	3	1		**0.95**	
digging birds(he diagnosis of damage to wildlife,terrestrial fauna)(30 years)	30,327 individuals.	2.719,23		3	1			
long term heritage loss and damage index								
archaeological assets,	1.035.410,00+925.494,00+77.698,00	25.783.612,50 m2	no natural recovery	3	1	**1**		
social short term								
1-immediate loss								
Deadths	1.4 milion people affected (baseline report)	19 PEOPLE	0.0013	4	0.75	**0.75**		
loss of cultural assets index								
Impacts on archaeological/cultural sites								
archaeological assets (buried)	1,035,410 m²	703,947 m² buried	68	7	0.666666667			
archaeological assets (sedimentary layers disturbed) m2	925,494	363,774	39.30592743	4	0.333333333			
archaeological assets (began to suffer accelerated degradation of archaeological) m2	77,698	67,727	87.16697985	9	0.888888889			
impacts on traditional land use and resources								
modification of the landscape or context of implementation of material cultural assets	3645	171	4.691358025	1	0			
interruption or transfer of access to and/or use of material cultural property	3645	79	2.167352538	1	0			
alteration of parts or sectors of historical and/or traditional routes and paths	3645	132	3.621399177	1	0	**0.222222222**	**0.486111111**	
shifts in cultural practices								**0.421296296**
change in cultural practices	140	35	25	3	0.222222222			
changing spaces related to cultural practices	140	31	22.14285714	3	0.222222222			
change in the circulation of cultural practices and goods	140	7	5	1	0			
changing the community relations network	140	36	25.71428571	3	0.222222222			
changing memory reference spaces	140	14	10	2	0.111111111			
access to traditional food sources: reflects stress on dietary practices								
change in access to raw materials and associated implements necessary for the production of cultural goods	140	4	2.857142857	1	0			
2-social service								
service supply index								
disruption of water supply								

damage to the use of water for public supply	39 municilalities	18 locations had their supply systems directly rendered temporarily unfeasible	60	6	0.555555556	**0.388888889**	**0.388888889**	
access to clean water and sanitation facility counts								
access to water(people aaffected)	1000000	300000	30	3	0.222222222			
3-health impact and mental issues								
mental issues index								
mental health impacts/issues								
mental disorders hospitalizations		two fold	100	10	1	**0.722222222**		
miners mental health			40.5	5	0.444444444			
social unrest index								
social unrest and turmoil (triggered by panic and loss of life)						**0**		
social suffering	140	9	6.428571429	1	0			
health problems index								
damage to atmosphere(and effect on people)		10times more than standard	900	10	1			
public health outcomes linked to contamination events								
mental disorders disorders due to population exposed to high levels of al, as, hg, and n (people)			60	6	0.555555556		**0.388888889**	
skin lesions disorders due to population exposed to high levels of al, as, hg, and n (people)			38	4	0.333333333	**0.444444444**		
malaise disorders due to population exposed to high levels of al, as, hg, and n (people)			40	4	0.333333333			
gastrointestinal disorders due to population exposed to high levels of al, as, hg, and n (people)			30	3	0.222222222			
bone pain due to population exposed to high levels of al, as, hg, and n (people)			25	3	0.222222222			
social long term								
5-secondary impacts from env and economic impacts								
loss of cultural assets index								**1**
archaeological assets,	1.035.410,00 + 925.494,00 + 77.698,00	25.783.612,50 m2	there is no natural recovery of an archaeological asset.	3	1	**1**	**1**	
env short term								
1-geology								
contamination of soils and sediments index								
contamination of soils and sediments								
aquatic>change in epts concentration in sediments inc1			7.69	8	0.777777778			
aquatic>change in epts concentration in sediments in c2a			30.76	4	0.333333333			
aquatic>change in epts concentration in sediments in c2b			76.92	8	0.777777778			
marin> increase in epts concentration in sediment(estuary of the doce river) al dissolved,as total, fe,, hg,, mn, ni, zn	legislated limits	27.6 times more, 16.4, 1.5,2.2,10,3.3,1.5	>90% change	10	1	**0.648148148**	**0.43**	
marin> increase in epts concentration in sediment marine region al dissolved,as total, fe,, hg,, mn, ni, zn	legislated limits	4.9, 5, 10.6,1.7,,36,,2.9	>90% change	10	1			
soil contamination by epts(ag, al, as, ba, cd,			0	1	0			

co, cr, cu, ni, pb, sb, hg, se, sn and zn,)								
injuries to sediments and sedimetns index								
injuries to sediments, watercourse opacity, and oxygenation								
aquatic>silting of hydroelectric reservoirs			28	3	0.222222222			
aquatic>(damage to sediment quality)change in the benthonic macroinvertebrate community present in the sediment in c1(sum of approximate proportion of minimum values of indicators analyzed in river environment in compartment 1)	41	90	125	10	1			
aquatic>change in the granulometric composition of the sediment in c1 (clay)			3.4+	1	0	**0.277777778**		
aquatic>change in the granulometric composition of the sediment in c2a(clay)			5.2%-	1	0			
aquatic>change in the granulometric composition of the sediment in c2(clay)			9.2%-	1	0			
aquatic>change in the granulometric composition of the sediment in c3(clay)			7.7%-	1	0			
marin> (damage to sediment quality) change in the structure of benthic communities of fish funds unconsolidated			50-	5	0.444444444			
seabed clay content			60%	6	0.555555556			
soil environment change index								
changes in soil permeability and water flow		100 TIMES MORE	9900	10	1			
change in bearing capacity and soil deformability kpa/preconsolidation stress	120	95	20.83333333	3	0.222222222	**0.666666667**		
tecnosoil formation(waste)			75	8	0.777777778			
changes in soil fertility and production potential (water ph)	5.9	6.3	7	7	0.666666667			
erosion and displacement imact index								
soil erosion impact								
increase in erosion processes(soil) t.ha-1 year-1	44.1	54.8	20	2	0.111111111			
sediment displacement								
marin> increase in sediment deposition		6 times greater	>90% change	10	1	**0.666666667**		
sediment dynamics in the landscape								
aquatic>changes in sediment transport dynamics along the doce river			(AVERAGE)856.15%	10	1			
indirect impact from soil and sediment index								**0.48**
damage to underground features	22	14 damaged	60	63.6	6.955555556			
land use/ land cover index								
land use and land cover change								
land use and land cover change(tailing area=33% increase change)			33%	4	0.333333333	**0.365079365**		

land use and land cover change(water resource=8.7% decrease change)			8.70%	1	0			
land use and land cover change(urban area=4.52% decrease change)			4.52%	1	0			
land use and land cover change(disturbed vegetation=81.62% decrease vegetation in the entire rio doce river basin.)			81.62%	9	0.888888889			
land degradation								
damage to protected areas	36 areas	22damaged	61	7	0.666666667			
marin>damage to protected areas	23 areas	16 damged	69	6	0.555555556			
solid waste generation areas	total of APDL= 28,082.34 hectares	3,503 hm² = 3,503 hectares(to be removed)	12.4	2	0.111111111			
2-ecology								
biochemical impact(index)								
mutagenic effects in various organisms and changes in the mitotic index.								
changes in the mitotic index(water)(containing 100% of river water)			30% reduction	3	0.222222222	**0.222222222**		
flora index								
vegetation loss/mortality								
loss of wood forest resources	an average of 154.24 cubic meters of wood per hectare,* 28,082.34 hectares total 4331420.1216m3	120,015.69 m³	2.7	1	0			
vegetation cover change						**0.37037037**		
change in vegetation cover			13.02% reduction	2	0.111111111			
increasing edge effectin c1 (landscape metrics (edge areas and number of fragments)	233	565(number of fragments)	>90% change	10	1			
terrestrial fauna index								
changes in local wildlife populations								
change in bees population			0	1	0			
changes in wildlife populations in (digging bird)(474 loss)	30,327	474	1.562963696	1	0			
disruption of ecosystems and habitats								
loss of connectivity in the landscape(fauna)			15% decrease	2	0.111111111			
terrestrial wildlife impact								
worsening physical conditions of the fauna		(24% fauna poulationshowed ectoparasites)	24%	3	0.222222222	**0.347222222**	**0.427211934**	
impacts on seabird (brown booby) (as)			0	1	0			
impacts on seabird (red-billed tropicbird) (as)		10 times MORE	>90% change	10	1			
impacts on seabird (trindade petrel) (as)		13 times	>90% change	10	1			
changes in habitat quality								
loss of habitat quality (environmental suitability loss)			50	5	0.444444444			
aquatic fauna index								
loss or deterioration of critical fish or wildlife habitat								
changes in the composition and structure of the fish community	137 spieces		50% reduced	5	0.444444444			
increasing the richness and abundance of exotic fishes(number)			90% increase	9	0.888888889	**0.62345679**		
impacts of environmental disasters		47% suitable area impacted	47%	5	0.444444444			

on shrimp species								
change in the phytoplankton community number of speices per station, c1	16	11	31%dropped	4	0.333333333			
change in the phytoplankton community frequency of occurrence of species at the river stations, c1			23%	3	0.222222222			
change in the phytoplankton community frequency of occurrence of species at the river stations, c2a			45%	5	0.444444444			
change in the phytoplankton community frequency of occurrence of species at the river stations, c2b			36%	4	0.333333333			
changes in zooplankton communities in c1(species richness)		60% reduction	6	0.555555556				
changes in zooplankton communities in c1(abundance)			98% reduction	10	1			
changes in zooplankton communities in c2a(number of species,)		14	2	0.111111111				
changes in zooplankton communities in c2b(species richness)		56	6	0.555555556				
changes in zooplankton communities in c2b((abundance)		50	5	0.444444444				
increase in bioaccumulation of ichtyofauna-fish-(cr)		an increase in concentrations up to two times for Cr	100	10	1			
increase in bioaccumulation of ichtyofauna -fish-(cu)		an increase in concentrations up to 38 times for Cu	>90% change	10	1			
increase in bioaccumulation of ichtyofauna -fish-(fe)		an increase in concentrations up to times, 25 times for Fe	>90% change	10	1			
increase in bioaccumulation of ichtyofauna -fish-(mn)		an increase in concentrations up to 10 times for Mn	>90% change	10	1			
increase in bioaccumulation of ichtyofauna -fish-(zn)		an increase in concentrations up to 10 times for Zn	>90% change	10	1			
marin>reduction of the richness and diversity of the ichtyofauna in the marine environment adjacent to the mouth of the doce river(estuarine ichthyofauna richness)	45	25	45.5% reduction	5	0.444444444			
water quality index								
water quality degradation								
marin>increasing solids concentrations in water(the doce river estuary (turbidity)		50 TIMES HIGHER	>90% change	10	1			
increasing solids concentrations in water(turbidity)	historical maximum	2,000 times higher	>90% change	10	1			
increased epts concentrations in water ai, as, cd, pb, cr, hg, mn, dissolved iron	legislated limits	320,10,34,165,57,4.4,9360,107	>90% change	10	1			
marin>increased epts concentration in water(doce river estuary) al dissolved,as total,cd,cr, hg, mn, zn	legislated limits	55,2,8,96,10,51,3	>90% change	10	1	**0.833333333**		
marin>increased epts concentration in water(marine region) al dissolved,as total,cd,cr, hg, mn, zn	legislated limits	2,130,202,5,4410,46,296	>90% change	10	1			
marin spm concentration(mg/l)	100	9000	>90% change	10	1			
suspended particulate matter (spm)(maximum)	23.0 g/m3	38.7 g/m3	68.26	7	0.666666667			

reduction of dissolved oxygen (do) concentrations in water	legislated limits		0	1	0			
water resource index								
change in the drainage area of watercourses(% of subbasin affected)			20%	2	0.111111111			
changes in the configuration of the drainage network of watercourses (geometric elements:width exponent b,depth exponent,velocity exponent)		HIGHEST % OF CHANGE IN ELEMENTS(width exponent changes)	25%	3	0.222222222	**0.166666667**		
env long term								
1-geology								
soil and sediment index								
tecnosoil impact g m-2(loss discounted c),	28.127,70 TON	307.710,88 TON		3	1	**1**	**1**	
2-ecology								
flora index								
vegetation impact				2	0.5	**0.5**		
aqua fauna index								
ichtyofauna	1,687,000	10.105.769,16		3	1	**1**		
marine area(loss of environmental suitability,) m2	2.051.816.010,93 Weighted :1.882.732.595,20m2= 188.273,26 ha	23.534.157.440,00m2=2.353.415,74 ha	163	3	1		**0.833333333**	
terrestrial fauna index								
digging birds(he diagnosis of damage to wildlife,terrestrial fauna)	30,327 individuals.	2.719,23		3	1	**1**		**0.916666667**

The productivity of bean, maize, and crotalaria, extracted from literature (Almeida et al., 2022), was assessed using the Target Hazard Quotient (THQ), which measures the cumulative non-carcinogenic risk to the population. A THQ value greater than 1 indicates a potential risk, suggesting that food consumption may lead to harmful effects. Conversely, a THQ value below 1 signifies an exposure level lower than the reference dose, implying that long-term consumption of the analyzed foods is unlikely to cause adverse health effects (Almeida et al., 2022).

(L. A. DA Silva Junior and Santos 2023) calculated the damages to buildings affected in the area According to their data, 152 buildings were impacted by the failure, some due to direct mud contact and others as a result of reconstruction activities.

The damages in mineral extraction processes indicator, extracted from Lactec report (Lactec 2020b), revealed that 469 mining processes were affected. The majority of these processes were in the research authorization phase (focused on the qualification and quantification of the mineral asset) at the time of the disaster. Regarding the type of substances involved in the mining sectors, most of the affected mining processes were related to the extraction of sand, followed by gold and clay (Lactec 2020b).

Buried archaeological assets impacts are defined as the accumulation of mining waste and other materials deposited on archaeological sites and buildings. In addition to mining waste, the damage includes rocks, soil, vegetation of various sizes, construction debris, household equipment, utensils, and transported movable archaeological artifacts, all of which can impact archaeological buildings. The disturbance of sedimentary layers impact refers to sudden or gradual changes that affect the morphology of archaeological soils and sediments, altering the archaeological matrix of the area. Another major damage related to archaeological assets is the accelerated degradation of archaeological materials. This damage is defined by the interaction of waste, soil, and other mixtures with archaeological remains and structures, whether solidified in floodplains and slopes or diluted in the waters of reservoirs, rivers, and the sea. Acting as a catalyst, these materials expedite the deterioration of preserved evidence. This type of damage was particularly significant in assessing the impact on underwater archaeological assets (Lactec 2020b).

Technosoil, is the waste soil when the waste from the Fundão dam failure stripped away the natural soil layer, 10.75 hm^3 of waste was deposited, forming a tailings layer with an average thickness of 1.04 m, replacing the natural alluvial soils. Regarding the impact of technosoil, the carbon stock (C) in the soil was used as a key metric, measured in tons per hectare, considering a depth of 20 cm. Based on the calculation done by Lactec team, 85 years is needed for the natural recovery of this damaged soil. However, this recovery could be earlier if the external recovery by human positive recovery activities happens (Alkimin De Lacerda 2021). Another short-term economic impact from the environmental damage is the impact on digging birds, which refers to the damage to wildlife and its associated economic consequences. The Trogon surrucura, a bird species widespread throughout this region and endemic to the Atlantic Forest, is also found along the Doce River basin. Lactec team selected this species as an indicator to assess the impacts of the dam failure on local wildlife. The measurement was conducted by considering the population of the species. For the long-term effect, 30 years needed to be considered as a natural recovery of the birds to the baseline level. (Alkimin De Lacerda 2021).

To assess the impacts on the marine area and their economic effects, The Contamination Factor (CF) was used as the metric to assess this impact. The observed increase was found to be up to 42 times greater when compared to the simulated natural deposition over the same period (CF = 42). The ichthyofauna was impacted by 44 hm^3 of mining waste that contained high concentrations of metals, water, and other materials and fish in the affected area died due to asphyxiation caused by an excess of suspended material and a drastic reduction in oxygen levels in the water. This was further corroborated by the exposure, swelling, and collapse of the fish gills found dead. In addition to the high mortality rate from asphyxiation, many fish were also buried. The number of fish affected was selected as the metric for this damage by the Lactec research group. 163 years are needed for natural recovery of fish in the affected area (Alkimin De Lacerda 2021; Lactec 2020a)

It is important to note that, although the Lactec reports include various classes of vegetation, only the impact on native vegetation was extracted since this indicator percentage of change was found. The metric in their study was the number of hectares were affected. The recovery time needed to have the same amount of vegetation in the impacted area is calculated as 25 years by natural recovery. However, Lactec team concluded that external recovery such as human intervention can accelerate the recovery process. (Lactec 2020a; Alkimin De Lacerda 2021; Lactec 2018)

Regarding the impacted people after the dam failure, it is reported that over one million people across 35 cities were impacted by the spill of approximately 50 million m³ of mud waste, leading to 19 fatalities(C. C. Pereira et al. 2024) .

The data used for the archaeological assets is the same as that used in the economic section which is described previously.(Lactec 2020a; Alkimin De Lacerda 2021). Even if a particular structure remains completely intact, the damage of its surrounding environment constitutes damage to cultural property. This results in the loss of part of its communicative, symbolic, and significant value, among other aspects. Therefore, this was considered as an indicator for the modification of the landscape or context of implementation of material cultural assets indicator. The "Alteration of Parts or Sectors of Historical and/or Traditional Routes and Paths" indicator refers to the loss or change of key elements within large structures and infrastructures that connect various human settlements such as towns, farms, sites, cities and other cultural assets. These routes and paths are integral to the experience, understanding, and appreciation of these assets.

The "Interruption or Transfer of Access to and/or Use of Material Cultural Property" indicator highlights when access to cultural assets by society has been disrupted or halted. This may happen if an area needs to be isolated due to ongoing construction, restoration work, or to prevent further damage to that area. A total of 35 assets suffered change in cultural practices, of which 37.1% celebrations, 28.6% expression, 28.6% places and 5.7% crafts, knowledge and ways of doing things. Also, the change in places of cultural practices is another indicator which shows 31 properties were damaged and the impact was considered in the framework.

The community relation network indicator shows the rupture of networks of transmission of knowledge and solidarity between individuals have knowledge related to cultural assets. Changing memory reference spaces focuses on the enjoyment of a given space, the historical continuity of sociocultural processes in those spaces across generations. A total of four assets damaged by the failure and access to traditional food sources was changed, 50% of which were forms of expression and 50% crafts, knowledge and ways of doing things. Water supply systems relying on Gualaxo do Norte, Doce, and Carmo rivers for raw water were shut down, as the existing treatment technologies were unable to produce safe drinking water from these sources and it damaged the access of public to the water supply system and 300000 people were affected(Lactec 2020b; G. W. Fernandes et al. 2016)

Regarding the scores and the impacts of mental health, score of 3.0 is used as the cutoff point for the clinical threshold for identifying individuals who are likely suffering from a common mental disorder based on studies conducted in primary care settings in Brazil. In addition, scores above 2.0 serve as a trigger for the implementation of preventive strategies. 40.5% of miners participated in a survey done after the failure by (Motta and Borges 2021)exceeded the alert score of Brazil, and 17 participants surpassed the cutoff point. Social suffering raised due to damage to the relationships, dissatisfaction with the actions taken by the Renova Foundation, and district about the usage of Doc River. Furthermore, the disorders caused from the failure of Fundão due to the existence of heavy metals such as Al, As, Hg, and N increased. (Cavalheiro Paulelli et al. 2022). Regarding the long-term social impact, the only available data pertains to the damage to archaeological assets, which cannot naturally recover. Additionally, further deterioration and increased damage are expected to occur over the years (Alkimin De Lacerda et al., 2021; Lactec, 2020).

For Potentially Toxic Elements (PTE) concentration in sediments, the available data showed the changes above historical maximum in different regions near the dam and the study includes changes in Al, AS, Ba, Cd, Co, Cr, Cu, Fe, Hg, Mn, Ni, Pb, Zn. The percentage of change was varied for different regions from 7.69% to 76.92%. PTE change in the marine area was calculated in Doce River estuary and marine sector and the changes in Al, AS, Ba, Cd, Co, Cr, Cu, Fe, Hg, Mn, Ni, Pb, Zn were considered. However, PTEs in the soil was not changed according to the reports by Lactec. Several other indicators show the damages to the sediments after the dam failure. The heist change was regarding the change in the benthonic macroinvertebrate community present in the sediment in the aquatic environment. According to the observations by Lactec, significant increase of sediment input was occurred in the studied stations and showing average change of 856.5% for sediment transport dynamics along the Doce river. Also, the data about the marine environment sediment shows 50% change in sediment quality. The indicator used for this part was change in the structure of benthic communities of fish funds unconsolidated. Furthermore, the clay content in the seabed was changed by 60% showing changes in the sediment quality in the marine area. Moreover, to calculate the sediment deposition in the marine area, calculation was performed through mathematical simulations of a hypothetical scenarios, first where the dam failure did not occur, to calculate the area and thickness of deposition naturally and second scenario included the effects of the disaster. The dataset used in the modeling were oceanographic, hydrological and meteorological data for before and after failure periods. The analysis of data showed more than 6 times increased disposition of sediment in the marin area(Lactec, 2020).

The mud wave removed soils, followed by waste deposition, resulting in changes to the soil properties and the failure effected the soil slop stability, permeability and fertility. According to Lactec the most change happened to soil permeability with 100 times change. Also, Inderbitzen, pinhole test, and crumb test were done by Lactec to assess the soil erosion, and it showed 10.7 t.ha-1 year-1 increase of erosion process after dam failure. The formation of a new soil order known as technosoil is another damage to the soil in the failure area. This technosoil contains a

cemented layer or at least 20% artifacts or human-made materials such as the Fe mining waste within the top 100 cm of the soil profile. In this context, technosoil has effectively replaced the original natural topsoil, significantly altering the physical and chemical properties of the soil. For the long-term effect, 85 years needed to be considered as a natural recovery of this effect. (Alkimin De Lacerda, Bastos, and Graf De Miranda 2017; Lactec 2020b; 2020a; Alkimin De Lacerda 2021)
The underground features damages were considered as indirect damage caused from sediment and soil damages in this study. To assess damage to underground features, from 22 sites 14 sites were considered damaged by Lactec. This assessment included cavities and shelters near the Santarém Dam, two former gold mining sites, and five cavities along the Doce River. 3 assets were buried and were damaged significantly. (Alkimin De Lacerda, Bastos, and Graf De Miranda 2017; Lactec 2020b)

the Land Change Modeler (LCM) tool was used for the land use and land cover changes and damages in the areas of municipalities of Mariana and Barra Longa, state of Minas Gerais, Brazil, cover in total area of 1578 km2 by(Aires et al. 2018) showing about 81% change in vegetation cover after dam failure. The protected areas considered for the damage assessment to protected areas after dam failure include Conservation Units (UCs) and other Protected Natural Areas for both terrestrial and marine environment. Indigenous Lands were also considered as protected natural areas by Lactec. (Lactec 2020b)

the cytogenotoxic effects of the released mine waste in the water studied as changes in the mitotic and samples with different amount of river water were tested. All impacted-site samples with more than 40% of river water exhibited significant reductions in the mitotic index. The impacted site samples containing 100% of river water had 25-35% reductions in mitotic index.(Quadra et al. 2019)

An average of 154.24 cubic meters of wood per hectare, totaling 120,015.69 m^3, with an error of approximately 13% was calculated as damage to wood forest resources while the total volume of wood resources in the area was 4331420.1216 m3. (Alkimin De Lacerda, Bastos, and Graf De Miranda 2017; Lactec 2020b; 2020e). Also, by remote sensing techniques and analysis of digital processing of images it was shown that 13.2% reduction of vegetation cover in the municipality of Mariana-MG.(C. A. da Silva Junior et al., 2018). For the long-term effects 25 years of natural recovery is needed for have the vegetation cover back to the baseline value at the time. The number of fragments and the proportion of edge areas were considered for edge effect indicator as a change in vegetation cover in the area. The number of fragments in the area defined by Lactec as "compartment 1 " (from Fundão dam to Barra Longa municipality) was increased after failure. (Lactec 2020b; Alkimin De Lacerda 2021)

Digging bird(a trough surrucura, common species throughout its distribution area) was selected as an indicator of damage to terrestrial fauna such as change in population, loss of connectivity in the landscape, worsening physical conditions of the fauna, and loss of habitat quality by lactec and the reduction of number of this species was shown after failure. For the long-term effect, 30 years needed to be considered as a natural recovery of the birds to the baseline level. However, there was not any change in bees' populations based on another study. For the habitat quality assessment, the environmental suitability across various fragments was considered. (Lactec 2020b; K. I. C. Vieira et al. 2020; Alkimin De Lacerda 2021). Also, the effects of failure on two types of seabirds were assessed by the impact of As on those seabirds and the As concentration in seabird blood was more than ten times increased after failure (Bauer et al., 2024).

Fish, zooplankton and phytoplankton were the indicators selected by Lactec for aquatic damage in the entire length of the Doce river and its main tributaries, extending from the site of the Fundão tailings dam to the boundary of the estuarine region, and lakes, lagoons in the fluvial-marine plain near Colatina and Linhares, and hydropower plant reservoirs, where damming restricts water flow. For the long-term effect, 163 years needed to be considered as a natural recovery of the fish as an indicator for ichthyofauna to the baseline level. phytoplankton were assessed by analyzing shifts in community structure, including species richness and density and the change in composition as frequency of occurrence of species. Bioaccumulation, referring to the increase of potential exotic elements in fish organs, was assessed by Lactec using 17 PTE, with data from 5 PTE presented in the table of this study. Also, rise of exotic species in the environment was confirmed by Lactec studies which it led to the decline or extinction of native populations. The exotic species were increased by 90% after failure in compared to a study in 2007, and it was shown by 19 samples with a focus on those originating from other Neotropical River basins (84.2%)(Lactec 2020b; Alkimin De Lacerda 2021; Lactec, n.d.; Alkimin De Lacerda, Bastos, and Graf De Miranda 2017; Lactec 2020a; 2020d).

Also, (W. G. Pereira et al. 2024) discussed the area of environmental suitability of shrimps impacted by tailings plumes as an indicator showing the impacts on marine fauna, and the impacted area ranged from 27 to 47 %.

In order to find the effects of dam failure on water quality, several indicators had been studied. An increase in turbidity levels was observed between the Fundão dam and the Baguari HPP dam and Doce River estuary and in the marine region by Lactec and showing 2000 times exceeding the historical data between Fundão and HPP dams and 50 times more for the marine area. Also, suspended particulate matter was increased significantly in the marine area. The concentration of the PTE in the water near the dam and in the marine area, the measurements showed up to 9360 times more than legislated limit after dam failure. Fundão dam failure also, effected on the water courses of the region and it changed 20% of the subbasins between Fundão dam and the Risoleta Neves Hydroelectric Plant and changes in the watercourse network configuration was showed by assessing the geometric components and the width of the river from downstream of the Fundão dam and upstream of the Risoleta Neves HPP was used in this study.(Lactec 2020b; Alkimin De Lacerda, Bastos, and Graf De Miranda 2017)