Strengths and weaknesses of a hybrid post-disaster management approach: the Doce River (Brazil) mine-tailing dam burst

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Abstract

Mine tailing dam bursts occur frequently with attendant implications for the environment and human populations. Institutional preparedness for such events plays an important role in their lasting impact. This study analyzes the stakeholder engagement in the new~~ly~~ governance framework created to recover the Doce River ecosystem following the 2015 disaster, where 34 million m^3 of tailings were released, killing 19 people and causing massive impacts on riverine life. Following the disaster, poorly conceived political and management decisions impeded and continue to impede the progress of ecosystem recovery. The post-event management structure shows a centralized and poorly diverse stakeholder pool. We conclude that poor governance structure, and weak law enforcement, are among the main reasons preventing the Doce River post-disaster watershed recovery. A watershed vulnerability analysis ~~combined~~ combining dam stability and socioeconomic data, ~~concluding~~ concluded that low ratings of socioeconomic performance substantially increase~~s~~ basin vulnerability. We recommend that the watershed committee should be fully involved in the implementation of the program and take a central role so that the most vulnerable communities (including indigenous people) take ownership of ecosystem recovery~~, including indigenous people~~.

Keywords: tailing pond, tailing dam, impoundment failure, Doce River, mining industry, environmental policy and governance, environmental impact assessment

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Glossary

FUNAI - National Indian Foundation (Fundação nacional do Índio)

Fundão tailing dam - Dam owned by Samarco that ruptured on the 5th of November 2015

Candonga dam - one of the 4 main hydroelectric dams retaining the tailings downstream the Fundão tailing dam

Samarco - Samarco Mineração S.A., mining industry co-owned by VALE and BHP Biliton

BHP Billiton - BHP Billiton Brasil Ltda.; Samarco´s co-share participant

VALE - Samarco´s co-share participant

MMA - Ministry of the Environment (Ministério do Meio Ambiente)

MME - Mining and Energy Ministry (Ministério de Minas e Energia)

IBAMA - Brazilian Institute for the Environment and Renewable Natural Resources (Instituto Brasileiro do Meio Ambiente e dos Recursos Naturais renováveis)

ICMbio - Biodiversity Conservation Chico Mendes Institute (Instituto Chico Mendes de Conservação e Biodiversidade)

DNPM - National Department of Mineral Research (Departamento Nacional de Pesquisas Minerais)

ANA - Water National Agency (Agência Nacional de Águas)

SEAMA - Espírito Santo State Secretary for the Environment (Secretaria de Meio Ambiente para o Estado de Espírito Santo)

SEAG - Espírito Santo State Secretary for Agriculture and Fisheries (Secretaria de Agricultura e Pesca do Estado do Espírito Santo)

IEMA - Institute of Environmental and Water Resources of Espírito Santo (Instituto Estadual do Meio Ambiente e Recursos Hídricos)

IDAF - Espírito Santo Agriculture, Animal Husbandry and Forestry Institute (Instituto de Defesa Agropecuária e Florestal do Espírito Santo)

AGERH - Espírito Santo State Agency of Water Resources (Agência Estadual de recursos Hídricos do Espírito Santo)

SEMAD - Minas Gerais State Secretary for the Environment and Sustainable Development (Secretaria de Estado de Meio Ambiente e Desenvolvimento Sustentável de Minas Gerais)

FEAM - State Environmental Agency of Minas Gerais (Fundação Estadual do Meio Ambiente - Minas Gerais)

IGAM - Minas Gerais Water State Institute (Instituto Mineiro de Gestão das Águas)

IEF - Minas Gerais Forestry State Institute (Instituto Estadual de Florestas - Minas Gerais)

CPRM - Mineral Resources Research Company (Companhia de Pesquisa de Recursos Minerais)

CIF - Inter-State Committee (Comitê Inter-Federativo)

RENOVA Foundation - Foundation managing the new Framework Agreement

MPF – Federal Prosecutors' Office (Ministério Público Federal)

1. Introduction

The mining industry has experienced several significant impoundment failures over the past 30 years (Davies et al., 2000; Davies, 2002; Rico et al., 2008) (Table 1). Tailing dam failures account for roughly 75% of mining-related environmental disasters worldwide~~-~~ (MMSD 2002). While there is a considerable literature on the geotechnical aspects of dam failure and on the pollution-related aspects of their impact (e.g. ~~(~~Rico et al. 2008), there has been relatively little research on the role of authorities in undertaking appropriate post-disaster actions. In this paper we document and evaluate the institutional response to the 2015 failure of a tailings dam in Brazil.

The 83,400 km² Doce River watershed spreads over two states - Minas Gerais and Espírito Santo (Figure 1). Due to its transboundary status, the Doce is administered at the Federal level by the Federal Water Agency (ANA) with regional watershed management committees. The overall land use in 2014 consisted of 72% farm land, 0.9% urban area, 6.6% husbandry and 19.2% natural area (IBGE 2016). As a tropical or sub-tropical region, it has two distinct seasons: wet summer from September to March, and dry winter from April to August. The Doce River is one of the most important on the East Brazilian coast (Oliveira et al. 2012) and hosts a population of circa 3.5 million inhabitants and an extensive dam system, with about 140 hydropower reservoirs of different scales (ANA, 2015). The Doce still hosts indigenous communities - the Krenak and the Pataxó. These two groups include 179 individuals and are under the tutelage of the National Indian Foundation (FUNAI).

On November 5th, 2015 a tailing dam collapsed upstream of the Doce River, state of Minas Gerais, Brazil, constituting the world's largest mining disaster in terms of volume (Table 1). The *Fundão* tailing dam released 34 million m³ of tailings to the Doce River watershed. This caused the disruption of the entire fluvial-marine continuum, including impacts on the local population (circa 700,000 inhabitants), domestic water supply, and irrigation. On the 21st of November 2015, tailings reached the coast of Espírito Santo leaving behind 19 human ~~casualties~~fatalities, 14 tons of macro-fauna (mainly fishes) killed by asphyxia, 1,469 ha of affected riparian vegetation, and a negative impact on over 660 km of the Doce River (IEMA 2017). Subsequent studies identified ecosystem service losses of over US$ 521 million per year (Garcia et al. 2017) in the Doce River watershed.

The ruptured dam was located in the mining complex known as Iron Quadrangle (Quadrilátero Ferrífero), Minas Gerais state, and is considered the largest open pit mining industry in the world (Santolin et al. 2015). Brazil produces 18% of the 2.33 billion metric tons of Fe-ore produced annually worldwide (Tuck 2015). Part of Brazil's recent economic growth is linked to the mining industry and its export of mineral commodities (from 1.6% in 2000 to 4.0% in 2014 of GDP). Samarco, one of the mining ventures exploring the area and owner of the ruptured dam, has an annual production capacity of more than 25 million tons of Fe-ore pellets and 1 million tonnes of Fe-concentrate. In 2014, Samarco had a revenue of US $2.6 billion in Espírito Santo (Samarco 2014), 0.3% of the 2015 Brazilian GDP according to The World Bank (World Bank 2017). Samarco's sales revenue is equivalent to 6,4% of Espírito Santo GDP and 1,6% of the Minas Gerais GDP (Samarco 2014). Vale S.A (Vale) and BHP Billiton Brazil LTDA are national companies that focus on mining, transportation, and production of ore. The two companies share ownership of Samarco (50% each).

Environmental impacts of dam failures are often more dramatic than other risks from mining (Grangeia et al. 2011; Kossoff et al. 2014), because of the quantities involved at the time of the disaster as well as the long-standing local, regional and even transboundary consequences to the economy and human well-being. Previous large-scale environmental disasters show that the post-disaster recovery can last for decades and sites will likely never return to the original state (Foley et al. 2005; Lima et al. 2016). Significant recent mining dam failures include the Merriespruit (South Africa) in 1994 (Fourie et al. 2000; Van Niekerk and Viljoen 2005) and the more recent Brumadinho tragedy (Porsani et al., 2019), among others (Table 1). In resource economy-based countries like Brazil, mining activities are a vital element for the economy. Sustainable resource exploitation should, however, be supported by well-structured environmental governance frameworks, to minimize environmental disturbance and prevent large-scale accidents (Schoenberger 2016). In the aftermath of the Doce River disaster, some suggested that fines and prosecutions could be used to finance ecosystem restoration (Meira et al. 2016), while others argued that weak official policies and poor monitoring, management and legislation would limit the degree of restoration (Nazareno and Vitule 2016). In the post-disaster period, a series of management actions were taken. The aim in this paper is to analyze the stakeholder engagement in the new governance structure created after the disaster and to propose ~~course correction~~amendments~~,~~ ~~to~~ that may help achieve the new governance structure's ~~effective~~ ultimate goal – ecosystem recovery.

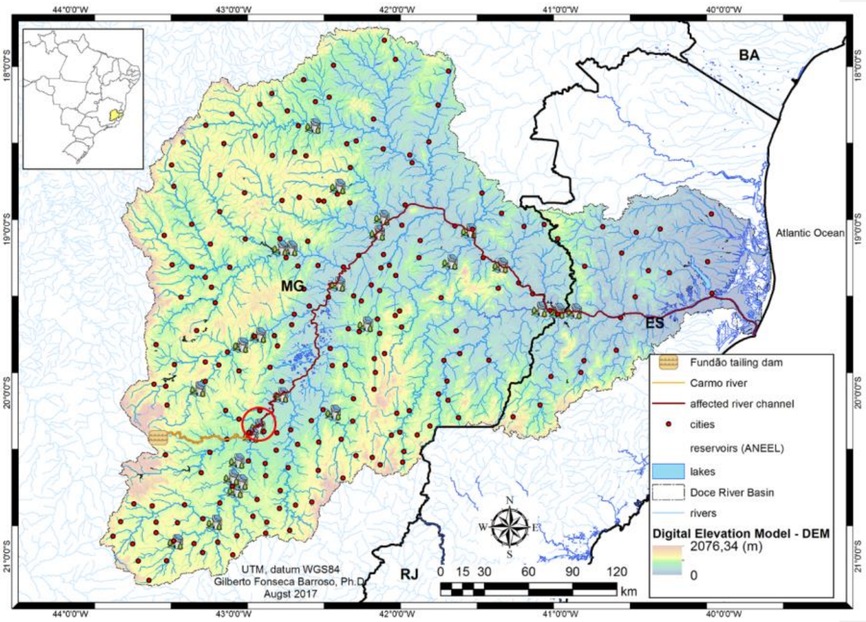

Figure 1 – Doce River Basin and impacted fluvial channel with mining tailings. Carmo River is identified in yellow; Candonga hydroelectric dam is circled in red. Legend: ES – Espirito Santo; MG – Minas Gerais.

2. Background

2.1. The Doce River disaster

The Fundão tailing dam (Figure 1) started operations in 2008 and had a capacity of 60 million m³ (500 m in length and 90 m in height). The first registered dam rupture ~~was~~ in 2009, ~~allegedly due~~was ascribed to base drainage defects (Samarco 2008). In 2011, a second incident occurred, with the release of tailings and refuse water (see Figure 1). In 2012, the tailing dam was restructured and upgraded (IBAMA 2016a). No contingency plan was in place for the Fundão tailing dam, nor for the Doce River watershed in the event of a dam failure.

The Fundão tailings dam ruptured on the 5th of November 2015. A total of 34 million m³ of mining ore tailings were released to the Doce River watershed (ANA 2015). Failure of the Fundão tailing dam affected more than 600 km of the river channel and the adjacent coastal area. 67.8 % (598.3 km) A total of 68 km of river channel was impacted.

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The 2015 flash dam rupture increased the Doce River surface flow from ~~the~~ 114 to 810 m³/s (CPRM 2015). These tailings had a specific density of 2 t/m³. Downstream of the tailing dam, the slurry gained momentum and flooded the towns of *Bento Rodrigues* and *Paracatu de Baixo* causing 19 casualties. The slurry progressed through the Carmo River and along the Doce River, annihilating 14 tons of freshwater fish, destroying 1,469 ha of land, 77 km of watercourses, and impacting protected areas and indigenous lowlands (IBAMA 2016b; IEMA 2017). Turbidity reached 33 g L^{-1} (Table 3), and sediments had enrichment factors of up to 4,000 in the case of Hg (Hatje et al. 2017), with average of 5 to the remaining trace metals (Gomes et al. 2017). After 16 days and 660 km, the slurry reached the Atlantic Ocean on November 21st, 2015. At this time, the Federal Prosecutors' Office (MPF) encouraged locals to collect live fish and safely guard them in nearby ponds and lakes while bystanders and researchers took sediment samples. Because there was no contingency plan in place, the MPF and other authorities had difficulty in taking decisions and coordinating the disaster aftermath (Figure 2). But several measures were taken:

- All marine fishery activities were banned at the coast (1500 km^2 sea area) for unlimited time by federal mandate;
- Freshwater fisheries were stopped in the middle and upper sections of Doce River, at the request of the state of Minas Gerais attorneys. Some communities have since officially resumed fisheries (Rodrigues 2017);
- Water supply was suspended;
- Risk assessment to other tailing dams was initiated (Morgenstern et al. 2016);
- Samarco committed to remove 1.3 Mm^3 of 10.5 Mm^3 tailings retained at Candonga's hydroelectric dam by February 2018 (Morgenstern et al. 2016)

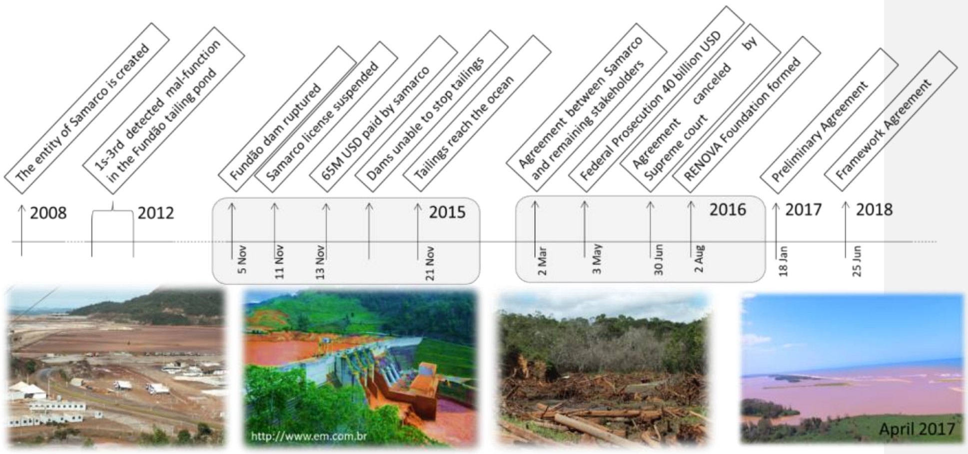


Figure 2 - A timeline following events in the upper Doce River, from the creation of Samarco (mining venture), the start of Fe-ore exploitation to the latest events regarding the ruptured tailing dam

Initially, the Brazilian Federal Police undertook an investigation to assess responsibility regarding the

Fundão tailing dam disaster. A parallel investigation ~~was~~ instigated by the mining company ~~and~~ was carried out by an international law office~~,~~ ~~concluding~~ concluded that incidents reported since 2009 in tandem with operational issues lead to the rupture. Specifically, the failure was linked to damage to the original dam due to increased saturation; slime deposition; and concrete structural problems (Morgenstern et al., 2016). In addition, the National Department of Mineral Production (DNPM) had corresponded with the company in 2013 informing them that the drainage system was insufficient and there was a lack of monitoring instruments (MPF 2016a). At this point, the Brazilian Federal Police argued that the mining company took a risk to profit and issued an arrest warrant ~~of~~ for 8 Samarco S/A executives.

Four years after the disaster, despite criminal investigations and the environmental law enforcement the ecosystem impacts in the Doce River are still indeterminate, although the first studies on the impact have been already published (Hatje et al. 2017; Gomes et al. 2017). Presently, the 16 million m³ of ~~refuse~~ waste left in the tailing dam are still draining into the Doce River (Chiaretti 2017). Funds have been allocated to the recovery of the Doce River, but the act of recovery has not yet started. After rupture, 16 million m³ of ~~refuse~~ waste were left in the tailing dam. Today, 959 thousand m³ were removed to be treated, with 2020 as the deadline for dam closure (https://www.fundacaorenova.org/dadosdareparacao/terra-e-agua/#manejo).

2.2. Environmental Governance in Brazil

To understand the post-disaster decision-making process, it is necessary to comprehend how the Brazilian environmental governance system works. Section S2 details the main Brazilian regulatory entities and their relationships (Figure S2). At the National level the MMA, IBAMA, ICMBio, ANA have responsibility for the environment and the MME deals with energy and mineral production. The MME includes the DNPM, the entity that supervises and monitors tailing ponds. Regarding the Doce River, there are equally responsible entities at the State level: IEMA and AGERH in Espírito Santo and FEAM, IGAM and IEF in Minas Gerais. The Doce River Basin Management Committee was created in 2002, to achieve the goals set through the Integrated Water Resource Management Plan of the Doce River (PIRH-Doce). When a watershed is transboundary, management is supervised at the Federal level but implemented at regional/State level.

Brazil is a resource-economy country highly dependent on commodity exports. The belief that environmental compliance hinders economy growth has prioritized mining and weakened environmental regulating agencies. Lead mainly by the public sector, environmental protection is allocated scarce financial resources or is ill-distributed among the existing bodies. Lack of transparency and communication among state, agencies, institutes, and organizations, may be the culprit for the overall current standstill e.g. (El

Bizri et al., 2016; Westra et al., 2013). In this overall context, to deal with the Doce River disaster, a new Framework Agreement was created by Samarco S/A.

2.3. The new Framework Agreement

The jurisdictions of environmental and water resources management systems in Brazil are separate, and the Framework Agreement was designed to overcome this divide. The new *Framework Agreement* combines the efforts of several stakeholders to recover the Doce River after the disaster. Samarco S/A set up this framework on March 2nd 2016 with the intent to provide recovery of environmental damage to the communities affected and prevent delays at the Federal Supreme court. Samarco S/A made then a *Framework Agreement* between Vale S.A (Vale), BHP Billiton Brazil LTDA, Federal Government of Brazil (IBAMA, ICMBio, ANA, DNPM, FUNAI), the States of Espírito Santo (IEMA, IDAF, AGERH) and Minas Gerais (IEF, IGAM, FEAM). A fund of up to US$6.3 billion (20 billion BRL) was setup for clean-up costs (and not US$1.1-billion as cited by Nazareno and Vitule, 2016). The *Framework Agreement* represents a new type of structure in the national governance paradigm, bringing members of different governmental bodies into a 3-axis structure (https://www.fundacaorenova.org/quem-faz-parte/). It is the first hybrid governance system in Brazil.

The *Framework Agreement* consists of three new entities: a regulatory body Inter-Federative Committee (CIF) (Figure 3); an independent foundation entitled the RENOVA Foundation, and several technical boards (IBAMA 2018). The CIF has a multi-level structure, composed of members of Environmental Ministry, the Federal Government, the State of Espírito Santo, the State of Minas Gerais, Espírito Santo and Minas Gerais municipalities impacted, the Doce River Hydrograph Basin Committee and Public Defenders of the States (Figure 3) and has the authority to implement agreement acts. The Renova Foundation is established treasurer, responsible for managing the US$6.3 billion restoration fund and for developing, proposing, enabling and implementing plans, programs, and projects that tackle the above-mentioned environmental priorities. The technical groups discuss and implement socio-environmental and socioeconomic programs aiming at the recovery of the impacts.

Both the technical boards and the Renova Foundation respond to the CIF, in a hierarchical structure, and operate according to its ruling (https://www.fundacaorenova.org/quem-faz-parte/). Nevertheless, one major player is not involved in the *Framework Agreement*. This organization, MPF, the Federal Prosecutors' Office, is a separate administration focusing on promoting social justice and democratic rights and is the main institution with legitimacy to approve agreements and other legal protocols. MPF did not participate in the agreement, stating that "the considerations given by the MPF were not taken into account by the remaining parties of the agreement (…) resulting in partial and incomplete settings, illegitimate/illegal procedures". They regard the *Framework Agreement* as "unconstitutional in its merits" (MPF 2016b).

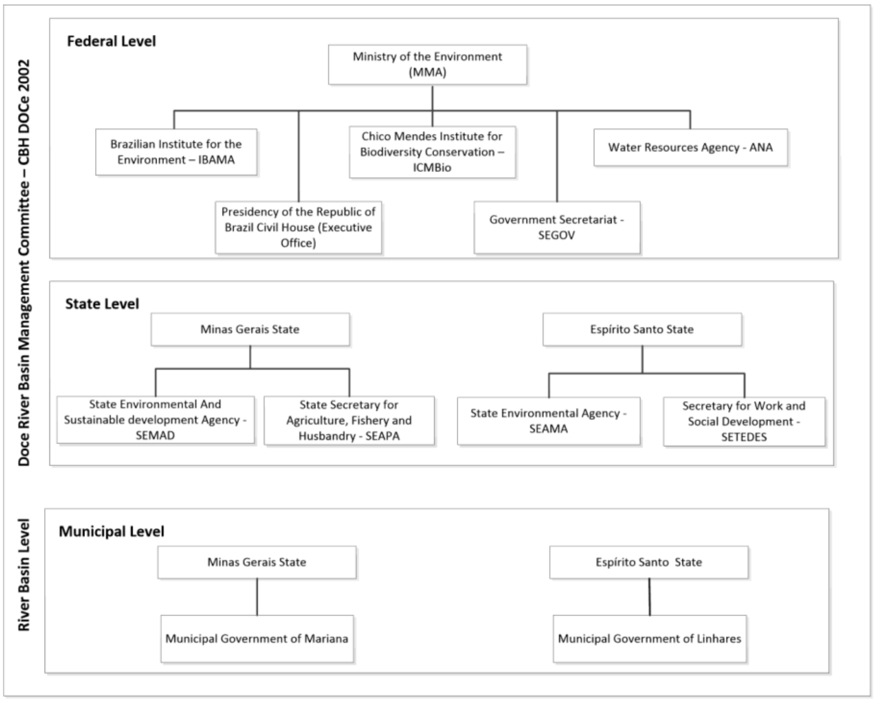


Figure 3 – Organogram representing the CIF and its multi-level structure.

3. Methodology

3.1. Stakeholder analysis

A narrative-based stakeholder analysis (Brown, 2006) focuses on stories that underpin our cognitive and emotional lives as agents of memory, emotion, and meaning (Brown, 2006). To derive a narrative-based stakeholder analysis, the authors based their viewings on the experience derived from the attendance of several Inter-State Committee (CIF) meetings (January/2016 – July/2018). Stakeholders were then evaluated and ranked according to the perceived importance and influence on they inferred during these meetings and the decision-making process itself. Brown (2006) defines the importance of stakeholder groups in terms of how their livelihoods were impacted by the outcome of decision-making and their influence over the decision-making process. In this study, we used 3 criteria to grade stakeholders: (i) effective communication in the CIF meetings, considering that some stakeholders were not represented; (ii) impact of the decisions on their welfare and well-being, and (iii) their level of interest in watershed restoration. A likert scale was then used, from 1 (low influence) to 5 (high influence), to qualitatively quantify the influence of each stakeholder on the process. If stakeholders possessed a similar grade, then they were placed close-together in the graphic (Figure 4a). Once the stakeholders were ranked, a stakeholder analysis was carried out according to Mitchell et al. (1997). Mitchell et al. (1997) identified 8 types of stakeholders according to their definitive power, legitimacy and urgency regarding the decision-making process: Dormant, Discretionary, Demanding, Dominant, Dangerous, Dependent, Definitive and the Nonstakeholder. Using the previously ranked stakeholders order, we then identified the type of each stakeholder involved in the Doce River restoration decision-making proces .

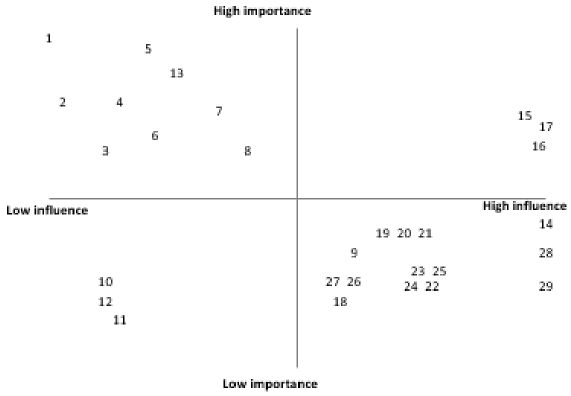
3.2. Basin vulnerability

A simple accumulated vulnerability index per major Brazilian basin was calculated using a dataset for tailing dam risk (DNPM 2016). Using the risk classes listed by the DNPM in combination with basin size (Table 2), we calculated the overall basin vulnerability (Table S1). The higher the vulnerability, the more likely the basin is to be impacted by a potential dam rupture. The dataset included a high number of non-classified dams (Table S1). We assumed that the missing data are due to either non-supervision or lack of personnel to collect data. Regardless, we considered two scenarios for such dams: a medium risk level for the missing data (vulnerability1, Table S1) and a high-risk level (vulnerability2, Table S1). Using available socio-economic data (Table S2), vulnerability was assessed (high, medium low) depending on the relative weight of each indicator. Maximum levels for each parameter were selected within the data-series (Table S2). Population and land use data were recalculated based on watershed limits (Figure S1), since official data were given per state (IBGE 2016; IBGE 2017). Vulnerability was then calculated as a percentage of each parameter maximum value. Vulnerability for each parameter was then defined as Low (if index is between 0-0,33), Medium (0,34 a 0,66) and High (> 0,67) and averaged to reach the final watershed vulnerability (Figure 5).

4. Results

4.1. Stakeholder Analysis

To evaluate stakeholders' role in the new framework agreement setup, a stakeholder analysis was carried out. The stakeholder analysis was based on Brown (2006), whose approach considers relative levels of influence and the importance of classifying stakeholders according to their power, values, and interests.



Legend:

Primary stakeholders	
1	Local communities
2	Local recreation users
3	Tourists
4	Recreation fishermen
5	Professional Fishermen
6	Hotel owners
7	Land developers
8	Industries
9	Watershed committee
10	AGERH
11	ANEEL

Secondary Stakeholders	
12	IDAF
13	Municípios
14	*Fundação Renova*
15	Samarco
16	Vale
17	BHP Billiton
18	MMA
19	Ibama
20	ICMbio
21	ANA
22	IGAM
23	IEF
24	FEAM
25	IEMA
26	DNPM
27	CPRM
28	CIF
29	Technical groups

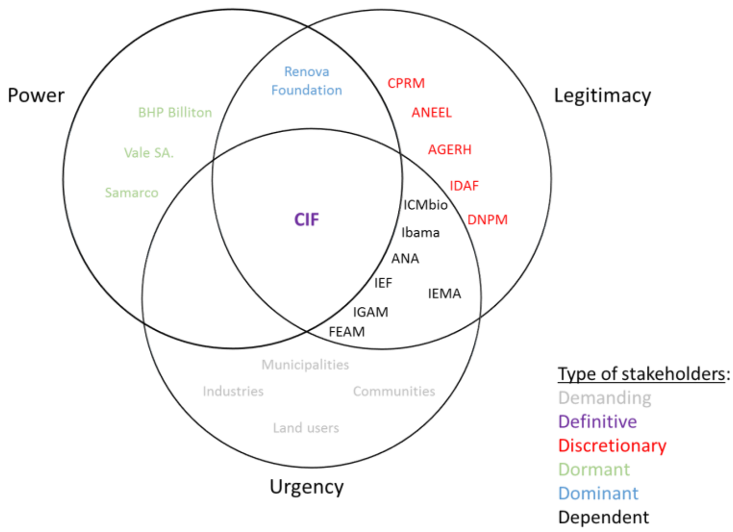


Figure 4 – (a) Stakeholder level of importance (Brown 2006) in relation to being impacted by the disaster and level of influence on decision-making on the post-disaster actions following the new Framework agreement and b) stakeholder typology according to (Mitchell et al. 1997)

29 stakeholders were involved in the new *Framework Agreement*, varying in degrees of decision-making power (Figure 4a). Following Brown's (2006) guidelines, stakeholders were categorized into primary and secondary, depending on the level of decision-making power. The upper left square of Figure 4a describes a type of stakeholder defined as *Demanding* by Mitchell et al. (1997), a group that has no power nor competences but is highly impacted by the decision-making process (Figure 4a). In the current case, local communities (1 in Figure 4a) and local professional fisherman (3) are considered the highest impacted stakeholders. Local communities include the local population living in the river's vicinity, and also the indigenous people, some of whom worship the river. For these people, the Doce provides water, food, shelter *and* a belief system. The group most impacted and influenced by the disaster, Local communities (1) have the lowest influence in the new governance system. The local professional fishermen (3) have higher influence since they form official associations that represent their well-being and interests. Both land-developers (7) and industries (8) are considered here as small local businesses, like farmers and dairy farms. Both (7) and (8) are currently facing economic and environmental impact, in terms of degraded land and river, which are the natural resources that sustained their business. AGERH (10), ANEEL (11) and IDAF (12) (Discretionary stakeholder) are Federal and State institutions that possess both expertise and legislative power but are neither greatly impacted by the disaster nor have great influence over the decision process. These are institutions that have little to no representation at the CIF and are not currently included

in the watershed recovery program, but do have legislative power at the State level (Figure S2, Section S3). They are considered *Discretionary* stakeholders (Mitchell et al. 1997). Samarco (15), Vale (16) and BHP (17) are identified as *Dormant* stakeholders (Mitchell et al. 1997), since they have financial influence but lack urgency and legitimacy in the effective ecosystem recovery. The three mining companies are involved in the prosecution process and are responsible for providing funds to finance the Doce River recovery. Another type of stakeholder are the *Dangerous* type, a role regularly taken by NGOs. However, Brazil does not have NGOs with sufficient power to influence the decision process and this category is consequently absent. The Fundação Renova (14) is the sole stakeholder defined as *Dominant*, since it has power with legitimacy to manage the funds that were allocated to the Doce River recovery. It is worth noting that the DNPM, the institute that supervises tailing dams in Brazil, is identified as neutral in terms of impact and influence (very close to the origin in Figure 4a and *Discretionary* stakeholder in Figure 4b). The DNPM has all the legitimacy to sanction and stop mining exploitation prior to disaster but after the tailing dam was ruptured, the DNPM had no competency relative to ecosystem and environmental restoration.

Mitchell (1997) describes the Dependent stakeholder as those who lack power but who have urgent legitimate claims because they depend upon other stakeholders for the power necessary to carry out their will. In this sense, we defined the majority of environmental agencies as dependent (Figure 4b). In the new Framework agreement, these autonomous agencies that normally have the authority to implement directives, supervise and execute sanctions are now dependent of CIF decisions. The *Definitive* stakeholder is a stakeholder that has all three driving attributes for effective decision-making (Mitchell et al. 1997). Here, we define CIF as the sole *Definitive* stakeholder in the decision process of the Doce recovery (Figure 4b). Empirically, the MPF has all the three main attributes as well, but it removed itself from the Framework agreement early in the process (described in Section 4.2).

Samarco (15), Vale (16) and BHP (17) are considered as powerful stakeholders because they have financial capacity and they provide the funds that will be used to recover the ecosystem. They are nonetheless *Dormant* stakeholders because they lack the urgency to recover the environment. This urgency might have increased in a post-disaster scenario, at the direction of the main legal authority – the MPF. However, since the MPF has removed itself from the Framework Agreement, the powerful stakeholders remain dormant.

4.2. Basin Vulnerability

Impacts of dam failure are mainly experienced at the local level but the activities of high-risk mining industries are supervised by a national body in Brazil – DNPM. Mining activities spread across the country with over 3000 listed tailing ponds (Table S1). Currently, there are numerous dams at risk of rupture in Brazil (Table S1) (DNPM 2016). Basin vulnerability can be calculated using tailing dams' risk and size

(Table S1) and socioeconomic data regarding indigenous people representation, GDP and administration improbity (Table S2). According to our calculations taking particular attention basin size, and using a simple likert scale (Table 2), this analysis shows that Brazil has considerable basin resilience (Figure S1) (Lacerda et al. 2002). The watersheds with the highest vulnerability are “Costeira do Norte Oriental” and the Doce River (Figure S1). But when a social dimension is added (Table S2), many basins have increased vulnerability (Table 2). Several basins present medium vulnerability to dam rupture (Figure 5), although no basin presents high risk currently. Figure 5 shows basins vulnerability, where we can see that almost all coastal watersheds have a medium vulnerability risk.

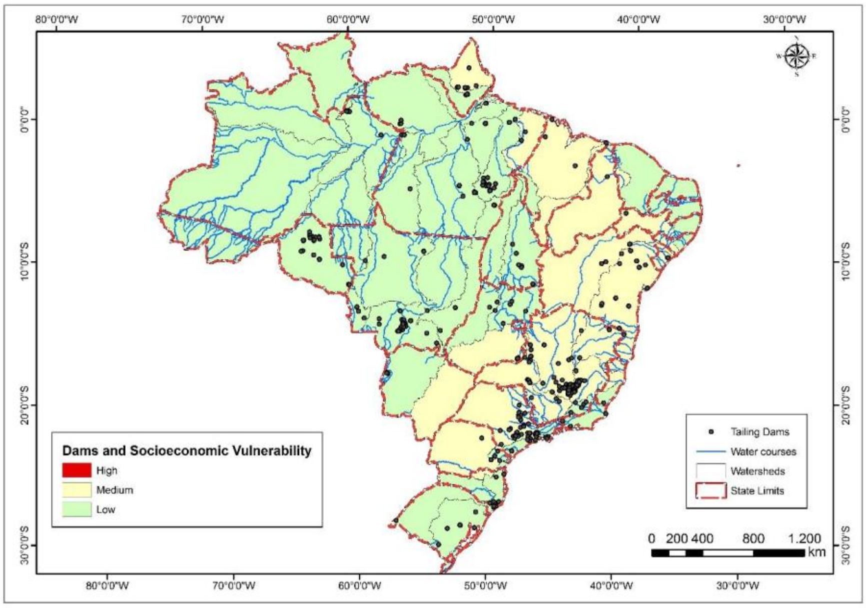


Figure 5 – Basin vulnerability based on dam risk failure assessed by DNPM (DNPM 2016), combined with the ratings attributed to basin size, and socioeconomic data according to the described in section S4.

5. Discussion

With a diverse and complex governance, Brazil offers a flexible environmental management system that may be considered an advantage when risks such as disasters arise. In the absence of pre-planned responses to mining tailings dambursts, this might be considered beneficial. The *Framework Agreement* was a novel approach, established within this flexible system to address a specific disaster event and it set out to involve all relevant stakeholders. Our analysis reveals several positive and negative aspects of such a structure.

The Agreement includes members from all the main environmental federal and state agencies, with available funds for ecosystem recovery, and there is sound national and international technical expertise available. According to Hardy (~~Hardy~~ 2010), this is a major positive, since effective agency-based partnerships comprise highly skilled technical experts, government officials, and representatives from regional and state agencies. As with other hybrid governance systems, this framework is a complex structure involving a multiplicity of actors and many interrelations between the 'local' and the 'global' (Muradian and Rival 2012). Partners in such governance systems tend to have common environmental issues and therefore coordinate activities and resources towards common research and development (Hardy 2010). Indeed, according to Renn et al. (2011), institutional diversity has several benefits:

- Increased flow of communication across environmental agencies
- Reduced bureaucracy
- Expedited watershed rehabilitation, since communication and decision-making are faster
- Simplified decision-making because scientific and technical information is customized
- Aggregated information can be provided to the public.

While the *Framework agreement* achieved diversity, the mining industry still has strong influence over the Renova Foundation and the overall decision-making process (Figure 4a). This is attributed to the following:

i. The MPF does not participate in the agreement, i.e., the national regulatory body is not in the CIF. Therefore, the *Framework Agreement* does not hold judicial power to implement and regulate recovery actions. According to Eckersley (2004), management decisions regarding public and common pool goods require that higher-level institutions and organizations be recognized as legitimate. Since the highest legal Brazilian regulatory body does not partake of the agreement, any decision and resulting action are not legally binding;

ii. The *Framework Agreement* establishes Samarco, the "polluter", as the creator of the Renova Foundation responsible for managing the financial resources being deployed in the restoration process. This implies that the polluter has control over the decision-making process, diminishing effective institutional diversity. Similar economic influence of the private sector over the Brazilian Government is illustrated by the 2015 regulation that prohibits donations by private companies to political parties (law 13,165 of electoral reform). Before then, political campaigns were financed by private companies up to a limit of 2% of their gross annual revenue. Specifically, a company with a turnover of 2 billion USD a year may donate up to 3 million USD to a given political party. Politicians have been criticized for this practice because they were focused on companies' growth to the detriment of the protection of the population and the environment (Westra et al. 2013).

The *Framework agreement* was conceived to expedite ecosystem recovery after the impacts of the disaster, and 4 years after the disaster ecosystem recovery is at its early stages (https://www.fundacaorenova.org/dadosdareparacao/terra-e-agua/#manejo). ~~And adding~~Considering the above-mentioned *Framework agreement* weaknesses, in tandem with the challenges in achieving a balanced stakeholder representation (Figure 4a, 4b), we ~~come to the~~ conclu~~sion~~de that the agreement in its present form is lackluster. According to Muradian and Rival (2012), solving the problems posed by loss of ecosystem services normally requires that ~~we~~ a move away from thinking in terms of single, ideal managerial approaches to combining governance structures, scales and tools. If the *Framework Agreement* is to be successful, governance must therefore move from a single center of power (McGinnis 2000). The *Framework Agreement* places itself between markets and hierarchies to create a hybrid governance structure, similar to the Chesapeake Bay transboundary watershed management (Just and Netanyahu 1998). In that case, policy decisions regarding restoration and protection of the Chesapeake Bay watershed have four distinctive decision-making levels: (a) consensus, (b) unilateral, (c) champion, and (d) voting (Chesapeake Bay Program, 2009; Diaz-Kope and Miller-Stevens, 2015). Similar to the Chesapeake Bay program (Chesapeake Bay Program 2009), the Framework Agreement should adopt distinctive decision-making levels that guide governance activities.

It is paramount for the Doce River future recovery that collaboration happens between the different layers of federal and state government, academia, industry and local communities, including indigenous people. This collaboration is implicit in the Framework Agreement but is not attained in reality because of stakeholder bias over decision-making (Figure 4b). CIF, the *definitive* stakeholder, and Renova Foundation, the *dominant* stakeholder, lead stakeholder decision-making with what may appear as economic bias, prioritizing mining over human and environmental welfare. Instead, watershed ecosystem recovery should be prioritized and concepts of ecological engineering and ecohydrology should be adopted (McClain and IAHS, 2002; Millenium Ecosystem Assessment 2005). To achieve this, we recommend the watershed committee (9) to take the central role as *Definitive* stakeholder. In addition, indigenous people's interest in wetland recovery should be better represented in the process. As Muradian and Rival (2012) state, state policies are ineffective without appropriate incentives or local engagement in rule making. Indigenous people like the Krenak not only rely on the Doce River for their livelihood, but also perceive the river as a deity. Engaging them in the Doce recovery, guided by technical support, could serve as an example for indigenous rights. This would be similar to the Kagera project (http://www.fao.org/family-farming/detail/en/c/449936/), a transboundary watershed between Burundi, Rwanda, Tanzania, and Uganda supported by FAO that assign local communities' responsibilities over protecting wetlands for water and food supply. This decentralized approach involves field work and teaching local communities.

With so many sources of risk and increased basin vulnerability (Figure 5), a good system needs to be developed to deal with tailings dam bursts. The Framework Agreement has strengths and weaknesses (as seen in the previous sub-section) but is not the perfect answer. Given the scale of mining operations in the Iron Quadrangle, monitoring, contingency plans, and legislative reinforcement need to be undertaken at the same management level. We already observed a similar disaster in Brazil recently e.g. (Oliveira et al. 2019) and they will continue to happen if action is not taken at the national level. Contingency plans are instrumental in preventing and minimizing environmental impacts along the entire fluvial-estuarine-marine continuum, and policy-making need to focus more on prevention at source (Lu et al. 2015). Forcing industries to implement contingency plans for possible dam failures now may mitigate uncertainty in the future (see Canadian Directive 085).

5. Final remarks

Brazil currently dismisses state participation in industrial resource exploitation. The new Framework agreement was formed to manage the Doce River post-disaster watershed recovery constitutes the first hybrid governance system in Brazil. In principle, the *Framework Agreement* to recover the Doce River would be diverse and well-structured but the authors found that decision-making is still centralized in the Inter-State committee (CIF) and efforts to minimize the industrial biases should be made. The authors recommend that the stakeholder watershed committee should take the central role and adopt ecological engineering and ecohydrology concepts to recover the ecosystem. Empowering the most vulnerable communities in watershed ecosystem recovery would assure collaboration between the different layers of federal and state government, academia, industry and local communities, including indigenous people. Furthermore, the socioeconomic data regarding indigenous people representation, GDP and administration improbity increases basin vulnerability. Political instability and population disbelief in government policies add to the already precarious state of the physical environment.

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Table 1: Environmental effects of mine tailings and industrial wastes impoundments failures. F: fluvial; L: lake; R: reservoir; C: coastal

Impoundment location, year of failure	**Main ore/waste materials released**	**Volume of tailings/wastes released M (m3)**	**Active (A)/ Inactive (I) and cause of failure**	**Affected water bodies**	**Environmental effects**	**Population affected**	**Reference**
Omai River (Guyana), 1994	Cyanide-laden	2.9	Piping failure	F Essequibo River	346 dead fish	No measurable effects on the downstream environment or human health	(Vick 1997)
The Merriespruit (South Africa), 1994	Gold tailings	0.6	Moisture / static liquefaction build up in the tailings due rainfall	F Sand River	bird sanctuary destruction	17 killed	(Fourie et al. 2000; Van Niekerk and Viljoen 2005)
Ingá, Sepetiba Bay (RJ, Brazil), 1996	Wastes of Zn ingots production for export	*unknown*	Dam collapse after intensive rainfall	F, C Sepetiba Bay	bay and mangrove pollution with metals mainly Zn and Cd; Impairment of coastal fisheries		(Freitas and Rodrigues 2014)
Los Frailes (Spain), 1998	Zinc, lead, copper and manganese-rich pyrite deposits	5	Static liquefaction	F, C Guadiamar River and estuary	affected a wide surface area, 4,634 acres /over 30,000 kilograms of dead fish were collected	Nine municipalities	(Pain et al. 2003)
The Baia Mare (Romania), 2000	Cyanide from former gold and silver extraction	100.000 containing 50-100 tons of cyanide (CN)	Design, operation and surveillance failure	F,C Lapus river, Somes, Tisza, Danube and Black Sea	1,200 tons of fish killed; 2,000 km of the Danube catchment area were affected	Interruption in the water supply in 24 localities; prohibition to use the river water for consumption,	(UNEP/OCHA 2000)

						domestic needs, animals drinking	
Cataguases (MG, Brazil), 2003	Caustic soda, and Al, Si, and Na wastes of pulp mill processing plant	1.4	A Dam collapse after intensive rainfall	F, C Paraíba do Sul River, north Rio de Janeito and South Espírito Santo coasts	river and coastal waters pollution with caustic effluents extensive fish kill collapse of water supply impairment of coastal fisheries		(Costa 2001)
Imperial Metals, Mount Polley (BC, Canada), 2014	Au and Cu ore tailings	18.6	An impoundment wall fail	F, L Hazeltine Creek, Polley Lake and Quesnel lake	erosion of channel and the floodplain 136 ha impacted		(MPMC 2015; Petticrew et al. 2015)
Gold King Mine, Silverton (CO, USA), 2015	Waste water spill with Cd, Pb, As, Be, Zn, Fe, and Cu	*unknown*	A Accident destroying the plug of groundwater	F Cement Creek and Animas river			(Bourcy and Weeks 2000)
Kolontar plant (Hungary), 2010	Al and alkaline wastes	6,5	A unknow	F Torna, Marcal, Rába and Danube	all aquatic life was destroyed rivers and soil with highly alkaline ph level	10 people killed 400 evacuated 6 municipalities were affected	The Kolontar report (Herard 2010)
Doce River, (MG-ES, Brazil), 2015	Iron ore tailings	56,4	The Fundão tailing dam collapse Foundation failure/poor maintenance	F, L, R, C Doce River	river and coastal waters pollution with iron ore tailings collapse of water supply	700,000 people without drinkable water 179 indigenous impacted 12 municipalities	(Miranda and Marques 2016) ANA, 2016

					Irrigation impairment Impairment of coastal fisheries 20 people dead	impacted	
Brumadinho, (MG-ES, Brazil), 2019	Iron ore tailings	11,7	The Córrego do Feijão tailing dam collapse Foundation failure/poor maintenance	F, L, R Paraopeba River and São Francisco River	river waters pollution with iron ore tailings collapse of water supply Irrigation impairment 300 people dead		

Table 2 – Summary of the variables considered to calculate basin vulnerability based on tailing dam risk class retrieved from (DNPM 2016) and its size. A simple accumulated vulnerability was calculated

Dam class (DNPM 2016)	Vulnerability A (likert scale)	Basin category	Scale (LOIX)	Vulnerability B (likert scale)	Accumulated Vulnerability *	Vulnerability B (likert scale)
A	5	small	>10.000	3	10-15	**High**
B	4	medium	10.000 - 200.000	2	5-10	**Medium**
C	3	large	< 200.000	1	0-5	**Low**
D	2					
E	1					

* simple calculation of Vulnerability A · Vulnerability B (Maximum value of 15)

Table 3 – Doce River list of impacts in the post-disaster and loss of environmental services. Data retrieved from (IEMA 2015)

Sector	Sector/Compartment	Description of impact	Quantification
Environment	Land ($83.400 km^2$)	Disturbance of riverine margins	1,469 hectares; 77 km of watercourses
		Lost of riverbanks and soil along the river	Unknown/n.d.
		Alteration of geomorphology	changed the overall natural character of the river
	River	Resuspension of airborne particulate matter from dry sediment at riverbank	Unknown/n.d.
		River bed silting	56,6 m^3 released
		Water quality decline*	As, B, Cr, Ni, Mn, Pb, V and Zn exceed Conama 357 for water quality
		Sediment quality decline*	As, Cr and Ni exceeded the norm Conama 454 for sediment quality
		Temporary perturbation of the food web	Unknown/n.d.
		Biodiversity losses	Unknown/n.d. - 14 t of dead fish, total of 29.292 collected specimens
		Temporary water turbidity	800.000 ntu
		Habitat alterations	Unknown/n.d.
		Endemic species extinction	Unknown/n.d.
	Ocean ($1500 km^2$)	Impacts on aquatic habitat	Turtle-nesting area (4000 births in 2015/2016)
		Beach erosion	400 m still trying to calculate this area
		Biodiversity losses	Unknown/n.d.
		Water and sediment quality decline*	
	Lakes	Water and sediment quality decline*	
Social	Local communities	Flooding and destruction of villages	19 people dead

	Fisheries	Interruption of fishery activities	Forbidden at the coast and until 25 m depth at Doce River mouth
	Tourism	Temporary suspension of touristic activities	
	Water supply	Suspension of water supply	12 municipalities
Economic	Industries	Interruption of industrial activities	at least 16 huge companies
	Power plants	Interruption of power generation	Downstream hydroelectric power plants ceased activities to retain the tailings. Candonga is still closed.
	Irrigation and cattle breeding	High turbidity caused damage to the pumping systems, distribution networks and water spray equipment.	Water turbidity of 800.000 ntu

* in (Hatje et al. 2017)