



Integrating Water Resources Management with Technological Disaster Risk Management: case of Mariana's disaster and Doce River basin

Integração da Gestão de Recursos Hídricos com a Gestão de Risco de Desastres Tecnológicos: o caso do desastre de Mariana e da bacia do rio Doce

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ABSTRACT: The collapse of the Fundão tailings dam in 2015 had severe consequences for the Doce River basin in Brazil, recognised as one of the world's largest dam-related disasters. Brazilian legislation stipulates that adverse events affecting water resources, including technological disasters (TDs), must be addressed at the basin level. However, effective integration of Water Resources Management (WRM) and Technological Disaster Risk Management (TDRM) in water planning remains uncommon, with limited research available. This study seeks to understand and promote WRM-TDRM integration. The Doce River basin serves as a case study, with an analysis of the TDs impact on the Integrated Water Resources Plan (IWRP-Doce) from its inception in 2010 through the 2023 revision. We examined whether WRM-TDRM integration was included in the Terms of Reference for both editions. A SWOT analysis revealed that TDRM had not been incorporated into the IWRP, and despite the disaster's scale, only minimal adjustments have been made. This highlights the need for TDs to be explicitly addressed in future Terms of Reference. The guidelines proposed in this study aim to support WRM-TDRM integration in river basins facing similar vulnerabilities to those of the Doce River basin.

Keywords: Water Resources; Man-Made Disaster; Risk Management; Mariana Dam Break; Doce River; Hydrographic Basin.

RESUMO: O colapso da barragem de rejeitos de Fundão em 2015 teve consequências graves para a bacia do rio Doce, no Brasil, reconhecido como um dos maiores desastres relacionados a barragens do mundo. A legislação brasileira estipula que eventos adversos que afetam os recursos hídricos, incluindo desastres tecnológicos (DTs), devem ser tratados em nível de bacia. No entanto, a integração eficaz da Gestão de Recursos Hídricos (GRH) e da Gestão de Riscos de Desastres Tecnológicos (GRDT) no planejamento hídrico ainda é incomum, com poucas pesquisas disponíveis. Este estudo busca compreender e promover a integração entre GRH e GRDT. A bacia do rio Doce serve como um estudo de caso, com uma análise do impacto dos TDs no Plano Integrado de Recursos Hídricos (PIRH Doce) desde sua criação em 2010 até a revisão de 2023. Examinamos se a integração GRH-GRDT foi incluída nos Termos de Referência para ambas as edições. Uma análise SWOT revelou que a GRDT não havia sido incorporada ao PIRH e, apesar da escala dos desastres, apenas ajustes mínimos foram feitos. Isso destaca a necessidade de os DTs serem explicitamente abordados nos Termos de Referência futuros. As diretrizes propostas neste estudo visam apoiar a integração GRH-GRDT em bacias hidrográficas que enfrentam vulnerabilidades semelhantes às da bacia do rio Doce.

Palavras-chave: Recursos Hídricos; Desastre Causado pelo Homem; Gestão de Riscos; Rompimento da Barragem de Mariana; Rio Doce; Bacia Hidrográfica.

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1. INTRODUCTION

Disaster can be defined as a serious disruption of the functioning of a community or a society at any scale due to hazardous events interacting with conditions of exposure, vulnerability and capacity, leading to one or more of the following: human, material, economic and environmental losses and impacts (United Nations Office for Disaster Risk Reduction, 2017). Whether in the socio-economic or socio-environmental dimension, disasters can disrupt notions of stability and have the potential to produce acute and chronic effects that can affect present and future generations (Spaliviero et al., 2011; Vaneli et al., 2022; Possantti & Silva, 2020; Londe et al., 2014; Kossoff et al., 2014).

Disasters are generally divided into two broad categories: natural and technological. Natural disasters occur due to exposure and vulnerability to natural hazards - such as hurricanes, heavy rains, droughts, earthquakes and epidemics. On the other hand, technological disasters occur due to exposure and vulnerability to technological hazards, resulting from above-normal failures in infrastructure and human activities - such as cargo transportation accidents, dam ruptures, reactor explosions and large urban fires (Mohamed Shaluf, 2007; Somasundaram et al., 2007; United Nations Office for Disaster Risk Reduction, 2018; Londe et al., 2014).

According to the United Nations Office for Disaster Risk Reduction, many emerging economies have rapidly expanded their hazardous operations — for instance, industrial activities with large environmental risks — by promoting specific segments such as oil, gas, chemical, and mining industries (United Nations Office for Disaster Risk Reduction, 2019). As for risk, it can essentially be defined as the combination of potential consequences and uncertainties associated with the occurrence of an event (Aven, 2023).

Brazil, an emerging economy, has seen an increase in the occurrence of technological disasters, these include significant disasters related to water resources that have occurred since the beginning of the 21st century (Paiva et al., 2020; Gonzalez et al., 2022; Leal Pacheco et al., 2022). Consequently, the implementation of disaster risk management is necessary. This management is 'the application of disaster risk reduction policies and strategies to prevent new disaster risk, reduce existing disaster risk and manage residual risk, contributing to the strengthening of resilience and reduction of disaster losses' (United Nations Office for Disaster Risk Reduction, 2017). Specifically, Technological Disaster Risk Management (TDRM) addresses the risks associated with technological disasters within this broader framework.

The collapse of the Fundão mining tailings dam in the municipality of Mariana, state of Minas Gerais, in November 2015, is a major example. It constitutes the largest tailings dam disaster ever recorded in terms of the volume of tailings released (45 million m³) (World Mine Tailings Failures, 2020). Part of this volume reached the Doce River and travelled about 650 km from Mariana to the Atlantic Ocean at the mouth of the Doce River in Espírito Santo State (Agência Nacional de Águas, 2016).

Disasters of this magnitude can disrupt the planning of the affected territory, including water resources planning, testing the resilience of society, its leaders, and public institutions, as well as highlighting political and institutional weaknesses that were previously unknown or neglected (Boin et al., 2008), and impacting initiatives in support of sustainable regional development. This seems to be the case with the Integrated Water Resources Plan of the Doce River Basin (IWRP-Doce), which, having its implementation started in 2010 and with a planning horizon expected until 2020, had to face major changes in the planned scenario in 2015 due to the collapse of the Fundão Dam.

In this context, water resources management (WRM), aiming to contribute to sustainable regional development, must consider the risks of technological disasters that may arise during the development of human activities, especially in the water resources planning process. Water resources planning, in itself, is a challenging process that seeks to meet agreed water needs through the establishment of goals and the proposal of actions, considering the spatial-temporal dynamism inherent to water resources and alignment with the premises of sustainable regional development (Agarwal et al., 2000; Global Water Partnership, 2005; Spaliviero et al., 2011, Allan et al., 2018). In this way, water resources planning holds significant potential to contribute to the prevention and reduction of water-related risks, including technological disasters, particularly when the integration between water resources management and disaster risk management is strategically addressed within the planning process.

In Brazil, the National Water Resources Policy aims to promote the integrated use of water resources for sustainable development and the prevention and defence against critical hydrological events of natural origin or resulting from the improper use of natural resources. As for 'integration,' it refers to the incorporation or union, in regular interaction, of independent elements into a uniform whole (Agarwal et al., 2000). While integration alone does not solve management problems (mixing two bad ingredients does not result in a good meal), it is essential for rationalising forces and maximising their potential (Agarwal et al., 2000).

To achieve this integration, the Policy mandates to coordinate water resources planning with the planning of water user sectors, as well as with regional, state, and national planning (Brasil, 1997). This legislation, along with the National Policy for Protection and Civil Defence (Brasil, 2012a), emphasises the need for integration with WRM and designates the watershed as the unit of analysis for the prevention of water-related disasters.

Still, it is observed that when water resources plans in Brazil incorporate disaster risk management, they tend to focus only on natural hazards. Technological disasters are often treated as unexpected accidents (Roche et al., 2017; Mohamed Shaluf, 2007). This appears to be a global trend, although some countries have advanced in considering technological risks in their water resources plans. One example is the Accidental Risk Sites (ARS) inventory, created after the dams collapses in the Tisza River basin, in Central Europe, in 2000. This instrument presents industrial sites associated with high risks of accidental pollution and contaminated sites in flood-prone areas in the Danube basin (Winkelmann-Oei et al., 2001).

Therefore, the policy guidelines and the practice of WRM in Brazil present gaps in its integration with TDRM, referred to in this work as 'WRM-TDRM integration'. Based on observations of the international water resources management landscape and the limited number of publications addressing this theme (Spaliviero et al., 2011; Londe et al., 2014; Alves et al., 2019), a hypothesis is that these gaps may be due to: i) a lack of conceptual understanding of the factors that support such integration; ii) a shortage of methodologies to promote WRM-TDRM integration; iii) limited risk awareness regarding the potential impact of such disasters on water resources planning; and iv) the absence of clear guidelines for adequately incorporating TDRM into water resources planning. Additionally, although it is reasonable to expect that major technological disasters involving water would affect water resources planning, few studies (Alves et al., 2019; International Commission for the Protection of the Danube River, 2019) have focused on analysing the impact of such events in real cases. The development of studies that address these gaps could foster a culture of prevention and resilience related to technological disasters within water resources management.

Therefore, this article aims to contribute to filling these gaps through the analysis of the impacts of the Fundão dam collapse on the IWRP-Doce. More specifically, this work identifies and discusses the challenges and the potential for integrating Water Resources Management (WRM) with Technological Disaster Risk Management (TDRM), particularly with regard to the incorporation of TDRM into water resources planning, as well as to propose guidelines that can be adapted to river basins around the world facing similar challenges and characteristics. It is worth noting that the scope of this research is focused on investigating such aspects within the water resources planning phase, based on the premise that effective integration between WRM and TDRM is strategic for the prevention and reduction of water-related technological disaster risks.

2. Key aspects of WRM-TDRM integration

Despite the scarcity of publications on WRM-TDRM integration, some key aspects can be found through the literature review. These aspects are dispersed across the literature on WRM, disaster risk management, technological disasters, management mechanisms and instruments, crisis management, and integration between managements. In this work, we will divide the aspects of direct integration with TDRM from those of indirect integration. A general discussion of these aspects will be addressed below.

2.1. Direct aspects of WRM-TDRM integration

Primarily, regarding direct integration, when it comes to integrating WRM and disaster risk management more broadly (covering both natural and technological disasters), it can be observed that water resource plans in Brazil and other Latin American countries tend to focus solely on natural disasters. In Brazil, the resolution that establishes the minimum content of water resources plans (Brasil, 2012b) does not specifically mention disaster risks, yet it is common to find droughts and floods (only related to natural disasters) addressed in these plans. Colombia incorporates natural disasters into its 'Watershed Management and Development Plans' but fails to emphasise or detail technological disasters. Countries such as Chile, Colombia, and Mexico are compelled to consider disasters due to El Niño and La Niña as key issues in their water resource planning, but their respective plans still show little interconnection with TDRM. Given the lack of research on the subject, it is not surprising that this trend also exists in other parts of the world.

This tendency of water resources planning to disregard technological disasters may stem from factors such as a low perception of risk associated with them and their lower occurrence and number of records compared to natural disasters. Nevertheless, technological disasters are not necessarily less severe than natural ones. Despite the lack of data on the occurrence of technological disasters and the extent of their impacts, Abeldaño Zúñiga & González Villoria (2018) found that one in three disasters in the Mexican from 1900 to 2016 fit this category. van Loenhout et al. (2020) showed that most technological disasters from 1980 to 2019 were related to transportation (including dangerous products) (69% from 2000 to 2019) and that industrial disasters affected the most people (64% from 2000 to 2019). Among the 10 countries with the most technological disasters from 2000 to 2022, emerging and newly industrialised countries are predominant, as shown in Figure 1.

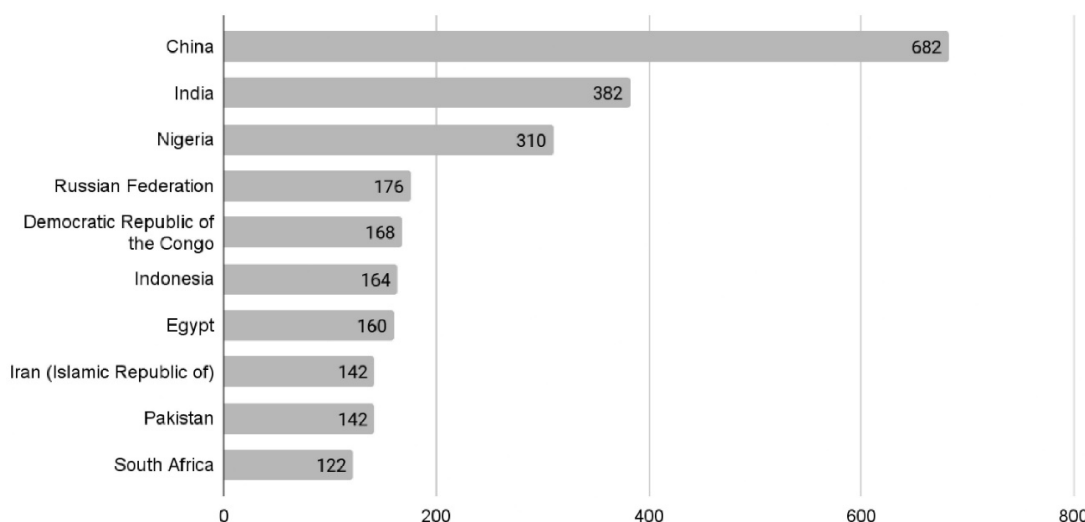


Figure 1 - Top 10 countries by occurrence of technological disasters (2000-2022). Source: Centre for Research on the Epidemiology of Disasters (2023).

Based on Quarantelli (1999) concepts, treating disaster risk management holistically (covering both natural and technological disasters) offers more value since many actions that prepare the infrastructure for one type of disaster would also do so for others (such as alert and alarm systems, for example). Quarantelli (1999) also mentions that one of the similarities between disasters and other environmental problems, such as pollution, is that they tend to originate from the same stress sources. Thus, sources that cause 'ordinary' pollution can cause 'accidental' pollution, reinforcing the need for a more explicit inclusion of TDRM in water resource plans.

Other challenges hinder the integration between WRM and TDRM, including data availability. For example, while data and information for natural disaster management are widely disseminated and often lie in the hands of public agencies or non-governmental organizations, much of the data and information pertaining to technological disasters lies in the possession of private companies (United Nations Office for Disaster Risk Reduction, 2019). These institutions can mask information or hinder access to it to avoid penalties and damage to their reputation. Moreover, even when available, such data usually neither suffice nor undergo systematization and validation by inspection bodies. Another issue arises since those responsible for responding to and recovering from the impacts of technological disasters are polluters themselves (the responsibility and polluter pays principles), unlike natural disasters, where the government tends to take responsibility and promote the necessary actions.

Therefore, incorporating the possibility of technological disasters into the planning of water resources, including those involving dams, could help identify the companies whose activities may contaminate water resources and systematise the data on accidents and pollution related to these projects. This approach was implemented in the Tisza River basin, a tributary of the Danube River, where the extensive ARS Inventory was developed and established. It captures contaminated areas and points at risk of pollution of water bodies by hazardous substances, working in conjunction with the Tisza River Basin Integrated Management Plan (Winkelmann-Oei et al., 2001; International Commission for the Protection of the Danube River, 2019). The Danube River Basin, like other regions in Europe, benefits from an inventory of hazardous substances and facilities that can release substances. A system similar to the ARS Inventory was developed in the Brazilian Paraíba do Sul River basin to predict critical events, incorporating activities with potential environmental risks, vulnerable points, and local dams (Agência Nacional de Águas, 2021).

2.2. Indirect aspects of WRM-TDRM integration

In addition to these forms of direct integration between WRM and TDRM, indirect aspects that specifically address the strengthening of water resources management have the potential to enhance this integration. The underlying premise is that the stronger the WRM, the greater the likelihood of its effective integration with TDRM.

These aspects are diverse, and their significance depends on the regional context (Gerlak et al., 2018; Ribeiro & Johnsson, 2018; Pahl-Wostl, 2017). Nevertheless, based on some of the basic elements of Integrated Water Resources Management (Agarwal et al., 2000), at least two large groups of aspects can be highlighted, which are generally interconnected: (i) the operability of WRM within the basin — that is, the internal strengthening of water resources management, which involves both the strategic focus and the effective implementation of management instruments; and (ii) the integration of WRM with other sectoral management — that is, the external strengthening of water resources management, considering that such management is both influenced by and influences other sectoral policies affecting the territory, requiring coordinated actions with other sectors, society, and different levels of government. These two groups of indirect integration aspects are essential for operationalizing (i.e., preparing an idea or project to become effectively practical) and strengthening WRM (Agarwal et al., 2000; Marinato, 2008).

Regarding the first group of indirect aspects — WRM operability in the basin — when water resources management professionals in a given region remain focused on the implementation of a feasible policy and promote the integration of management instruments compatible with local realities, more effective action becomes possible (Agarwal et al., 2000; Porto & Porto, 2008), reducing overlaps, enhancing synergies, and supporting more informed decision-making. In addition, it fosters an enabling environment for identifying and sharing knowledge on water governance (Marinato, 2008; Global Water Partnership, 2025; Tedesco, 2009). Well-known initiatives such as GWP's Integrated Water Resources Management Action Hub (Global Water Partnership, 2025) illustrate how methods and experiences in the application of instruments can be useful for WRM professionals. These WRM instruments are not universally mandatory; for instance, in Brazil, the instruments highlighted in the Brazilian National Water Resources Plan are only five — Water Resource Plans, Water Quality Objectives, Water Permit, Water Charges, and the Water Resources Information System (Figure 2).

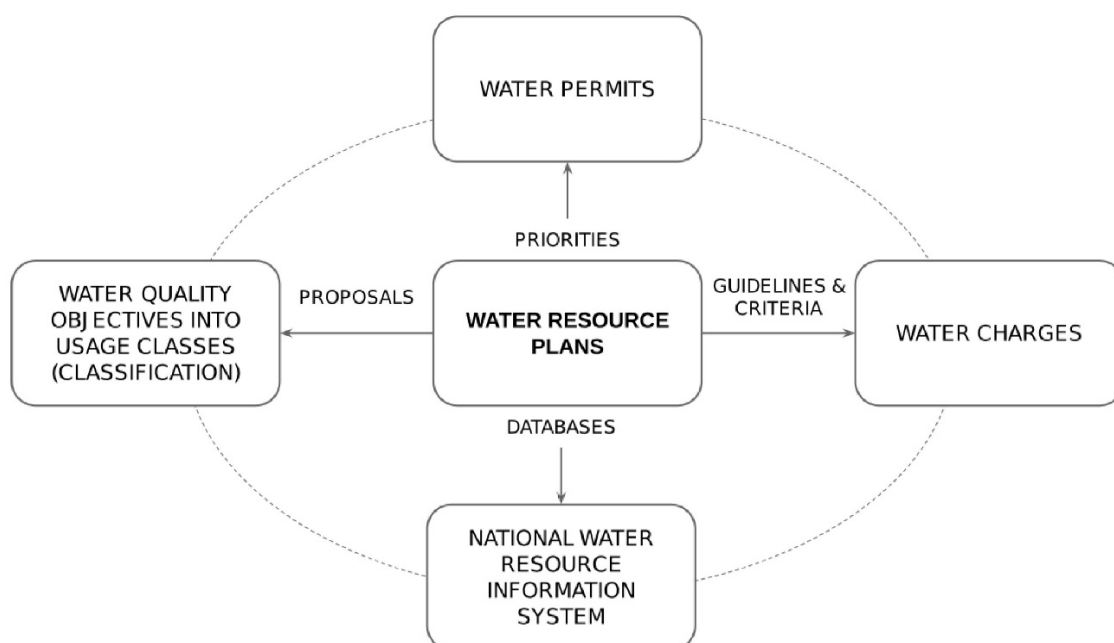


Figure 2 - Management instruments of the National Water Resources Policy in Brazil and their interrelation.
Source: Adapted from Agência Nacional de Águas (2017).

In the second group of aspects — integration with other sectoral management — the first point to highlight is the integration with management instruments and policies from other sectors. Some authors (Marinato, 2008; Tedesco, 2009; Grangeiro et al., 2020) point out that such integration is strategic for aligning policies affecting the territory, strengthening intersectoral coordination,

and addressing existing interdependencies. The literature on Integrated Water Resources Management also emphasises management intersectorality (Agarwal et al., 2000), and nexus approaches reinforce the need for effective instrumental integration to manage interdependencies (e.g., water–energy–food security) (Pahl-Wostl, 2017). In practice, water resources planning can serve as a platform to align these instruments, ensuring that sectoral policies complement water management objectives, and vice versa. Therefore, well-designed articulations enable actions in which each entity operates within its own instruments and responsibilities, avoiding the overload of the water resources plan and water management system (Lanna, 2001).

Another indirect aspect to be considered refers to the coordination among levels of government. Such articulation enables more coordinated actions across local, regional, and national scales, strengthening policy alignment and integrated management. In the context of WRM-TDRM integration, coordination with local government levels (such as municipalities, districts...) is especially relevant, given the importance of local governments in effectively managing disasters (Bae et al., 2016). This is partly because local areas are most aware of the risks they face but typically have the least access to specialised human resources to address them (Bae et al., 2016). The shared responsibility for watercourses in Brazil — with some under federal jurisdiction and others under the states — requires coordination among these entities. Furthermore, although municipalities in Brazil have no direct legal mandate for water resources management, integration at this level is also pertinent (Grangeiro et al., 2020).

In addition to intergovernmental articulation, engagement with civil society and water users is also an important aspect, one of Integrated Water Resources Management's pillars (Agarwal et al., 2000). Spaliviero et al. (2011) argue that a participatory approach helps developing countries (where data are scarce, and capacity building is relatively low) to create more effective water resource plans that integrate water, territory, and disaster management. Participation is the most effective way to ensure the implementation of decisions (Porto & Porto, 2008).

Finally, it is worth highlighting the decentralization of management as an indirect aspect. It consists of the process of transferring authority, responsibilities, and decision-making power from the central government to regional, local, or collegial instances (Porto & Porto, 2008). In this way, decentralization enables greater capacity to adapt decisions to local realities, promotes the direct involvement of affected stakeholders, improves intersectoral coordination, and strengthens the legitimacy and acceptance of public policies. According to Bae et al. (2016), this also applies to disaster risk management, and they recommend enhanced national government leadership, oversight, and coordination functions (which states and municipalities can also adopt) for successful decentralised disaster management.

In this way, the direct pursuit of integration between WRM and TDRM is facilitated by indirect integration — that is, through the internal strengthening of water resources management, along with external integration with other management bodies within the territory of interest.

3. Methodology

The chosen case study and the methodological steps to elaborate this research are shown below.

3.1. Context of the study area

The Doce River basin (Figure 3) covers approximately 86,000 km², encompassing 200 municipalities in Minas Gerais State and 30 in Espírito Santo State – an area comparable to the size of Portugal (92,000 km²). Stretching around 880 km, the Doce River originates in Minas Gerais State and discharges into the Atlantic Ocean in Espírito Santo State. Economically, the region is highly significant for Brazil, hosting the largest steel complex in Latin America and contributing substantially to the country's exports of iron ore, steel, and cellulose (Tedesco, 2009).

In compliance with national and state water resources legislation, the Hydrographic Basin Committees comprise representatives from national, state, and municipal government bodies and agencies; raw water users, both public and private; civil society organizations; and communities within their geographic areas of management, considering the jurisdiction (national or state) of their respective water bodies. At the time of the dam collapse, the seats on the Doce River Hydrographic Basin Committee were occupied by nominees from each category from each Doce River tributary committee (due to a spatial integrative approach), indicated in Figure 3, and by federal and Minas Gerais State government representatives. In Brazil, a Hydrographic Basin Committees (also known as Water Basin Committees or River Basin Committees) constitute the 'Water Parliament', that is, a space where representatives of a watershed community discuss and deliberate on water resource management, sharing management responsibilities with the government (Agência Nacional de Águas, 2011).

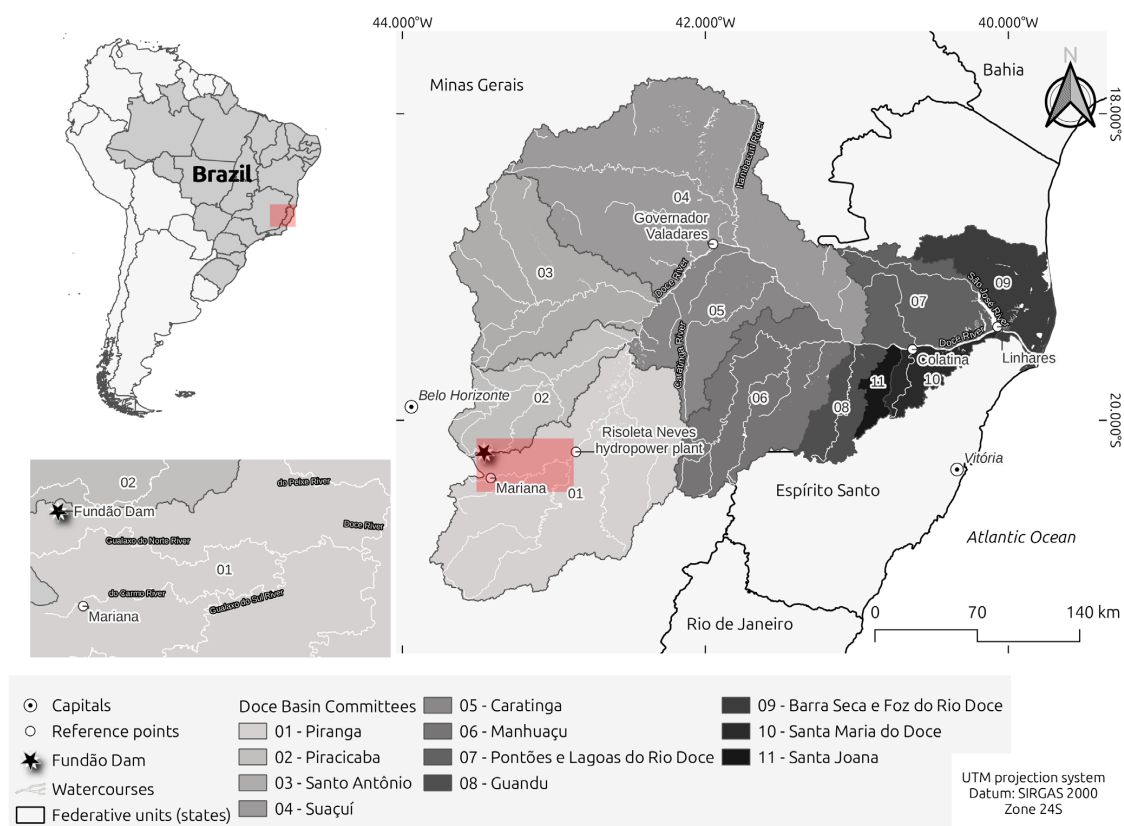


Figure 3 - Doce River Basin and its respective Hydrographic Basin Committees. Map lines delineate study areas and do not necessarily depict accepted national boundaries.

Another major milestone for WRM in the basin was the approval of the IWRP-Doce in 2010, which resulted from a participatory process carried out between 2008 and 2009. The planning horizon for the actions spanned 10 years (2010 to 2020), aiming at the effective management of the basin's surface and groundwater resources to ensure their multiple, rational, and sustainable use for the benefit of current and future generations (Brasil, 2012b, p. 14).

The IWRP (2010-2020) is organised into three volumes: Volume I – Doce River Basin Diagnosis and Prognosis (Comitê da Bacia do Rio Doce, 2010a), Volume II – Goals and Action Programs (Comitê da Bacia do Rio Doce, 2010b), and Volume III – Guidelines for the Management of the Doce River Basin (Comitê da Bacia do Rio Doce, 2010c). In addition, an Executive Report (Comitê da Bacia do Rio Doce, 2010d) summarising the Plan was prepared. Unlike a traditional basin plan, it consists of an articulated set of action plans for each basin of the Doce River's main tributaries, as well as for the Doce River itself.

The guidelines for elaborating the IWRP-Doce (2010-2020) were defined in a document called the 'Term of Reference (ToR) for the elaboration of the integrated plan of the Doce River basin and water resources action plans for the Doce River tributary basins' (Comitê da Bacia do Rio Doce, 2007). This important document aids in understanding the principles and objectives of the managers who constructed the plan. As stated by Rabelo et al. (2013, p. 185), 'If the guidelines and laws are the idealised reality, the ToR-Doce [the 2007 ToR] is the planned reality at the executive level.'

On November 5, 2015, one of the most dramatic events in the history of the Doce River basin occurred: the collapse of the Fundão iron ore tailings dam in the municipality of Mariana, Minas Gerais, owned by Samarco Mineradora S.A., a joint venture between Vale S.A. and BHP Billiton Limited & Plc. With the collapse, about 45 million m³ of tailings (World Mine Tailings Failures, 2020) abruptly reached the drainage network of the basin. The tailings travelled along the Gualaxo do Norte, Do Carmo, and Doce rivers for approximately 650 km across the Minas Gerais and Espírito Santo States until they reached the Atlantic Ocean (Agência Nacional de Águas, 2016; Roche et al., 2017).

The collapse of the Fundão Dam caused extensive and widespread damage across inland regions of Minas Gerais and Espírito Santo, coastal areas of Espírito Santo, and marine-oceanic zones. In the social and economic spheres, 19 individuals were killed (Freitas et al., 2016); 600 families were displaced; and 400,000 people experienced interrupted supplies, fishing embargoes, damaged tourism, a retracted local economy, and harm to Indigenous peoples and traditional communities (such as artisanal fishers,

quilombola groups, etc.) (Roche et al., 2017), problems in water collection and treatment (Agência Nacional de Águas, 2016; Roche et al., 2017; Freitas et al., 2016), job losses (Freitas et al., 2016), destruction of cultural heritage monuments (Roche et al., 2017; Freitas et al., 2016), and significant psychological damage (Losekann et al., 2015). The affected rivers and lagoons showed substantial environmental impacts: the death of aquatic macrofauna, especially planktonic organisms (the basis of the food chain), suppression of riparian forests in the initially damaged area (Roche et al., 2017), impairment of water infiltration, bioaccumulation of heavy metals (Freitas et al., 2016), and increased erosion processes (Minas Gerais, 2016).

On March 2, 2016, an agreement — the Transaction and Conduct Adjustment Term — was signed by several national institutions, along with the companies responsible for the collapse. This type of conduct adjustment agreement is an out-of-court settlement between public bodies and an individual or legal entity that has violated or threatens to violate a collective right. In this specific case, the Term aimed to promote the recovery, mitigation, remediation, restoration, and compensation for the social, environmental, and economic impacts caused by the collapse, as well as to indemnify unrecoverable areas (Reparação Bacia do Rio Doce, 2016). On June 25, 2018, a Governance and Conduct Adjustment Term was signed including the Public Prosecutor's Office and the Federal Public Defender's Offices of Minas Gerais and Espírito Santo (Brasil, 2018).

A private non-profit foundation (the Renova Foundation) was created based on the Transaction and Conduct Adjustment Term to implement social, environmental and economic reparative programmes (to mitigate, remedy and repair impacts) and compensatory programmes (to compensate for impacts that cannot be mitigated or repaired). An advisory and supervisory Interfederative Committee was also established for the foundation, consisting of representatives from the federal government, and from the government of the Minas Gerais and Espírito Santo states, the affected municipalities, Doce River Hydrographic Basin Committee, and — after the Governance and Conduct Adjustment Term — representatives of the Public Defender's Office and impacted communities (Agência Nacional de Águas, 2016).

In 2021, the IWRP-Doce began to be updated as a result of the 2020 ToR, revising the diagnosis and prognosis of water resources, goals and action programs, and the guidelines for managing water resources in the Doce River Basin, adopting a 20-year planning horizon (2023-2042). In September 2023, the updated IWRP-Doce was approved by the Doce River Hydrographic Basin Committee.

3.2. Comparison of WRM-TDRM Integration considering the Doce river basin water resources planning before and after the Fundão dam collapse

To understand the functioning of WRM and TDRM, and to identify characteristics that facilitate their integration (to fill this gap in literature), an extensive review of scientific literature and national/international reports was conducted. The research focused on WRM, TDRM, technological disasters, management mechanisms and instruments, crisis management, and inter-management integration.

From this literature, criteria were selected to serve as references for comparison (before and after) to assess if, and how (directly or indirectly), the integration between WRM and TDRM was considered. These selected aspects indicate the water resources managers' interest in promoting this integration. The identified aspects were organized into three groups:

- I. Integration of WRM instruments with TDRM: Reflects direct articulation with specific management, such as the integration of WRM and TDRM instruments.
- II. IWRM operability in the basin: Focuses on WRM's operability and the integration between its own instruments.
- III. Integration with other sectoral management: Represents collaboration between WRM and other sectors.

The first (I) addresses direct integration, while the latter two groups (II and III) address the indirect integration of WRM into TDRM. A compilation of these aspects is presented in Section 2.

Subsequently, documentary research was conducted, listing relevant documents to indicate how technological disasters were or have been addressed during the planning and execution of actions within the scope of the IWRP-Doce (2010–2020). The documents were analysed in terms of: type, objective (what?), scope (where?), deadlines and periods of validity/action (when?), those responsible for implementation (who?), interference in the planning and execution of actions in the basin (how?), and relevance to the research. Based on this survey, it was decided to analyse the aspects of integration from two documents, the two Terms of Reference (ToRs): the 2007 ToR, which provided the guidelines for the elaboration of the first version of the IWRP-Doce (with a planning horizon from 2010 to 2020),

and the 2020 ToR, which provided guidelines for the preparation of the updated IWRP-Doce, with a planning horizon from 2023 to 2042. A comparative table between both ToRs was created to answer (with yes or no) the following question for each integration aspect: 'Were the following desires/aspects expressed in the ToR?'

The ToR is a document with guidelines that should explicitly guide the entire process of drafting a plan — in this case, the water resources plan — for an individual evaluator or team of evaluators (Roberts et al., 2011). The ToR can then be used as the foundation for a contractual agreement between the individual or group conducting the evaluation and the entity commissioning the work (Roberts et al., 2011). If the ToR ignores any relevant issue, there is less chance of it being considered in the process of designing and implementing the plan. Therefore, drafting ToRs constitutes a crucial phase of water resources planning.

By comparing the situation before and after the dam collapse, this stage helps to map the changes and continuities in the managers' approach, contributing to an understanding of the challenges and potential of integration, providing the basis for the subsequent proposal of guidelines.

3.3. Discussion of the effects of the technological disaster associated with the collapse of the Fundão dam on the IWRP-Doce

The investigation focused on the literature to assess and discuss the impact of the Fundão Dam Collapse on the IWRP-Doce. This literature review allowed for the analysis of the Fundão Dam collapse, its effects on water resources planning, and the consequences of similar technological disasters on water resource management.

Using the same set of documents related to the Doce River Basin water resources planning collected previously (Section 3.3), the analysis of the Mariana Disaster's effects on planning concentrated solely on the IWRP-Doce (Comitê da Bacia do Rio Doce, 2010a, b, c, d). Particular attention was paid to the executive report (Comitê da Bacia do Rio Doce, 2010d), as it summarises the key aspects of the IWRP-Doce, reflecting the perspectives of the Doce River Basin Committee, the Technical Advisory Group, and the planning company. Volume II (Comitê da Bacia do Rio Doce, 2010b) was also thoroughly analysed, as it contains what the 2007 ToR termed 'the plan itself', which comprises the strategies for achieving the objectives based on the most critical diagnostic and prognostic findings identified during the plan's development.

Then, guided by information on the social, economic, and environmental consequences of the Fundão Dam collapse found in the literature, the IWRP-Doce (2010-2020) was analysed, and the possible effects of the Fundão Dam collapse were compiled.

For this analysis, the study began with a macro-level examination (effects on planning stages) and proceeded to a microanalysis (effects on the action plan) of the IWRP. The study also sought to identify reflections of these effects on the updated IWRP-Doce, which we will refer to as 'IWRP-Doce (2023-2042)' (AGEDOCE, 2010; Agência Nacional de Águas, 2023). The macro effects on the common stages of water resources planning were identified and set as the minimum standards in the Brazilian National Council of Water Resources Resolution nº 145/2012 (Brasil, 2012b, p. 3), as follows: integrated diagnosis, scenario projection, and guidelines and programs. Results were synthesised and arranged in a table. The analytical approach by planning stages regarding macro impacts was similar to that adopted by Alves et al. (2019). The micro effects of the dam collapse were identified and summarised according to the effects on the objectives, programs, subprograms, and projects of the main themes of IWRP-Doce (2010-2020). The results were synthesised and organised in tables.

The results of this stage support the identification of concrete evidence to warn about the impact of technological disasters on water resources planning. This helps the study to identify the challenges and the potential of WRM-TDRM integration and, ultimately, to propose guidelines. Thus, these findings directly feed into the subsequent stage (Section 3.4).

3.4. Identification of the challenges and potentialities for integrating WRM into TDRM in the Doce River basin and formulation of guidelines

This section summarizes the study's findings, identifying and discussing aspects that can foster greater integration between WRM and TDRM within the Doce River basin. This analysis is based on the analyses of the ToRs (Section 3.2 and 4.1) and the effects of the technological disaster on the IWRP-Doce (2010-2020) (Section 3.3 and 4.2), from the perspective of the current potentialities and challenges.

Thus, the aspects identified during previous analyses were presented in a SWOT (Strengths, Weaknesses, Opportunities, and Threats) matrix and then discussed. The framework was composed of four blocks: vertical blocks were divided into positive (potentialities) and negative (challenges) influences, while horizontal blocks were divided between internal (controllable within the basin) and external (non-controllable within the basin) influences. Frameworks such as the two-by-two SWOT matrix are commonly used by project managers (Ishaq et al., 2019; Marttunen et al., 2017) and can assist in the formulation of guidelines.

Therefore, the SWOT matrix was done in a very straightforward manner: observing the results of the previous steps and placing at least one guideline for promoting WRM-TDRM integration for each aspect identified in the SWOT. These guidelines have been proposed in list form and in general language to highlight ways of advancing in terms of the potentialities and challenges encountered.

In short, this concluding stage is the point of convergence where all analyses are transformed into practical and conceptual contributions, fulfilling the study's objective: to diagnose the core problem and subsequently offer solutions in the form of strategic guidelines to fill the gap in literature.

4. Results and discussion

4.1. The WRM-TDRM integration in the IWRP-Doce before and after the Fundão dam disaster

This stage evaluated the ToRs for producing the first version of IWRP-Doce in 2007 and its update in 2020, in order to assess how this crucial phase of water resources planning incorporated the integration between WRM and TDRM.

Chart 1 presents the criteria suggested by the scientific literature review in this study for a comparative evaluation. It is argued that water resources planning that incorporates and effectively considers the three chosen groups of aspects would be better prepared to prevent and address crises related to technological disasters, such as the Fundão Dam collapse.

Chart 1 - Aspects considered (or not) in the 2007 and 2020 ToRs that favour the integration between WRM and TDRM in the IWRP-Doce.

Aspect group	Aspects of integration	2007 ToR	2020 ToR
(I) Integration of WRM instruments with TDRM	a) Integration of WRM instruments with disaster risk management	Yes	Yes
	b) Integration of WRM instruments with TDRM	No	Yes
	c) Integration of WRM with dam failure	No	No
	d) Identification of activities that may contaminate watercourses in cases of accidents	No	No
(II) WRM operability in the basin	e) Integration between WRM instruments	Yes	Yes
	f) Focus on implementation	Yes	Yes
(III) Integration with other sectoral management	g) Integration between WRM and instruments and police from other sectors	Yes	Yes
	h) Integration of actions across government levels (federal, state, and municipal)	Yes	Yes
	i) Social participation	Yes	Yes
	j) Management decentralization	Yes	Yes

4.1.1. Direct WRM-TDRM integration: Integration of WRM instruments with TDRM

Evaluating the first group of aspects (Chart 1) reveals that both ToRs showed a deficient approach toward direct WRM-TDRM integration. Although they addressed some aspects, such as the integration of WRM with disaster risk management in both ToRs and with some TDRM instruments in the 2020 ToR, they lacked an in-depth approach, particularly on preparedness for and prevention of technological disasters. This finding will be discussed below, covering each aspect in more detail.

With regard to aspect I.a) — the integration of WRM instruments with disaster risk management more broadly —, both ToRs addressed this aspect, although they leaned towards natural disaster risk reduction.

Consequently, the WRM in the Doce River Basin has followed the pattern of South America in not considering technological hazards in its water resources plans. For example, both documents emphasise managing critical hydrological events (floods, droughts), with special emphasis on integrating the Water Resources Information System with the Doce River Basin Flood Warning System — a guideline in the 2007 ToR. The way the analysed ToRs are written also seems to limit the scope of the plans by specifying terms such as ‘extreme hydrological events’, instead of adopting a more general term such as ‘extreme events involving water resources’.

As for aspect I.b) — the integration of WRM instruments with TDRM —, there was no integration in the 2007 ToR, whereas the 2020 ToR included direct integration, albeit not comprehensive. In the Piranga River Basin, one of the main tributaries of the Doce river, members of the respective Hydrographic Basin Committee identified technological risks at the time the 2007 ToR was drafted, yet it still failed to discuss and further develop the subject. The 2020 ToR brings aspects of direct integration between WRM and TDRM when addressing response and reconstruction actions associated with the Fundão Dam collapse, but offers no guidelines for actions focused on risk prevention or mitigation.

Additionally, aspect I.c) — the integration of WRM with dam failure risk — was ignored in the 2007 ToR, whereas the 2020 ToR addressed the post-collapse recovery of the Fundão Dam but did not deal with the risk of other disasters involving dams. Therefore, an opportunity to incorporate dam disaster risks was missed in the 2007 ToR, despite the Piranga Hydrographic Basin Committee raising the possibility of incorporating actions against industrial accident risks into planning. This subject was disregarded during the writing of the 2007 ToR. A similar situation occurred in the 2020 ToR, where, even after the collapse, broader issues of preparing for and preventing new disasters involving dams were not addressed. Thus, it can be said that the aftermath of the Mariana disaster, an event that had already occurred, is the only disaster risk management issue addressed outside the scope of ‘natural disasters’.

Lastly, in analysing aspect I.d), it was found that both ToRs do not provide guidelines to identify activities that could contaminate watercourses in the event of accidents in the basin. In the 2007 ToR, there was only an interest in identifying point and diffuse pollution sources, but no concrete tasks. In the 2020 ToR, this aspect only covered simulations and the identification of point and diffuse sources of pollution but did not specify accidental loads.

Results for this first group of aspects somewhat reflect the limited number of actions on the subject in both versions of the IWRP-Doce action plan (2010-2020 and 2023-2042). In the IWRP-Doce (2010-2020), there was basically no reference to TDRM. In comparison, the updated version of the IWRP-Doce (2023-2042) contains only one action that more directly refers to technological disasters, entitled ‘Monitoring industrial and mining enterprise risk management and contingency actions aimed at water resources’. Its main action aims at ‘holding virtual seminars to discuss the results obtained by the risk management and emergency response process and the Action and Emergency Plans prepared for dams and other events related to water resources’ (Agência Nacional de Águas, 2023). The proposition of this program and the respective action is positive, as it arises from the lessons learned from the 2015 technological disaster.

Despite the history and relevance of the theme in the Doce River basin, there remains a lack of more direct actions in the updated IWRP to promote greater integration between WRM and TDRM in the region. Another action, closer to aspect I.d), refers to ‘evaluation and identification of toxicity in surface waters of the Doce River basin’ and involves ‘evaluating and identifying sources of possibly toxic pollutants and proposing actions’ (Agência Nacional de Águas, 2023). Even so, the scope of such action essentially involves monitoring and data analysis, such as identifying current toxicity monitoring points and relevant stretches in the basin that lack monitoring and require analysis.

4.1.2. Indirect WRM-TDRM integration: WRM operationality in the basin and integration with other sectoral management

In this section, the evaluation will focus on whether the deficiency related to WRM-TDRM integration occurred only in the direct approach, or if other indirect aspects favourable to such integration were also disregarded.

As for the second and third groups of aspects, both were highlighted throughout the ToRs, as presented in Chart 1. This emphasis occurred through an internal strengthening of WRM (in a proposal for the plan’s feasibility), considering intergovernmental integration, social participation, and decentralization — aspects useful for both WRM and TDRM individually, as well as for their integration. Each aspect will be detailed below.

As for aspect II.e) — Integration between WRM instruments — both ToRs utilised the integrative nature of water resources plans and aimed to promote guidelines for their coordination with other instruments, including less common ones such as water allocation and financial compensation for the use of water resources. However, the 2020 ToR focused on requiring the fulfilment or maintenance of water quality targets (classes) according to the predominant uses expected for certain stretches of the basin's water bodies. The establishment of these targets was considered essential after the Fundão Dam collapse disaster.

Additionally, for the second group of aspects, both ToRs aimed to develop an operational plan, demonstrating a viable and feasible implementation — related to aspect II.f) – Focus on implementation. One of these attempts was to restrict actions to those within the scope of the Water Resources Management System that could be implemented by WRM instruments.

Furthermore, the 2007 ToR addressed the need for a 'control, correction/revision mechanism' to deal with situations where 'disturbing effects of supposedly stable and controllable external conditions in the formulation of its programs were detected' (Comitê da Bacia do Rio Doce, 2007, p. 20). However, the mechanism to handle these situations was not developed during the production of the IWRP-Doce (2010-2020), which may have compromised the achievement of its goals.

The updated IWRP-Doce (2023-2042) did not highlight or propose a direct action to develop and apply this control, correction/revision mechanism. Thus, during its implementation phase, plan executors should seek to integrate more directly with TDRM and incorporate mechanisms to make it adaptable to crisis scenarios.

It is also worth noting that the need for greater operability of the IWRP-Doce required the 2020 ToR to establish guidelines in this regard. These guidelines positively impacted the updated IWRP-Doce (2023-2042), as they resulted in the development of an Operational Plan Manual, a planning guide to provide greater effectiveness in plan implementation and avoid delays, especially in short-term actions.

As for the third set of aspects, which addresses integration with other administrations, both ToRs discussed the need for dialogue between the water resources sector and stakeholders interested in the interaction between water resources policy instruments and those of other sectoral policies. Thus, it was found that the ToRs addressed coordination with other user sectors (aspect III.g), coordination with federal, state, and municipal levels of government (aspect III.h), and coordination with civil society, communities, and water resources users (aspect III.i). Furthermore, decentralization can also be observed in the ToRs, as the role of the Doce River Basin Committee (CBH-Doce) is shown to be central in the participatory and democratic water management process in the basin, sharing responsibilities with the tributary basin committees (aspect III.j). Rabelo, Teixeira e Espluga (2013) considered this arrangement an unprecedented initiative in Brazil.

However, after the Fundão Dam collapse, coordination with key stakeholders, participatory processes, and decentralization became even more challenging (aspect III.j). One of the main reasons for this was the emergence of a new political-institutional arrangement in the Doce River basin, specifically to address the socioeconomic and socio-environmental impacts caused by the disaster. The 2016 Transaction and Conduct Adjustment Term (due to the scope of the actors involved, actions, and financial resources made available) began to gain more visibility than the IWRP-Doce (2010-2020).

Supporting this fact, it was found that the 2020 ToR aimed to make the IWRP-Doce 'a reference document for the management of water resources in the basin' (Agência Nacional de Águas, 2020, p. 36), a position that seems to have been overshadowed after the technological disaster. Similarly, the emergence of the Interfederative Committee and the Renova Foundation as new regional actors changed the institutional arrangement of the basin, overshadowing the role of the Doce River Hydrographic Basin Committee and the Hydrographic Basin Committees of the tributaries.

4.2. Effects of the disaster on the IWRP-Doce

Before the collapse of the Fundão ore tailings dam in 2015, the Doce River basin had a water resources plan – the IWRP-Doce (2010-2020) — since 2010. This section will analyse the impacts of the technological disaster on the water resources planning. The aim is to determine whether the 2007 ToR — which, even as shown in Chart 1, mainly addressed indirect integration between administrations and largely neglected aspects of direct integration — have successfully induced a water resources plan that takes technological disasters into account. This analysis will also include a discussion of the considerations for updating this water resources plan.

4.2.1. Effects on Planning Steps

Chart 2 summarises the main effects of the technological disaster on the planning stages of the water resources of the Doce River basin: integrated diagnosis, projection of scenarios, and guidelines and programs.

As shown in Chart 2, the severity of the Fundão dam collapse and the derived uncertainties gave rise to a significant effort toward updating the diagnosis of the water resources planning for the Doce River basin and its tributaries, especially regarding water quality. Since an integrated diagnosis was a fundamental step in understanding the situation of the Doce River basin when the plan was built, sudden environmental changes can affect not only the detailed diagnosis but also the validity of the scenarios projected at that time.

Chart 2 - Effects on the planning stages of IWRP-Doce (2010-2020)

Integrated Diagnosis (Volume I)	Projection of Scenarios (Volume I)	Guidelines and Programs (Volumes II and III)
The diagnosis was impaired, and a greater effort was needed to update it, since most of the effects of the rupture are felt in the main canal of the basin.	The prognosis scenario was far from the post-rupture scenario. Technological risks and disasters were neither considered, nor was the possibility of sudden changes in the system of water collection and consumption of the Doce River, which contributed to the unpreparedness of the Plan.	Restoration actions have become a priority regarding improvement actions originally planned and proposed in the IWRP planning horizon. Issues related to biodiversity recovery, control of heavy metals, and monitoring new parameters have become as important as poor sewerage and erosion – the most discussed issues before the collapse.

The IWRP-Doce (2010-2020) prognosis discarded the possibility that extreme situations such as wars or natural catastrophes would occur, and so destroyed its water collection and consumption infrastructure. *Alves et al. (2019)* conclude that this constituted one of the causes for the unpreparedness of IWRP-Doce toward technological disasters.

However, the practice of formulating prognoses in other plans suggests that by discarding certain extreme scenarios, the Plan only considered that the system of WRM (in Brazil the National System of Water Resources Management) would have no degree of control over the implementation of its instruments in these situations. Thus, in those cases, the Water Resources Plan would lose its strategic character as action planner, which would offer no reason to formulate a prognosis but only alert managers about the inefficiency of the system (*Espírito Santo, 2023*).

Anyway, *Alves et al. (2019)* argument is partially sustained, as the Plan neither brought scenarios close to the collapse of the mining tailings dam nor considered the possibility of technological disasters. Moreover, the collapse affected the water collection and consumption system of the main channel. Although it did not reach the extreme of lack of control, for example, due to a war, projections considered a greater performance by management instruments than what was achieved, making the prognosis inefficient in preparing the IWRP-Doce for possible needs due to sudden changes in its scope.

The Plan included no ‘activation of a control, correction/review mechanism’ to address situations with ‘destabilising effects of the external condition (supposedly stable and controllable in the formulation of its programs)’ despite the 2007 ToR providing for it (*Comitê da Bacia do Rio Doce, 2007, p. 20*).

The IWRP-Doce update prognosis (2023-2042) demonstrated a clear methodological improvement. The composition of future scenarios considered multiple aspects (nine in all): the basin’s past, planned investments, current behaviour, socioeconomic growth, among others, including climate change. However, no scenario in the updated IWRP-Doce (2023-2042) explicitly accounted for the possibility of technological disasters.

As Chart 2 highlights, the guidelines and programs the IWRP-Doce (2010-2020) proposed to solve the problems of the basin and achieve the desired goals were also affected as they were based on the Diagnosis and Prognosis stages. While the goals established for the basin aimed to improve the quality, quantity, and management of water resources based on a pre-disaster scenario, the technological disaster associated with the collapse of the Fundão dam generated acute and chronic impacts (*Rede Rio Doce Mar, 2019; Vaneli et al., 2022*) that altered many relations and characteristics in the IWRP-Doce (2010-2020) diagnosis.

Alves et al. (2019) found at least two effects in the IWRP guidelines and programs: 1) parameters such as aquatic biodiversity and metals — less prominent than those related to sewerage (such as thermotolerant coliforms) and erosion (such as turbidity) — have gained importance after the disaster; and 2) the difficulty of achieving the goals originally proposed by the IWRP-Doce (2010-2020), established before the technological disaster, given that after the disaster there was a greater concentration of efforts to recover what had been impacted, instead of continuing to implement the actions that had already been planned.

4.2.2. Effects on the action plan

This section analyses and discusses in great detail — a microanalysis — the effects of the technological disaster on the seven thematic lines that constitute the action program of the IWRP-Doce (2010-2020). Chart 3 illustrates the thematic lines of the IWRP-Doce along with their respective objectives and summarises the disaster's impact on these themes. It's important to note that each thematic line encompasses a set of programs, projects, and actions that are part of the IWRP-Doce action plan.

Water Quality (I) and Water Quantity (II). Further analysis of water quality highlighted the effects of the technological disaster. The IWRP-Doce (2010-2020) was prepared in 2010 to improve the basin's water quality over the following years. However, the 2015 technological disaster worsened the basin's water state, particularly in terms of water quality.

The contributions of mining tailings and sediments from the collapse of the Fundão dam made it even more challenging to define and discuss proposals for the desired water quality targets, which were addressed in the update of the IWRP-Doce. For instance, in the pre-disaster scenario, the IWRP-Doce (2010-2020) described the '[...] control of erosion and the accelerated silting process observed in the water bodies of the basin [...],' particularly due to land use and occupation, as '[...] the greatest technical and operational challenge of the program [...]' (Comitê da Bacia do Rio Doce, 2010d, p. 81). The technological disaster exacerbated this challenge since the wave of mining tailings impacted the affected water bodies, raising levels of suspended sediment, mischaracterizing banks and riverbeds, and increasing siltation (Vaneli et al., 2022). Consequently, tributary basins should demand further actions to ensure that the quality of the Doce river's water aligns with the predominant planned uses.

The technological disaster demonstrated that extracting water from the affected water bodies became more difficult due to the uncertain (and, in some cases, inferior) water quality in some areas. This uncertainty led several water resource users to seek alternative sources of groundwater and surface water, while others began using mineral water due to temporary stoppages in water extraction from the Doce River. As highlighted in Chart 3, this sudden change in water source can transfer, generate, or exacerbate conflicts over water use in these new areas.

Susceptibility to Floods (III). As for floods, the Doce River Basin Alert System has been in operation since 1997 (Comitê da Bacia do Rio Doce, 2010a, p. 408). Despite the alert system's objective usefulness in reducing natural disaster risks, it is interesting to consider how effective this system was during the passage of the tailings wave during the technological disaster, and whether it might be time to develop a specific system for such events. Additionally, integration with Civil Defence, which had a greater focus on flood-related disasters, was given the highest priority for implementation in the plan.

Universalization of Sanitation (IV) and Increase of Legally Protected Areas (V). Regarding the universalization of water supply and sewerage (in Brazil, both are generally included under the term sanitation), the plan aimed to increase the environmental sanitation indicator to the state average, but had limited financial resources to do so. After the disaster, financial resources were made available through Transaction and Conduct Adjustment Term to the affected municipalities for the preparation or revision of municipal sanitation plans, the development of sewage system projects, and the implementation of sewage collection and treatment facilities (Vaneli et al., 2022).

Similarly, actions within the plan to increase legally protected areas were mainly focused on erosion control in the basin. In this context, one of the impacts of the technological disaster was the suppression of vegetation in these areas (called 'permanent preservation areas' in Brazil) along the banks of rivers affected by the tailings wave (Vaneli et al., 2022), especially in the stretches closest to the dam site. To compensate for the damages, the Transaction and Conduct Adjustment Term established reforestation measures in various areas of the basin, whether directly affected or not.

Implementation of Water Resources Management Instruments (VI) and Implementation of IWRP-Doce Actions (VII). Finally, the last two themes aim to improve the integration between key actors and water resources management instruments, and strengthen their implementation. In the IWRP-Doce (2010-2020), the programs were so interdependent that the non-implementation, incomplete, or ineffective execution of any proposed action could compromise the achievement of other goals (Comitê da Bacia do Rio Doce, 2010d, p. 50). In line with this premise, the technological disaster associated with the collapse of the Fundão ore tailings dam affected the entire plan.

However, after the disaster, both the strengths and weaknesses in implementing instruments to support the management of water resources in the Doce River basin became apparent. For example, actions related to inspection and monitoring increased. Firstly, having the National Water Resources and Sanitation Agency (ANA) as a focal point for dam supervision at the national level aids in the integration of WRM-TDRM. Moreover, research required by the Renova Foundation – such as the Systematic Qualitative-Quantitative Monitoring Program for Water and Sediment and the Aquatic Biodiversity Monitoring Program – and independent studies aimed to fill data and information gaps.

This monitoring and enforcement information can be highly beneficial to the Basin Water Resources Information System. Nonetheless, other instruments — such as water charges and water permits — which already had a low level of implementation in the basin, may remain difficult to implement in the post-disaster scenario. Part of the new difficulties in implementing these instruments may arise due to post-disaster information conflicts, which generate uncertainties regarding the real quality of the water (Espindola et al., 2019, p. 149).

Chart 3 - Major themes of the IWRP-Doce action plan, their respective objectives and the disaster effects.

Major Themes	Objectives	Disaster effects
I - Water Quality	Gradually improve water quality in the most critical areas. Servicing the water-quality objectives in the usage classes.	Prioritization of actions to repair and restore the quality of water impacted by mining tailings, and proposing new water quality goals and objectives.
II - Water Quantity — Water Balances	Achieve a scenario with no water deficits, which would meet consumptive uses. Eliminate, reduce, or manage situations of use conflict throughout the year and ensure the predominance of the most noble uses.	Explore the supply of an alternative source, possibly changing water balance; Shifting conflicts to new sources.
III - Susceptibility to Floods	Reduce flood damage.	Altering flood areas, especially in the region before the Risoleta Neves hydropower plant.
IV - Universalization of Sanitation	Increase in the environmental sanitation indicator up to the state average	Promoting actions regarding Transaction and Conduct Adjustment Term; new sources of funding emerge.
V - Increase of Legally Protected Areas	Achieve 10% of areas under formal protection, with at least one fully protected conservation unit in each tributary basin and institute a consistent action to restore permanently protected areas in the basin.	Renova Foundation implemented actions to recover legally protected areas and reforestation actions, both where the tailings suppressed vegetation and in areas beyond the collapse impact.
VI - Implementation of Water Resources Management Instruments	Implement all Water Resources Management Instruments (basin plan, water-quality objectives in the usage class, grant, collection, information system).	IWRP weakening regarding the charge for the use of fresh water and the charter; reinforcement of the Importance of implementing a water-quality classification for water bodies pointed out the need for the Water Resources Information System to be interconnected with data on dams.
VII - Implementation of IWRP-Doce Actions	Establish an organizational structure (material, human resources, and procedures) that supports the management of IWRP-Doce actions.	The institutional arrangement that emerged after the disaster, when the Transaction and Conduct Adjustment Term was implemented, removed the centrality of the Doce River Hydrographic Basin Committee over the basin's water resources management, reducing its strength as the main articulator — a fear that had been registered in the executive report of IWRP-Doce (Comitê da Bacia do Rio Doce, 2010d, p. 78).

Regarding the implementation of IWRP-Doce (2010-2020) actions, although financial issues have been one of its greatest obstacles, 'the lack of financial resources [...] is not an exclusive prerogative of the Doce River basin' (Comitê da Bacia do Rio Doce, 2010d, p. 78). Thus, IWRP-Doce considered it a priority to initiate an institutional arrangement that, by approving the operation of a basin agency to support the Doce River Hydrographic Basin Committee, would enable the acquisition of its own resources. Without this, guarantees for resource allocation or the involvement of other partners could not be obtained. Consequently, an adequate and strengthened institutional arrangement was essential for the success of the basin WRM in achieving the established goals as planned.

In this context, the Brazilian tradition shows that when water resources management lacks its own financial resources, the water management system ceases to be a reference, and the actors in the basin begin to seek resources and support from other environments (Comitê da Bacia do Rio Doce, 2010d, p. 78). Hence, as previously discussed, after the technological disaster, a new political-institutional arrangement was formed in the basin, with new actors taking the lead (Renova Foundation and Interfederative Committee), and the Transaction and Conduct Adjustment Term began to gain the space that was previously occupied only by the IWRP-Doce.

In short, we agree with Alves et al. (2019) that the IWRP-Doce (2010-2020) was intended to be a robust plan but failed to cope with the technological disaster. As demonstrated, the existence and incorporation of aspects that favour indirect integration between WRM and TDRM in water resources planning are insufficient to prepare infrastructures against the impacts of technological disasters. In addition to considering aspects that favour indirect integration between WRM and TDRM, the consideration of aspects that favour direct integration between these managements should be strongly encouraged. Ideally, this should be clearly and explicitly signalled and described in the ToRs that guide the preparation of water resources plans. Thus, a trend seems to be established: the greater the emphasis on a subject in the ToR, the greater the emphasis it will have in the plan; the less it appears in the ToR, the less likely it is that the aspect will be considered — as was the case with the TDRM in the IWRP-Doce.

The results so far point to the need for a more comprehensive view of water resource management and risk and disaster management in general, from the perspective of water security based on acceptable risk. Based on the literature on water security (Grey & Sadoff, 2007; United Nations Water, 2013; Hall & Borgomeo, 2013; Garrick & Hall, 2014; Octavianti & Charles, 2019; Marcal et al., 2021), and inspired by the discussions of Allan et al. (2018), we can define water security, from a broad perspective, as “the degree to which agreed water needs are met sustainably, accompanied by an acceptable level of risk of failure to meet those needs”.

Under this definition, the Water Resources Plan is one of the instruments that establishes agreements to meet water needs. However, it is not the only one, since several other agents that exercise power over the territory deal with water needs that are not within the scope of a water resources plan or water resources management itself (Octavianti, 2020). Even so, the needs that a water resources plan (and other plans related to water security) aims to meet are often fraught with uncertainties related to ensuring that they are met and to the scenarios that can be formulated for analysis and planning (Cunha, 2023; McMillan et al., 2018; Rinaldi, 2023; Pérez-Blanco, 2022).

This leads to at least two main considerations: one regarding the robustness of the proposed solutions and the other regarding collaboration between the multiple actors, due to the powers they exercise.

For the first consideration, the constant changes in contemporary society (climatic, political, land use, etc.) should lead to a paradigm shift among planners, so that they do not consider risks as stationary or fully controllable (Pahl-Wostl et al., 2008; Pérez-Blanco, 2022). Thus, planning must evolve from the pursuit of absolute control to the adaptive management of water risks at levels acceptable to the community in the territory in question (Pahl-Wostl et al., 2008). Given that risks are intrinsically linked to uncertainties (Aven, 2023), and that uncertainties are increasingly profound, with multiple plausible future scenarios (Pérez-Blanco, 2022; Cunha, 2023), plans need to be robust in their actions, which implies: i) avoiding policies that lead to unfavourable contingencies that can be identified in advance; and ii) avoiding trajectories dependent on specific paths, so as to allow future adaptation to unpredictable events (Pérez-Blanco, 2022). In this context of uncertainty, a really robust plan would be one that performs satisfactorily in most conceivable futures (Pérez-Blanco, 2022).

Regarding the second point (collaboration between multiple actors), it should be noted that, in the pursuit of water security, needs are interconnected, with multiple sectors able to exercise decision-making power in the territory. The sustainable development of the region, therefore, depends on effective collaboration between these actors who exercise power over issues involving water (Loucks & Beek, 2017; Maganda, 2016; Pahl-Wostl, 2017; Octavianti & Charles, 2019; Quintslr et al., 2021; Rahman et al., 2024). The Mariana Disaster is an example of this dynamic, illustrating cascading disasters, where an initial technological accident triggers linear and non-linear losses that spread through interconnected water, energy, and food systems (Rahman et al., 2024). In the face of events such as these, it is understood that compartmentalized planning, focused only on specific sectors, without the broad involvement of all those who can intervene or influence the problem, hinders prevention and slows down the appropriate response that would be appropriate to multiple risk events (Rahman et al., 2024).

4.3. Identification of the challenges and potentialities in WRM-TDRM integration in the Doce River basin and proposal of guidelines

Analysis of the ToRs and the effects of the Fundão dam collapse on the IWRP-Doce (2010-2020) revealed strengths and weaknesses in providing greater integration between WRM and TDRM in the Doce River basin. Meanwhile, the federal government’s responsibility over the Doce River highlighted some aspects that were external to the basin (opportunities and threats). In Charts 4 and 5, in that order, the conducted SWOT analysis and the proposed guidelines to promote the integration between WRM-TDRM are presented.

Following the SWOT matrix analysis, the strengths of the WRM in the Doce River basin showed that the planning was not limited to the implementation of routine management instruments in support of the water resources policy (corresponding to strength S1), which is an advance, although it requires improvement in the operationalization of the management instruments in the face of crises (corresponding to weakness W1).

As an example of the strong aspect (strength S1), it can be seen that the plan and the ToRs explicitly refer to ‘Compensation to Municipalities’ and ‘Water Allocation’, instruments not listed in the National Water Resources Policy — certainly, this Policy does not limit the instruments that can be used in water resources management only to those listed (Porto & Porto, 2008). The plan has also been following the proposal that water resources planning instruments be executed in an integrated manner.

Continuing to strive for continuous improvement of this internal WRM integration may help the plan overcome the difficulty in applying management instruments, especially in extreme scenarios, that is, outside the routine of water resources management (weakness W1). Therefore, it is recommended (corresponding to guideline G1) to promote WRM-TDRM integration by strengthening, diversifying, and integrating WRM management instruments so that they can be used even in situations of natural and technological disasters.

Other strengths highlighted refer to the robustness of the IWRP-Doce (2010-2020) and the search for an operational plan in both analysed ToRs (strength S2), even though they are counterbalanced by the lack of preparation and prevention against technological disasters (weakness W2). Regarding robustness, many issues that this study considered as necessary aspects for WRM-TDRM integration (especially indirect ones) appeared in the IWRP-Doce (2010-2020) and in the ToRs. On the other hand, this plan disregarded issues related to technological disasters, such as dam collapses, which made it unable to handle this situation.

Chart 4 - SWOT analysis of WRM-TDRM integration in the Doce River basin.

	Potentialities	Challenges
Inner (Doce River Basin)	Strengths (S) <ul style="list-style-type: none"> • S1 - Internal integration between WRM instruments beyond routine instruments; • S2 - Robust IWRP-Doce (2010-2020) and update with a focus on the operationality of the plan; • S3 - Social and governmental participation in an integration committee model (Doce River Hydrographic Basin Committee); • S4 - The integration of Doce River Hydrographic Basin Committee (and IWRP-Doce) with Civil Defence for the management of risks and natural disasters can bridge the incorporation of TRDM; • S5 - Incorporation of the Transaction and Conduct Adjustment Term into the IWRP (for recovery and compensation actions); • S6 - Research and monitoring projects that generate information for managers. 	Weaknesses (W) <ul style="list-style-type: none"> • W1 - Difficulty in the application and operationalization of WRM instruments, especially in extreme event scenarios; • W2 - Lack of incorporation of guidelines in the new ToR for prevention and preparedness for technological disasters; • W3 - Lack of perception of the risk of contamination of water resources by technological accidents; • W4 - Fear that TRDM will overshadow the objectives of the IWRP; • W5 - The disaster risk management in the documents focuses on natural hazards and fails to address risks and disasters that holistically affect water resources; • W6 - Lack of a trigger to update the plan in cases of crisis.
	External (Brazil)	Opportunities (O) <ul style="list-style-type: none"> • O1 - Growth of national learning about the risks of dam failures, which highlights the need for prevention; • O2 - National Water Resources and Sanitation Agency as an articulating agent in the management of the risks of dam failures; • O3 - Occurrence of training actions on the subject.

Chart 5 - Guidelines (G) for the integration of WRM-TDRM in the Doce River basin.

G1 - Promote the strengthening, diversification, and integration of WRM instruments so that they can be used in natural and technological disaster situations.
G2 - Invest in the development and implementation of strategies to unite WRM with TDRM, especially in river basins that have activities that can cause technological disasters.
G3 - Foster the integration of the water resources management system with Civil Defence, working in water resources planning and joint preparation for natural and technological disasters.
G4 - Facilitate the articulation of the water resources plan with other management instruments whose objectives are to respond to previous disasters.
G5 - Support the development of research and monitoring that assists in the execution of studies to evaluate the “before and after” impact scenarios and develop knowledge on WRM-TDRM integration.
G6 - Advocate for the design and development of methodologies that support WRM-TDRM integration.
G7 - Conduct an inventory to identify sectors and companies whose activities can trigger technological disasters related to water resources.
G8 - Ensure that sectors and companies that may cause technological disasters have specific risk prevention and management plans and that the implementation of these plans is closely monitored by water resource management bodies, civil defence, and other legally competent bodies.
G9 - Promote the perception of risk related to the occurrence of technological disasters from the phase of drafting a ToR for water resources planning, focusing on preparation and prevention.
G10 - Work to ensure that the ToRs explicitly outline actions aimed at promoting the integration between WRM and TDRM in water resources planning, addressing the topic with focus and providing general methodological guidelines on how this can be achieved.
G11 - Ensure that issues of responsibility of other actors, whose practices may affect the quality and quantity of water resources, are also considered in the plan.
G12 - Support the operability of the water resources plan through the formulation of a mechanism that allows its adaptation during crises.
G13 - Advocate for learning from previous disasters by training actors to prevent, prepare for, and respond to possible new disasters.
G14 - Promote the study of the potential impact of other technological disasters (beyond those related to dam failures) on water resources, which can provide relevant information for strengthening WRM-TDRM integration.

Regarding operability, it is a characteristic that tends to enhance WRM-TDRM integration. The desire to build a functional plan implies the need to consider the risks that may lead to its failure. As discussed in this paper, technological disasters pose a risk to water resource planning that requires consideration (Roche et al., 2017; Rahman et al., 2024). Therefore, it is essential to invest in the definition and implementation of strategies to unify actions of WRM with TDRM, especially in river basins where activities with the potential to generate technological disasters exist (such as the Doce River basin) (guideline G2).

It also became evident, as an internal potential in the SWOT analysis, the search for integration with actors and management instruments from other sectors operating in the basin (strengths S3, S4, and S5). Social participation (strength S3), enabled by the water resources collegiate system, is essential for both WRM and TDRM. The IWRP-Doce (2010-2020) prioritised articulation with Civil Defence in risk management and natural disaster issues (strength S4). Additionally, the updated version of the IWRP-Doce (2023-2042) sought integration with the Transaction and Conduct Adjustment Term instrument, marking a beginning for WRM-TDRM integration, especially concerning disaster response actions (strength S5). Therefore, considering the discussed strengths, guidelines can be indicated as follows: improving and encouraging the integration of the water resource management system with Civil Defence, working in water resource planning and joint preparation for natural and technological disasters (guideline G3); and encouraging the articulation of the water resource plan with other management instruments whose objectives are to respond to previous disasters (such as Transaction and Conduct Adjustment Term and its subsequent agreements) (guideline G4).

As a final strength aspect in the SWOT matrix (strength S6), the tendency to produce information about the technological disaster and its effects was verified, which can help overcome the lack of practical methods and limited experience to promote the integration of WRM and TDRM (a challenge, external to the basin itself, related to threat T1). Regarding strength S6, it was observed that emerging

research and monitoring (such as the Qualitative-Quantitative Monitoring Program and the Aquatic Biodiversity Monitoring Program, under the former Renova Foundation, now the 'Repairs Doce River Basin' entity, in Portuguese, '*Reparação Bacia do Rio Doce*') have already generated relevant information about the 'before and after' of the disaster, which can assist in deepening knowledge about WRM-TDRM integration. As for the mentioned threat (threat T1), this study found no suitable methodology for integrating the studied management instances, highlighting the need for research to fill this gap. Therefore, it is evident that scientific studies focused on pre- and post-disaster scenarios and the creation of methodologies to integrate WRM and TDRM are necessary guidelines for planning water resources in river basins (guidelines G5 and G6).

With reference to the plan's weaknesses, it was found that the lack of explicit incorporation of technological disaster risk management in water resource plans may stem from at least two factors: lack of risk perception (weakness W3) and fear of adding too many topics to the plan (weakness W4).

The lack of risk perception (weakness W3) can be explained by several factors, among which stand out: the culture of considering only risks related to more frequent events or those that have recent examples in popular memory and the lack of sufficient data and information about these risks (Slovic et al., 2004; Levasseur et al., 2024). For example, the 2020 ToR only addressed dam failures — just one of the many technological disasters that can affect water resources and that still remain in popular memory. This approach was mainly due to the connection with Transaction and Conduct Adjustment Term, which, despite supporting the response and recovery phases of the disaster caused by the Fundão dam rupture, did not emphasise prevention and preparation against other technological risks in the basin. Therefore, three guidelines can be proposed from this weakness. First, a greater perception of risks could arise through the preparation of an inventory that identifies companies whose activities can contaminate water resources (guideline G7), similar to those produced for the Danube River basin in Europe and the Paraíba do Sul River basin in Brazil. Second, with or without an inventory, it is still necessary to ensure that sectors and companies with the potential to cause technological disasters have specific risk prevention and management plans and that the implementation of these plans is closely monitored by water resource management bodies, civil defence agencies, and other legally competent bodies (guideline G8). Third, it is important to address the perception of risk related to the occurrence of technological disasters and WRM-TDRM integration already in the ToR preparation phase (guidelines G9 and G10), continuing with water resources planning.

Regarding the fear of adding too many topics to the plan (weakness W4), a common concern refers to the development of water resource plans that cannot extend their scope beyond their objective (Lanna, 2001, p. 217; Zoby, 2015, p. 200). In this context, several points of the new ToR indicate that the proposed actions should be those where the Water Resource Management System is governable, notably those actions attributed to the Hydrographic Basin Committees, the water resource management bodies, and the delegated entities (Agência Nacional de Águas, 2020). However, this study emphasises that focusing on planning along these lines does not necessarily guarantee its operability. For when an action is of interest to water resource management, it must be considered in water resource planning, even if it is the responsibility of another public policy sector, so that this planning increases its chances of being effective. The IWRP-Doce (2010-2020) stands out positively in this perspective. For example, the plan includes guidelines on the full protection of areas and the establishment of conservation units, which are the responsibility of the National Environment System, that is, environmental policy. Another example is water supply and sewerage in the basin, where, in Brazil, financing usually comes from sources other than water use charges, but which the IWRP-Doce (2010-2020) sought to articulate due to the importance of the issue for water resource policy. Consequently, issues that fall under the responsibility of other actors, whose practices can affect the quality and quantity of water resources, also need to be addressed or at least considered in the plan (guideline G11), which can be done through guidelines for articulation with these actors.

Still in this context, it was found that the water resources plan did not consider or value the management of technological disaster risks (weakness W5). Considering the management of natural and technological disaster risks together is a promising way to have a more holistic view of the hazards and risks existing in basins, such as the Doce River basin — given its management instruments like the flood alert and alarm system implemented there. In this regard, one of the highest priority goals in the IWRP refers to the coordination between the Doce River Hydrographic Basin Committee and Civil Defence. The main lesson learned from these events is that the cost of remediation is always much higher than the introduction of appropriate safety measures, regardless of implementation costs (International Commission for the Protection of the Danube River, 2019); this was the conclusion reached in the Integrated Management Plan for the Tisza River Basin two decades after the collapses of the Baia Mare and Baia Borsa ore tailings dams in the Tisza River basin, a tributary of the Danube River.

Another weakness of the plan was the lack of a mechanism that would allow its update and correction during crises such as technological disasters (weakness W6). This weakness could mean that the entire plan will be doomed to ineffectiveness in the event of a disaster and without any forecast of actions to be implemented for this situation. Therefore, it is necessary to study an adaptive management model to be considered in the water resources plan in a way that prepares it for possible new occurrences and makes it adaptable (guideline G12) (Pérez-Blanco, 2022). One possible example from which to draw initial inspiration is the Brazilian Civil Defence Contingency Plans, which are generally updated annually or after each disaster.

Finally, some national opportunities emerged shortly after the Mariana disaster to support WRM-TDRM integration (related to opportunities O1, O2, and O3), which can serve as preliminary ways to deal with the possibility of other types of technological disasters (threat T2). The lessons learned about dam safety (opportunity O1), the fact that National Water Resources and Sanitation Agency is a focal point for dam safety (opportunity O2), and the training conducted by Civil Defence and National Water Resources and Sanitation Agency on the subject tend to be very useful for various basins (opportunity O3). Actions of this nature should be encouraged (guideline G13). Nevertheless, much needs to be developed regarding the incorporation of other disasters into water resource planning, beyond those related to dam ruptures. It seems that the risks of disasters related to the transportation of hazardous materials and accidents related to other types of enterprises continue to be overlooked in water resource planning, so addressing actions on this topic is a necessary step forward (guideline G14).

It is highlighted that the development of this study faced some challenges that could be addressed in future research, especially regarding the limitations of tools for scenario and plan analysis and the establishment of strategies for implementing the proposed guidelines. First, although the SWOT matrix is a valuable analysis tool, it is known to simplify some systemic complexities, a limitation that could be addressed through the incorporation of interviews with stakeholders or field data to further strengthen the investigation in future studies. Secondly, it is recognised that the strategies necessary for implementing the proposed guidelines may vary depending on several factors (such as available resources, involved stakeholders, and priority areas), and therefore were not detailed in this work. Moreover, the existence of few studies on the impacts of technological disasters on water resources planning prevented a broader comparative analysis with other international case studies.

5. Conclusion

Despite the limited literature on the subject, this work identified and discussed aspects that globally enhance or challenge both the integration of Water Resources Management (WRM) with Technological Disaster Risk Management (TDRM) and the incorporation of TDRM into water resources planning. It was based on the premise that such integration is strategic for the prevention and reduction of water-related risks, and that technological disasters — although often treated as unforeseen accidents — can significantly disrupt territorial planning, including water resources planning.

Using the impact of the Fundão Dam Collapse (Minas Gerais, Brazil) on the planning of the Doce River Basin Integrated Water Resources Plan (IWRP-Doce) as a case study, it was observed that the robustness of a plan — by considering only indirectly favourable aspects for WRM-TDRM integration but not directly favourable ones — is not sufficient to prepare it to face the crisis resulting from a technological disaster. Among the main reasons for this are the lack of explicit incorporation of TDRM and the absence of preparedness, prevention, and adaptation mechanisms from the Terms of Reference drafting phase onward.

The analysis conducted allowed for the identification of strengths, weaknesses, opportunities, and threats that directly influence the potential for integration between WRM and TDRM. Based on this analysis, the study proposed a set of 14 strategic guidelines in support of this integration within water resources planning. Due to the general nature of the proposed guidelines, and considering both the size of the studied basin (with dimensions similar to those of Portugal) and the magnitude of the disaster, they can assist in the water resources planning of river basins with characteristics similar to those of the Doce River Basin and hold particular value for regions with transboundary basins.

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