

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

3
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13
14
15 **Abstract**

16 Mine tailing dam bursts occur frequently with attendant implications for the environment and human
17 populations. Institutional preparedness for such events plays an important role in their lasting impact. This
18 study analyzes the stakeholder engagement in the new ~~ly~~ governance framework created to recover the Doce
19 River ecosystem following the 2015 disaster, where 34 million m³ of tailings were released, killing 19
20 people and causing massive impacts on riverine life. Following the disaster, poorly conceived political and
21 management decisions impeded and continue to impede the progress of ecosystem recovery. The post-event
22 management structure shows a centralized and poorly diverse stakeholder pool. We conclude that poor
23 governance structure, and weak law enforcement, are among the main reasons preventing the Doce River
24 post-disaster watershed recovery. A watershed vulnerability analysis ~~combined-combining~~ dam stability
25 and socioeconomic data, ~~concluding-concluded~~ that low ratings of socioeconomic performance
26 substantially ~~increases~~ basin vulnerability. We recommend that the watershed committee should be fully
27 involved in the implementation of the program and take a central role so that the most vulnerable
28 communities (including indigenous people) take ownership of ecosystem recovery, ~~including indigenous~~
29 people.

30
31 **Keywords:** tailing pond, tailing dam, impoundment failure, Doce River, mining industry, environmental policy and
32 governance, environmental impact assessment

33

¹ These authors contributed equally to the conception of this paper

34 **Glossary**

- 35 FUNAI - National Indian Foundation (Fundação nacional do Índio)
- 36 Fundão tailing dam - Dam owned by Samarco that ruptured on the 5th of November 2015
- 37 Candonga dam - one of the 4 main hydroelectric dams retaining the tailings downstream the Fundão tailing dam
- 38 Samarco - Samarco Mineração S.A., mining industry co-owned by VALE and BHP Biliton
- 39 BHP Billiton - BHP Billiton Brasil Ltda.; Samarco's co-share participant
- 40 VALE - Samarco's co-share participant
- 41 MMA - Ministry of the Environment (Ministério do Meio Ambiente)
- 42 MME - Mining and Energy Ministry (Ministério de Minas e Energia)
- 43 IBAMA - Brazilian Institute for the Environment and Renewable Natural Resources (Instituto Brasileiro do Meio Ambiente e dos Recursos Naturais renováveis)
- 45 ICMBio - Biodiversity Conservation Chico Mendes Institute (Instituto Chico Mendes de Conservação e Biodiversidade)
- 47 DNPM - National Department of Mineral Research (Departamento Nacional de Pesquisas Minerais)
- 48 ANA - Water National Agency (Agência Nacional de Águas)
- 49 SEAMA - Espírito Santo State Secretary for the Environment (Secretaria de Meio Ambiente para o Estado de Espírito Santo)
- 50 Santo)
- 51 SEAG - Espírito Santo State Secretary for Agriculture and Fisheries (Secretaria de Agricultura e Pesca do Estado do Espírito Santo)
- 52 Espírito Santo)
- 53 IEMA - Institute of Environmental and Water Resources of Espírito Santo (Instituto Estadual do Meio Ambiente e Recursos Hídricos)
- 54 Recursos Hídricos)
- 55 IDAF - Espírito Santo Agriculture, Animal Husbandry and Forestry Institute (Instituto de Defesa Agropecuária e Florestal do Espírito Santo)
- 56 Florestal do Espírito Santo)
- 57 AGERH - Espírito Santo State Agency of Water Resources (Agência Estadual de recursos Hídricos do Espírito Santo)
- 58 SEMAD - Minas Gerais State Secretary for the Environment and Sustainable Development (Secretaria de Estado de Meio Ambiente e Desenvolvimento Sustentável de Minas Gerais)
- 59 Meio Ambiente e Desenvolvimento Sustentável de Minas Gerais)
- 60 FEAM - State Environmental Agency of Minas Gerais (Fundação Estadual do Meio Ambiente - Minas Gerais)
- 61 IGAM - Minas Gerais Water State Institute (Instituto Mineiro de Gestão das Águas)
- 62 IEF - Minas Gerais Forestry State Institute (Instituto Estadual de Florestas - Minas Gerais)
- 63 CPRM - Mineral Resources Research Company (Companhia de Pesquisa de Recursos Minerais)
- 64 CIF - Inter-State Committee (Comitê Inter-Federativo)
- 65 RENOVA Foundation - Foundation managing the new Framework Agreement
- 66 MPF – Federal Prosecutors' Office (Ministério Público Federal)
- 67

68 **1. Introduction**

69 The mining industry has experienced several significant impoundment failures over the past 30 years
70 (Davies et al., 2000; Davies, 2002; Rico et al., 2008) (Table 1). Tailing dam failures account for roughly
71 75% of mining-related environmental disasters worldwide- (MMSD 2002). While there is a considerable
72 literature on the geotechnical aspects of dam failure and on the pollution-related aspects of their impact
73 (e.g. Rico et al. 2008), there has been relatively little research on the role of authorities in undertaking
74 appropriate post-disaster actions. In this paper we document and evaluate the institutional response to the
75 2015 failure of a tailings dam in Brazil.

76
77 The 83,400 km² Doce River watershed spreads over two states - Minas Gerais and Espírito Santo (Figure
78 1). Due to its transboundary status, the Doce is administered at the Federal level by the Federal Water
79 Agency (ANA) with regional watershed management committees. The overall land use in 2014 consisted
80 of 72% farm land, 0.9% urban area, 6.6% husbandry and 19.2% natural area (IBGE 2016). As a tropical or
81 sub-tropical region, it has two distinct seasons: wet summer from September to March, and dry winter from
82 April to August. The Doce River is one of the most important on the East Brazilian coast (Oliveira et al.
83 2012) and hosts a population of circa 3.5 million inhabitants and an extensive dam system, with about 140
84 hydropower reservoirs of different scales (ANA, 2015). The Doce still hosts indigenous communities - the
85 Krenak and the Pataxó. These two groups include 179 individuals and are under the tutelage of the National
86 Indian Foundation (FUNAI).

87
88 On November 5th 2015 a tailing dam collapsed upstream of the Doce River, state of Minas Gerais, Brazil,
89 constituting the world's largest mining disaster in terms of volume (Table 1). The *Fundão* tailing dam
90 released 34 million m³ of tailings to the Doce River watershed. This caused the disruption of the entire
91 fluvial-marine continuum, including impacts on the local population (circa 700,000 inhabitants), domestic
92 water supply, and irrigation. On the 21st of November 2015, tailings reached the coast of Espírito Santo
93 leaving behind 19 human casualties/fatalities, 14 tons of macro-fauna (mainly fishes) killed by asphyxia,
94 1,469 ha of affected riparian vegetation, and a negative impact on over 660 km of the Doce River (IEMA
95 2017). Subsequent studies identified ecosystem service losses of over US\$ 521 million per year (Garcia et
96 al. 2017) in the Doce River watershed.

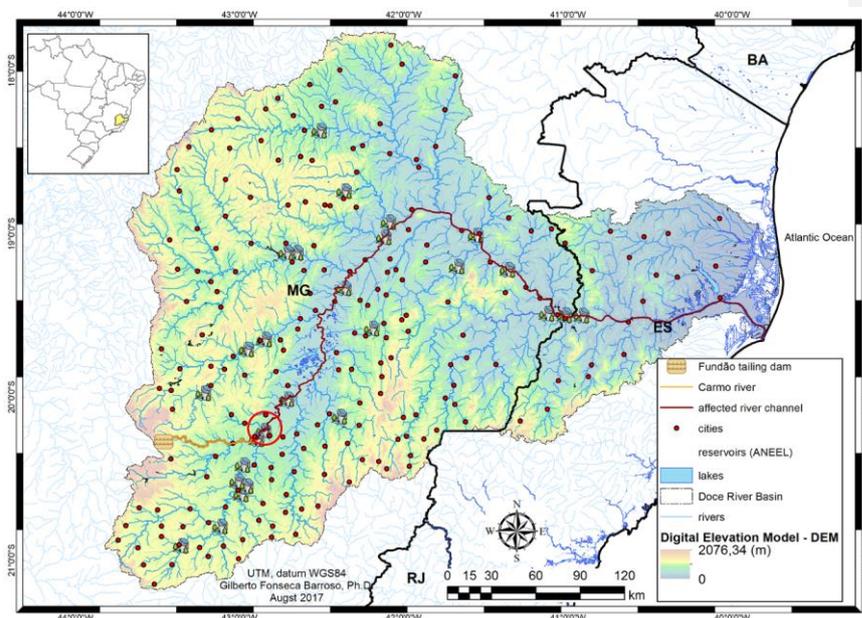
97
98 The ruptured dam was located in the mining complex known as Iron Quadrangle (Quadrilátero Ferrífero),
99 Minas Gerais state, and is considered the largest open pit mining industry in the world (Santolin et al. 2015).
100 Brazil produces 18% of the 2.33 billion metric tons of Fe-ore produced annually worldwide (Tuck 2015).
101 Part of Brazil's recent economic growth is linked to the mining industry and its export of mineral
102 commodities (from 1.6% in 2000 to 4.0% in 2014 of GDP). Samarco, one of the mining ventures exploring

103 the area and owner of the ruptured dam, has an annual production capacity of more than 25 million tons of
104 Fe-ore pellets and 1 million tonnes of Fe-concentrate. In 2014, Samarco had a revenue of US \$2.6 billion
105 in Espírito Santo (Samarco 2014), 0.3% of the 2015 Brazilian GDP according to The World Bank (World
106 Bank 2017). Samarco's sales revenue is equivalent to 6,4% of Espírito Santo GDP and 1,6% of the Minas
107 Gerais GDP (Samarco 2014). Vale S.A (Vale) and BHP Billiton Brazil LTDA are national companies that
108 focus on mining, transportation, and production of ore. The two companies share ownership of Samarco
109 (50% each).

110

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

128



129
 130 Figure 1 – Doce River Basin and impacted fluvial channel with mining tailings. Carmo River is identified in yellow;
 131 Candonga hydroelectric dam is circled in red. Legend: ES – Espírito Santo; MG – Minas Gerais.

132
 133 **2. Background**

134 **2.1. The Doce River disaster**

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

141
 142 The Fundão tailings dam ruptured on the 5th of November 2015. A total of 34 million m³ of mining ore
 143 tailings were released to the Doce River watershed (ANA 2015). Failure of the Fundão tailing dam affected
 144 more than 600 km of the river channel and the adjacent coastal area. ~~67.8 % (598.3 km)~~ A total of 68
 145 km of river channel was impacted.

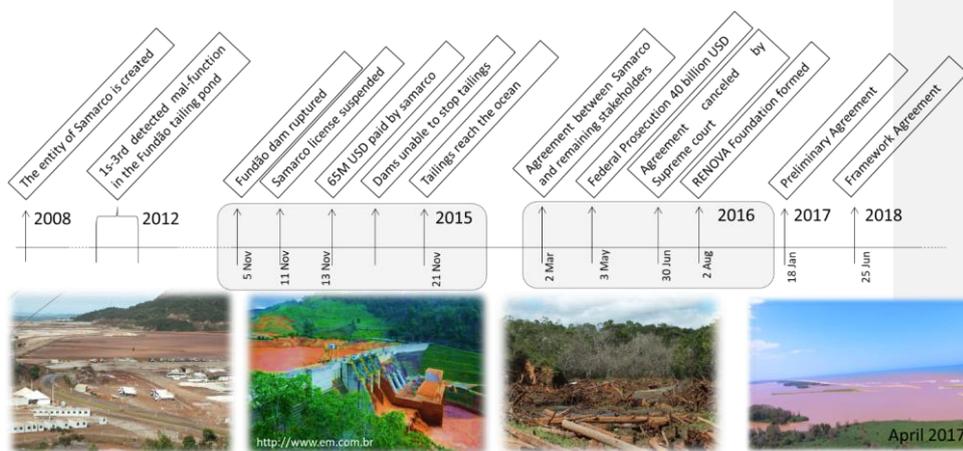
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146
 147 The 2015 flash dam rupture increased the Doce River surface flow from ~~the~~ 114 to 810 m³/s (CPRM 2015).
 148 These tailings had a specific density of 2 t/m³. Downstream of the tailing dam, the slurry gained momentum

149 and flooded the towns of *Bento Rodrigues* and *Paracatu de Baixo* causing 19 casualties. The slurry
 150 progressed through the Carmo River and along the Doce River, annihilating 14 tons of freshwater fish,
 151 destroying 1,469 ha of land, 77 km of watercourses, and impacting protected areas and indigenous lowlands
 152 (IBAMA 2016b; IEMA 2017). Turbidity reached 33 g L^{-1} (Table 3), and sediments had enrichment factors
 153 of up to 4,000 in the case of Hg (Hatje et al. 2017), with average of 5 to the remaining trace metals (Gomes
 154 et al. 2017). After 16 days and 660 km, the slurry reached the Atlantic Ocean on November 21st. 2015. At
 155 this time, the Federal Prosecutors' Office (MPF) encouraged locals to collect live fish and safely guard
 156 them in nearby ponds and lakes while bystanders and researchers took sediment samples. Because there
 157 was no contingency plan in place, the MPF and other authorities had difficulty in taking decisions and
 158 coordinating the disaster aftermath (Figure 2). But several measures were taken:

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

168



169
 170 Figure 2 - A timeline following events in the upper Doce River, from the creation of Samarco (mining venture), the
 171 start of Fe-ore exploitation to the latest events regarding the ruptured tailing dam
 172

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

174 Fundão tailing dam disaster. A parallel investigation ~~was~~-instigated by the mining company ~~and~~-was carried
175 out by an international law office, ~~concluding~~-~~concluded~~ that incidents reported since 2009 in tandem with
176 operational issues lead to the rupture. Specifically, the failure was linked to damage to the original dam due
177 to increased saturation; slime deposition; and concrete structural problems (Morgenstern et al., 2016). In
178 addition, the National Department of Mineral Production (DNPM) ~~had~~ corresponded with the company in
179 2013 informing them that the drainage system was insufficient and there was a lack of monitoring
180 instruments (MPF 2016a). At this point, the Brazilian Federal Police argued that the mining company took
181 a risk to profit and issued ~~an~~-arrest warrant ~~of~~-~~for~~ 8 Samarco S/A executives.

182

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

191

192 **2.2. Environmental Governance in Brazil**

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

203

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

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

211

212 **2.3. The new Framework Agreement**

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

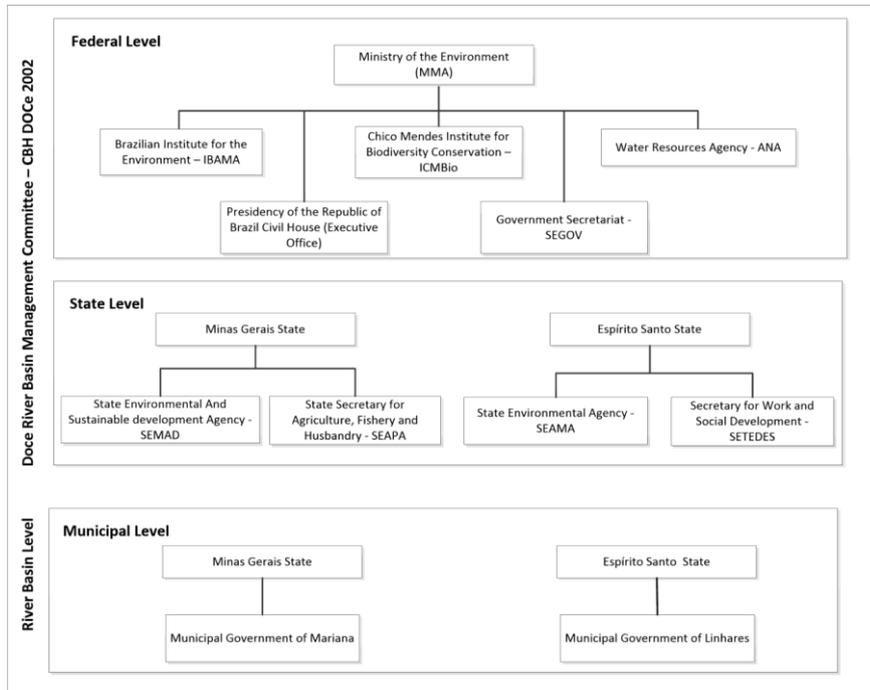
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226 The *Framework Agreement* consists of three new entities: a regulatory body Inter-Federative Committee
227 (CIF) (Figure 3); an independent foundation entitled the RENOVA Foundation, and several technical
228 boards (IBAMA 2018). The CIF has a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

236

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

244 procedures”. They regard the *Framework Agreement* as “unconstitutional in its merits” (MPF 2016b).
 245



246
 247 Figure 3 – Organogram representing the CIF and its multi-level structure.
 248

249
 250 **3. Methodology**

251 **3.1. Stakeholder analysis**

252 A narrative-based stakeholder analysis (Brown, 2006) focuses on stories that underpin our cognitive and
 253 emotional lives as agents of memory, emotion, and meaning (Brown, 2006). To derive a narrative-based
 254 stakeholder analysis, the authors based their viewings on the experience derived from the attendance of
 255 several Inter-State Committee (CIF) meetings (January/2016 – July/2018). Stakeholders were then
 256 evaluated and ranked according to the perceived importance and influence on they inferred during these
 257 meetings and the decision-making process itself. Brown (2006) defines the importance of stakeholder
 258 groups in terms of how their livelihoods were impacted by the outcome of decision-making and their
 259 influence over the decision-making process. In this study, we used 3 criteria to grade stakeholders: (i)
 260 effective communication in the CIF meetings, considering that some stakeholders were not represented; (ii)
 261 impact of the decisions on their welfare and well-being, and (iii) their level of interest in watershed

262 restoration. A likert scale was then used, from 1 (low influence) to 5 (high influence), to qualitatively
263 quantify the influence of each stakeholder on the process. If stakeholders possessed a similar grade, then
264 they were placed close-together in the graphic (Figure 4a). Once the stakeholders were ranked, a stakeholder
265 analysis was carried out according to Mitchell et al. (1997). Mitchell et al. (1997) identified 8 types of
266 stakeholders according to their definitive power, legitimacy and urgency regarding the decision-making
267 process: Dormant, Discretionary, Demanding, Dominant, Dangerous, Dependent, Definitive and the
268 Nonstakeholder. Using the previously ranked stakeholders order, we then identified the type of each
269 stakeholder involved in the Doce River restoration decision-making proces .

270

271 **3.2. Basin vulnerability**

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

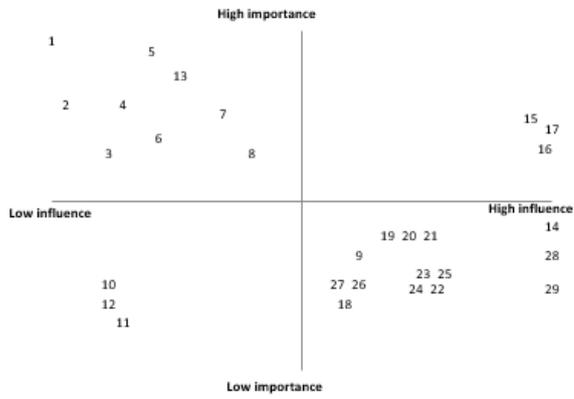
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287

288 **4. Results**

289 **4.1. Stakeholder Analysis**

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



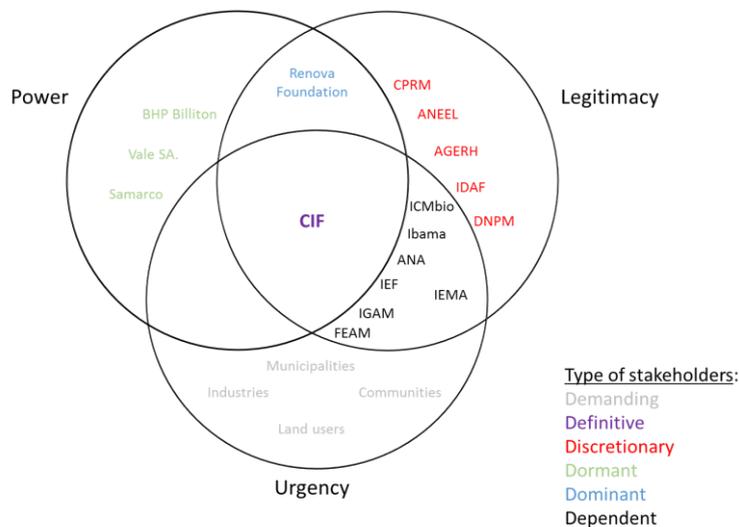
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294

Legend:

Primary stakeholders	Secondary Stakeholders
1 Local communities	12 IDAF
2 Local recreation users	13 Municípios
3 Tourists	14 <i>Fundação Renova</i>
4 Recreation fishermen	15 Samarco
5 Professional Fishermen	16 Vale
6 Hotel owners	17 BHP Billiton
7 Land developers	18 MMA
8 Industries	19 Ibama
9 Watershed committee	20 ICMbio
10 AGERH	21 ANA
11 ANEEL	22 IGAM
	23 IEF
	24 FEAM
	25 IEMA
	26 DNPM
	27 CPRM
	28 CIF
	29 Technical groups

295



296
 297 Figure 4 – (a) Stakeholder level of importance (Brown 2006) in relation to being impacted by the disaster and level of
 298 influence on decision-making on the post-disaster actions following the new Framework agreement and b) stakeholder
 299 typology according to (Mitchell et al. 1997)

300
 301 29 stakeholders were involved in the new *Framework Agreement*, varying in degrees of decision-making
 302 power (Figure 4a). Following Brown's (2006) guidelines, stakeholders were categorized into primary and
 303 secondary, depending on the level of decision-making power. The upper left square of Figure 4a describes
 304 a type of stakeholder defined as *Demanding* by Mitchell et al. (1997), a group that has no power nor
 305 competences but is highly impacted by the decision-making process (Figure 4a). In the current case, local
 306 communities (1 in Figure 4a) and local professional fisherman (3) are considered the highest impacted
 307 stakeholders. Local communities include the local population living in the river's vicinity, and also the
 308 indigenous people, some of whom worship the river. For these people, the Doce provides water, food,
 309 shelter *and* a belief system. The group most impacted and influenced by the disaster, Local communities
 310 (1) have the lowest influence in the new governance system. The local professional fishermen (3) have
 311 higher influence since they form official associations that represent their well-being and interests. Both
 312 land-developers (7) and industries (8) are considered here as small local businesses, like farmers and dairy
 313 farms. Both (7) and (8) are currently facing economic and environmental impact, in terms of degraded land
 314 and river, which are the natural resources that sustained their business. AGERH (10), ANEEL (11) and
 315 IDAF (12) (Discretionary stakeholder) are Federal and State institutions that possess both expertise and
 316 legislative power but are neither greatly impacted by the disaster nor have great influence over the decision
 317 process. These are institutions that have little to no representation at the CIF and are not currently included

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

331
332 Mitchell (1997) describes the Dependent stakeholder as those who lack power but who have urgent
333 legitimate claims because they depend upon other stakeholders for the power necessary to carry out their
334 will. In this sense, we defined the majority of environmental agencies as dependent (Figure 4b). In the new
335 Framework agreement, these autonomous agencies that normally have the authority to implement
336 directives, supervise and execute sanctions are now dependent of CIF decisions. The *Definitive* stakeholder
337 is a stakeholder that has all three driving attributes for effective decision-making (Mitchell et al. 1997).
338 Here, we define CIF as the sole *Definitive* stakeholder in the decision process of the Doce recovery (Figure
339 4b). Empirically, the MPF has all the three main attributes as well, but it removed itself from the Framework
340 agreement early in the process (described in Section 4.2).

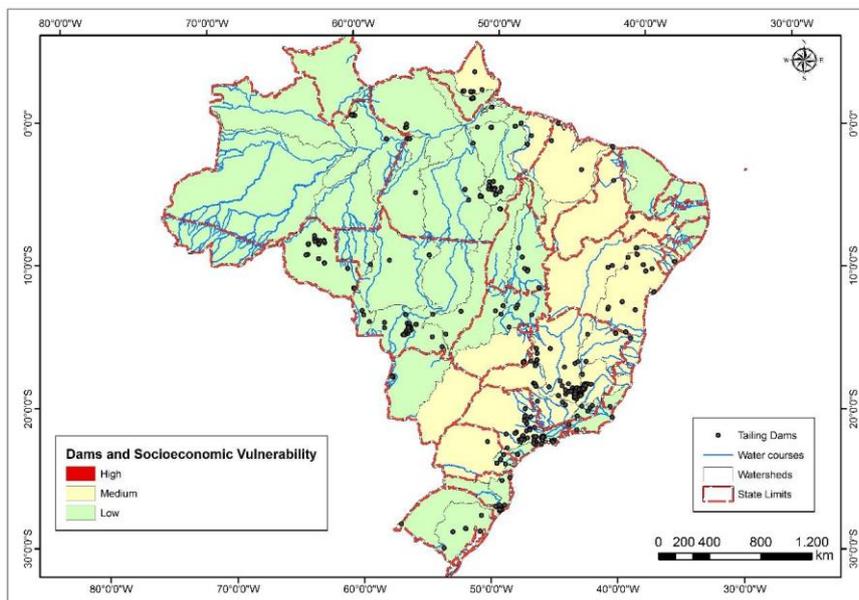
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342 Samarco (15), Vale (16) and BHP (17) are considered as powerful stakeholders because they have financial
343 capacity and they provide the funds that will be used to recover the ecosystem. They are nonetheless
344 *Dormant* stakeholders because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

347

348 **4.2. Basin Vulnerability**

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

353 (Table S1) and socioeconomic data regarding indigenous people representation, GDP and administration
354 improbity (Table S2). According to our calculations taking particular attention basin size, and using a
355 simple likert scale (Table 2), this analysis shows that Brazil has considerable basin resilience (Figure S1)
356 (Lacerda et al. 2002). The watersheds with the highest vulnerability are “Costeira do Norte Oriental” and
357 the Doce River (Figure S1). But when a social dimension is added (Table S2), many basins have increased
358 vulnerability (Table 2). Several basins present medium vulnerability to dam rupture (Figure 5), although
359 no basin presents high risk currently. Figure 5 shows basins vulnerability, where we can see that almost all
360 coastal watersheds have a medium vulnerability risk.
361



362
363 Figure 5 – Basin vulnerability based on dam risk failure assessed by DNPM (DNPM 2016), combined with the
364 ratings attributed to basin size, and socioeconomic data according to the described in section S4.
365

366

367 5. Discussion

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

373

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

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

388

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

- 391 i. The MPF does not participate in the agreement, i.e., the national regulatory body is not in the CIF.
392 Therefore, the *Framework Agreement* does not hold judicial power to implement and regulate
393 recovery actions. According to Eckersley (2004), management decisions regarding public and
394 common pool goods require that higher-level institutions and organizations be recognized as
395 legitimate. Since the highest legal Brazilian regulatory body does not partake of the agreement,
396 any decision and resulting action are not legally binding;
- 397 ii. The *Framework Agreement* establishes Samarco, the “polluter”, as the creator of the Renova
398 Foundation responsible for managing the financial resources being deployed in the restoration
399 process. This implies that the polluter has control over the decision-making process, diminishing
400 effective institutional diversity. Similar economic influence of the private sector over the Brazilian
401 Government is illustrated by the 2015 regulation that prohibits donations by private companies to
402 political parties (law 13,165 of electoral reform). Before then, political campaigns were financed
403 by private companies up to a limit of 2% of their gross annual revenue. Specifically, a company
404 with a turnover of 2 billion USD a year may donate up to 3 million USD to a given political party.
405 Politicians have been criticized for this practice because they were focused on companies' growth
406 to the detriment of the protection of the population and the environment (Westra et al. 2013).

407

408 The *Framework agreement* was conceived to expedite ecosystem recovery after the impacts of the disaster,

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

424

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

442

443 With so many sources of risk and increased basin vulnerability (Figure 5), a good system needs to be

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

453

454 **5. Final remarks**

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

467

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472

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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	<i>unknown</i>	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 Guadamar 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 Janeiro 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	<i>unknown</i>	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 (DNP M 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)