Doce River Large Scale Environmental Catastrophe:
Decision and Policy-making Outcomes

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Introduction

The mining industry has experienced several significant impoundment failures over the last 30 years (Davies 2002; Rico et al. 2008) (Table 1). Aftereffect of the continuing pressure on resource exploitation, tailing dam failures account for roughly 75% of mining-related environmental disasters (MMSD 2002). On 5 Nov 2015, a tailings dam collapsed upstream the Doce River, state of Minas Gerais, Brazil in one of the worst large-scale mining disasters in terms of tailings volume and distance travelled. The *Fundão* tailing dam released 34 million m^3 of tailings that overspread the Doce river watershed. This disrupted the entire fluvial-marine continuum, including impacts on local population (circa 700,000 inhabitants), potable water supply, and irrigation. The 21 Nov 2015, the tailings reached the Espírito Santo coast leaving behind 19 people dead and 14 tons of dead fish (IEMA 2017). Recent studies indicate ecosystem service losses over US$ 521 million per year (Garcia et al. 2017) in the Doce River watershed.

The mining industry is one of the major economic drivers of the Brazilian economy. In 2015, one of the leading mining companies in Brazil – Samarco – had a profit of approximately two billion USD, 0.3% of the 2015 Brazilian GDP, according to the World Bank (2017). Resource economy-based countries, like Brazil, support mining activities as a key commodity. In some cases, a well-structured environmental governance framework is established to minimise environmental disturbance and prevent large-scale accidents, e.g. Australia and Canada (Schoenberger 2016). However, this does not ensure the absence of large-scale disasters (Table 1). Mining is the primary driver of landscape changes, providing enormous flows of target minerals and associated wastes, altering drainage systems, land uses, and vegetation structure, promoting soil loss and erosion, and introducing both new structures and new meanings to the landscape (Bridge 2004). Located in river basins, mineral ore tillage impoundments represent a considerable threat to water security and ecological integrity of the drainage systems.

Environmental risks have been associated with dam stability and rupture, surface and groundwater contamination, acid mine drainage, and precipitation of secondary minerals (Grangeia et al. 2011; Kossoff et al. 2014). Previous large-scale environmental disasters show that post-disaster recovery time can take decades and will likely never return to the original state (Foley et al. 2005; Lima et al. 2016). In fact, the mining industry has experienced several significant dam failures in the recent history: the Merriespruit (South Africa) gold tailings spill resulted in 17 fatalities in 1994 (Fourie et al. 2000; Van Niekerk and Viljoen 2005); also in 1994 there was a dam failure and release of cyanide-laden water to the Omai River, tributary to the Essequibo River, Guyana. In Los Frailes (Spain), a zinc mine collapsed in 1998, releasing an estimated 5 Mm^3 of acidic waste rich in toxic metals from pyrite ore processing (Pain et al. 2003); 20,000 tons of residue was flushed into the Viseu River in 2000 and 0.1 Mm^3 of liquid and suspended waste of gold and silver producing plant were released into the Lapus/Somes/Tisza/Danube river catchment system at Baia Mare (Romania) (UNEP/OCHA 2000). Environmental disasters of impoundment failures are very impressive, not only regarding the quantity of tillage released, but also due to the extensive effects of transported slurry, dissolved metals and fine reactive metal particles, and huge loads of suspended sediments which may reach coastal waters. Widespread effects are related to biophysical, social and economic impacts that happen in an acute mode, with long-standing consequences overwhelming local, regional, and even transboundary economies and human well-being.

In the Doce River, the ruptured dam is part of a complex system created to contain Fe-ore mining waste slurry. Iron ore mining is spread worldwide, with around 60% of the mining focusing on developing countries. While some research has been directed towards the tailings toxicity within the riverine environment (Segura et al. 2016), the massive total suspended solids were one of the leading causes of riverine fauna mass destruction (CPRM 2015). Long-term quality and sediment safety are still being assessed, although it has been speculated that the tailings are laced with a high amount of metals, including arsenic, copper, and mercury (Escobar 2015). Tailings have been previously studied by Pires et al. (2003) at the Germano dam (Figure 1), concluding that sediments were high in Cr (600 ppm). Nevertheless, tailings are classified as non-hazardous by the Brazilian national standard NBR 10.004 (Pires et al. 2003). Despite toxicity, over 2.33 billion metric tons of Fe-ore are produced annually, with Brazil representing 18% of this total production (Tuck 2015). Iron-ore mining is mainly located in the Upper Doce River basin in the State of Minas Gerais, where approximately 18% of the global Fe-ore is produced.

Despite the high number of studies addressing large-scale disasters (Rico et al. 2008), there is a real lack of information regarding post-disaster procedures. The Fundão tailing dam rupture was the biggest environmental disaster in Brazilian history, but also one of the most notorious in the world in terms of volume (Table 1). Immediate opinions diverged regarding post-disaster procedures: while some defended that fines and prosecutions would mostly finance ecosystem restoration and preventive protection of riverbanks and coast (Meira et al. 2016), others dispute that biodiversity is threatened by weak official policies and inadequate monitoring, management and legislation (Nazareno and Vitule 2016). To rehabilitate the Doce River watershed, we need to establish a reference time-point to reclaim the ecosystem to its previous condition (Rooney et al. 2012; Lima et al. 2016). However, the Doce River was already a degraded watershed (Ribeiro et al. 2011), with both deficiencies in water flow quantity and quality. These watershed management issues can be linked to governance systems, mainly because they reflect the result of mismanagement and unregulated resource exploitation (Biermann et al. 2016).

In a post-disaster period, a series of actions were taken to manage it and provide environmental rehabilitation. As of late, Brazilian authorities have created a Framework Agreement together with the mining industry (Samarco) to combine and coordinate social and environmental recovery programs. Effective environmental and resource governance is essential to prevent and remediate environmental impacts of the mining industry, particularly tailings dam failures. In this chapter, we discuss governmental actions after the Fundão tailing dam rupture and its environmental impacts in the Doce River watershed. Remediation and integrated watershed management have not been considered in the perspective of the hydrological continuum from basin headwaters to the adjacent coastal ocean. The present book chapter addresses Brazilian environmental governance in the decision-making process during and after the large-scale Doce River disaster and its implications for watershed rehabilitation.

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 (m^3)	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	(Vick 1997)
The Merriespruit (South Africa) 1994	Gold tailings	0.6	Moisture / static liquefaction build up in the tailings due to 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)

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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; interdiction to use the river water for consumption, domestic needs, animals drinking	(UNEP/OCHA 2000)
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)

Impoundment location, year of failure	Main ore/waste materials released	Volume of tailings/wastes released M (m^3)	Active (A)/ Inactive (I) and cause of failure	Affected water bodies	Environmental effects	Population affected	Reference
Gold King Mine, Silverton (CO, USA) 2015	Wastewater 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 high 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	Fundão tailing dam collapse. Foundation failure/poor maintenance	F, L, R, C Doce River	River and coastal waters pollution; collapse of water supply. Irrigation and coastal fisheries impairment	19 fatalities 700,000 people without drinking water; 179 indigenous and 12 municipalities impacted	(Miranda and Marques 2016) ANA 2016
Brumadinho, Belo Horizonte 2019	Iron ore tailings	12	I Tailings dam Nº1 failure (stress-induced liquefaction)	F River Paraopeba and its tributaries	River waters pollution (250 km extension)	300 fatalities 3,485 people	(Cambridge and Darren 2019; Freitas et al. 2019)

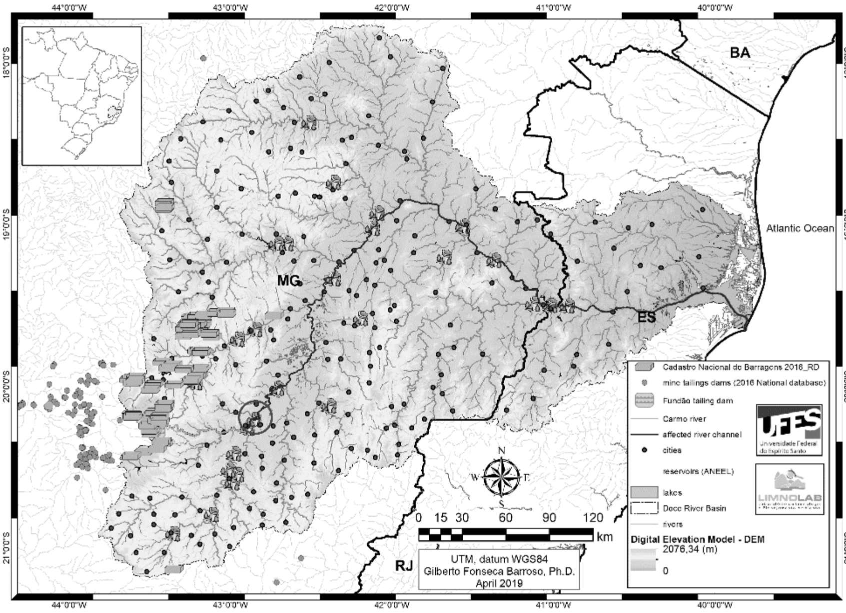

Figure 1. Doce River Basin and impacted fluvial channel with mining tailings.
The Candonga hydroelectric dam is circled.

The Doce River

Pre-disaster

The Doce River is placed in the Southeast of Brazil, and it spreads over two states - Minas Gerais and Espírito Santo (Figure 1). Due to its transboundary status, the Doce administration is done by the Federal Water Agency (ANA) with regional watershed management committees. With over 83,400 km², the Doce River watershed spreads over the states of Minas Gerais (70%) and Espírito Santo (30%), making it one of the largest Southeastern Atlantic watersheds (Figure 1). The overall land use in 2014 consisted of 72% farmland, 0.9% urban area, 6.6% husbandry 19.2% natural area and 1.3% the Doce River itself (IBGE 2016). As a tropical or subtropical 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 in the East Brazilian coast, after the São Francisco river, in water and suspended sediments loads to the ocean (Oliveira et al. 2012). It hosts a population of circa 3.5 million inhabitants. From the native population, we highlight two of the original local indigenous communities - the Krenak and the Pataxó. These two groups amount to 179 individuals and are under the National Indian Foundation (FUNAI) tutelage. Historically, the region of Minas Gerais in southeast Brazil is well known for mining activities. The city of Ouro Preto was one of the most important towns in the country, with most of its history associated with gold mining, beginning in the 18th century.

The ruptured tailing dam is located at the Iron Quadrangle (Quadrilátero Ferrífero), Minas Gerais state, and is considered the world largest open-pit mining industry (Santolin et al. 2015). Samarco, one of the mining industries 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 one million tons of Fe-concentrate. Samarco has revenue of US $2,6 billion per year in Espírito Santo (Samarco 2014). Part of the Brazilian economic growth can be linked to the financial success of the mining industry and its export of mineral commodities in the last few years (from 1.6% in 2000 to 4.0% in 2014 of GDP). 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. and BHP Billiton Brazil LTDA are national companies that focus on mining, transportation, and production of ore. The two companies share ownership over Samarco (50% each). The elemental steps of the productive chain of mining industry can be seen as exploration, extraction, processing and tailing production (Boger 2013). In extraction, ore is mined from rocks. Fine-grained rocks are then washed and, depending on the mineral; some chemicals are added to improve processing and remove minerals. After the extraction of minerals, tailings are discarded as slurries in open impoundments known as tailing dams.

The rupture of tailing dams is not new at the Iron Quadrangle region. This specific tailing dam endured a series of incidents before the rupture in November 2015. The Fundão tailing dam (Figure 1), with 60 million m^3 capacity (500 m in length and 90 m in height), started operations in 2008 (Samarco 2008). The first incident occurred in 2009 due to base drainage defects, shortly after the start of dam operations. In 2011, a second incident occurred, with tailings and wastewater released to one affluent of Doce River. Therefore, in 2012, the tailing dam was restructured and upgraded, resuming operations (IBAMA 2016a). Reports show some misinformation transmitted by Samarco and VALE to the National Department of Mineral Research (DNPM, governing body overseeing dam operations), and overuse of the dam (4 Mm^3 exceeding its limit capacity) (IBAMA 2016b). Several changes were made to the original project design to increase dam stability. These changes were untested, and the dam resumed operations as unscathed (IBAMA 2016b). Tailing dams are not like water retention dams. They are built in stages as mining and waste production progresses, and they are built usually of mine wastes rather than concrete (Schoenberger 2016). The dam was used for mine wastes until the rupture on 5 Nov 2015. No industrial action is registered after this; no alert was given. Ultimately, there was no contingency plan in place for the Fundão tailing dam, nor for the Doce River watershed.

The Doce River and its tributaries have an extensive dam system, reservoirs, and aqueducts with multiple purposes, e.g. hydropower [27 reservoirs and 113 smaller ones (< 3.0 km^2)]. The Doce River has undergone a remarkable surface water flow reduction in the last 70 years, from 1,260 m^3/s in the 1940s to 648 m^3/s in 2010s (ANA 2015). The mean annual discharge at the most downstream gauge at Colatina, about 140 km from the river mouth, is 800 m^3/s. In 2015, the Doce River surface water flow had a record minimum of 114 m^3/s, just before the tailing dam rupture. The amount of river discharge is related to watershed rainfall intensity and variability. Intra-annual rainfall variability is remarkably high in the centre and southeastern Brazil. According to Zhang et al. (2018) around 80% of annual rainfall occurs in the SE wet season (November to March), with 68% of annual river discharges produced between December to April. Annual rainfall variability has been 0.6 to 1.4 times the climatological mean, with 0.3 to 2.0 times the river discharge mean. For Colatina, 140 km upstream the river mouth in the Atlantic Ocean, the Doce River discharge varied from 111 to 9.000 m^3/s from 2011 to 2014. Such variability brings many challenges to water resources management, including hydropower production. In 2014-2015, SE Brazil faced an intense drought that threatened water and energy security. Lack of rainfall and scorching summers generated the most pronounced water crisis in the last 50 years (Nobre et al. 2016).

The mining industry, together with hydroelectric dams, increasing forestry exploitation and unplanned urban sprawl have turned the Doce River in a heavily impacted watershed. Before the tailing dam rupture, the watershed had recurrent flooding and continuous exposure of the local population to waterborne diseases (Guedes et al. 2015). Contamination by fecal coliforms, the presence of resistant yeast strains in surface waters (Medeiros et al. 2008) and high cyanobacteria counts (ANA 2015) have been reported due to the lack of sewage treatment. It is estimated that 70% of domestic wastewater is discharged untreated to the basin fluvial network (ANA 2017). Land-use changes, such as unplanned disordered occupation, mining, cattle breeding and *Eucalyptus* spp. forestry are leading causes of Doce River watershed environmental degradation (Medeiros et al. 2008; Segura et al. 2016). Regarding water and sediment quality, previous studies report Fe and metal enrichment in the sediments (Oliveira and Quaresma 2017; Rodrigues et al. 2014), most of them exceeding international quality guidelines (Santolin et al.

2015), including high levels of arsenic in soils surrounding Samarco mines (Alves and Rietzler 2015).

The Disaster

The Fundão tailings dam, owned and managed by Samarco, ruptured on 5 Nov 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. From the total length of Doce River (881.4 km), 67.8 % (598.3 km) was affected by the incident. If we add the most affected tributaries Gualaxo do Norte and Carmo river, it sums a total of 685.8 km river channel impacted (Figure 1). The most severely impacted section of the fluvial system was the 87.5 km of Gualaxo do Norte (small river tributary to Carmo River).

The fast-flash dam rupture increased the surface flow from 114 to 810 m^3/s (CPRM 2015). The tailings had a specific density of 2 t/m^3. Immediately after, the tailings induced hydraulic pressure creating a wave that when combined with the downstream volume of the Santarem dam flooded the towns of *Bento Rodrigues* and *Paracatu de Baixo* killing 19 people. A significant part of sediment loadings was intercepted by the first hydroelectricity generation reservoir (Figure 1). Candonga reservoir (circled on Figure1) has a volume of 54.4 million m^3, but it was already silted by natural sediments, so only 10.5 Mm^3 of the tailings were retained there. The hydroelectric dam is undergoing dredging to restore its capacity for hydropower generation.

The wave progressed through the Carmo River and along the Doce River annihilating 14 tons of freshwater fish. It took 16 days to travel approximately 660 km and four hydropower dams until reaching the Atlantic Ocean on 21 Nov 2015. At this inlet, the local population led by the MPF (Federal Prosecutors' Office) started to collect live fish and safely guard them in nearby ponds and lakes. Researchers and population took suspended sediment samples in general, and locals and nationals made numerous visits unsupervised. The lack of a contingency plan either supervised by the industry or governmental agencies made decision-making and actions difficult to coordinate in the immediate disaster aftermath (Figure 2). According to IBAMA (Brazilian Institute for the Environment and Renewable Natural Resources), the rupture of the Fundão tailing dam destroyed 1,469 ha, along 77 km of watercourses, including protected areas and degraded local indigenous lowlands (IBAMA 2016b). Soil erosion increased drastically, adding to the total suspended solids during the flood. Turbidity was high (Table 2) translating into a suspended sediment loading of up to 33,000 mg L^{-1} (Hatje et al. 2017). Sediments reached the highest enrichment factors for Hg (4,234), Co (133), Fe (43), and Ni (16), whereas As (55), Ba (64), Cr (16), Cu (17), Mn (41), Pb (38) and Zn (82) highest EFs were observed for suspended particulate matter (SPM) (Hatje et al. 2017). Gomes et al. (2017) concluded that the tailings plume increased trace metal concentrations of up to 5 times to the estuary. Lastly, riverine riverbanks underwent massive rupture, with waste depositions in the margins.

Post-disaster Actions

Brazilian Federal Police performed an investigation to assess the Fundão tailing dam status and indict responsibility for the accident. A parallel investigation by the mining company and stakeholders was carried out by an international law office to determine the immediate cause of the rupture. This study concluded that a series of incidents during the dam construction, together with its operation, lead to the conditions that allowed the rupture. According to Morgenstern et al. (2016), these included damage to the original dam due to increased saturation; slime deposition; and existing structural problems. Therefore, the adjustment in the dam outline and the saturated conditions made the structure vulnerable to liquefaction. In 2013, the National Department of Mineral Production (DNPM) (MPF 2016a) already informed the company that the drainage system was insufficient, and there was a lack of monitoring instruments. The Brazilian Federal Police argued that the mining company took a risk for profit and issued the prison of eight Samarco chief executives.

Parallel to responsibility attribution, the country was left with a devastated watershed. A monitoring campaign lead by IEMA comprised an overall environmental impact assessment in the impacted Espírito Santo area (IEMA 2017). A summarised global overview is given in Table 2. Main impacts consisted of:

- 19 fatalities
- 14 tons of macro-fauna killed by asphyxia, mainly fishes
- Destruction of riparian vegetation: 1,469 ha, along 77 km of watercourses
- Impact over 660 km of the Doce River, the estuary and its coastal region

Table 2. Doce River list of impacts in the post-disaster and loss of environmental services. Data retrieved from (IEMA 2015)

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
		Resuspension of airborne particulate matter from dry sediment at riverbank	Unknown/n.d.
	River	River bed silting	56,6 m^3 released
		Water quality decline*	As, B, Cr, Ni, Mn, Pb, V and Zn exceed water quality regulations
		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*	

Sector	Compartment	Description of impact	Quantification
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	
Economic	Water supply	Suspension of water supply	12 municipalities
	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), n.d. – non determined

Regarding surface water quality, besides the suspension of water supply in the affected municipalities, the presence of metals and changes on other parameters indicates the need for continuously monitoring the affected environment, as well as the remediation or recovery. Immediate actions consisted of:

- All marine fishery activities were interrupted at the coast (sea area of 1,500 km^2) for unlimited time due to federal mandate;
- Freshwater fisheries were interrupted in the middle and upper sections of Doce River, as requested by the state of Minas Gerais attorneys. Some places have officially resumed fisheries (Rodrigues 2017);
- Water supply was suspended;
- Carry out risk assessment to other tailing dams within the Iron Quadrangle (Morgenstern et al. 2016);
- Samarco committed to removing 1.3 Mm^3 of 10.5 Mm^3 tailings retained at Candonga's hydroelectric dam by February 2018 (Morgenstern et al. 2016).

Although a major economic driver and lucrative business, mineral resource exploitation has an environmental cost that impacts humans directly. It disrupts ecosystems that provide food and water (provisioning services), regulation of disturbances (regulating services), habitat for wildlife (supporting services), and aesthetics (cultural services). However, incorporation of ecosystem services into ecosystem management policy and decision-making remains inadequate (Anton et al. 2011; Costanza et al. 1997). Four years after the disaster, despite criminal investigations and environmental law enforcement, the impacts in the Doce River are still indeterminate, although the first studies have been already published (Gomes et al. 2017; Hatje et al. 2017). After rupture, 16 million m^3 of refuse were left in the tailings dam. Until today, 959,000 m^3 were removed to be treated, and 2020 is the deadline for dam closure (Fundação Renova 2019).

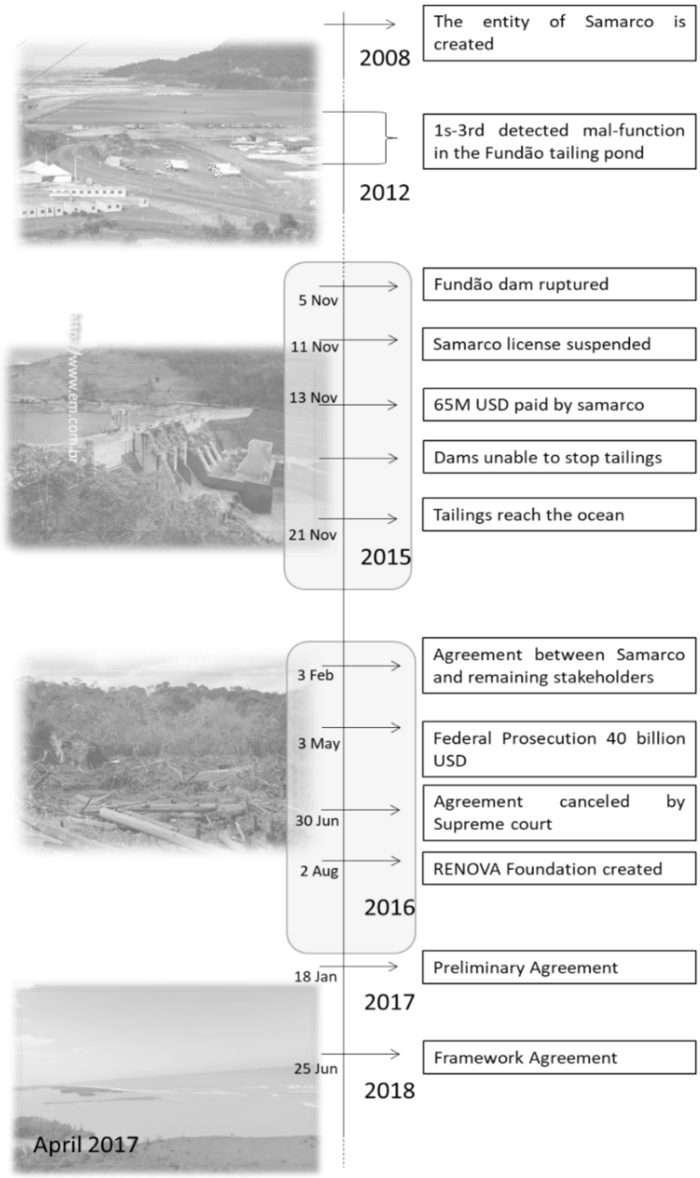

Figure 2. Timeline from the creation of Samarco, the start of Fe-ore exploitation to the latest events regarding the ruptured tailing dam

Environmental Governance in Brazil

The Fundão tailing pond rupture raised awareness on the Brazilian Environmental Protection system. Despite the pressing environmental issues of any given country, citizens rely on the environmental protection systems or agencies to assure and provide both environmental and health security and to act in an emergency crisis. To understand the decision-making process after the disaster, it is necessary to envisage how the Brazilian environmental governance system works. At National level, the environmental institutions are MMA, IBAMA, ICMBio, ANA, whereas MME deals with energy and mineral production. The MME houses the DNPM that supervises and monitors tailing ponds. In the Doce River, there are equally responsible entities at 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, with the belief that environment compliance hinders economic growth. This has prioritised mining and weaken environmental industry and regulating agencies. Between the accidents of Fundão (2015) and Brumadinho (2019), instead of changing the political framework to provide effective safety to populations around mining areas, what happened was the flexibilization of some legal provisions, such as reduction of licensing steps (Armada 2019). 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 organisations, may be the culprit for the overall current standstill.

The New Governance Framework

A 'new Governance Framework' was created to deal with the Doce river disaster, a local, transboundary structure that addresses the Doce River disasters and its aftermath. To accelerate the watershed environmental recovery process and prevent delays at the Federal Supreme court, Samarco made a *Framework Agreement* between Vale S.A, 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), signed on 2 Mar 2016. This mechanism to remedy the Doce River disaster was created without any consultation or participation of the affected communities (Nabuco and Aleixo 2019). The *Framework Agreement* is formed by three new entities (Figure 4a): the RENOVA Foundation, Inter-Federative Committee (CIF) (Figures 3 and 4), and technical boards.

The CIF has a multi-level structure, composed of agencies at the Federal, State and Municipal level. The CIF has authority to conduct the agreement acts, it has been formally designated to approve the projects and activities, and consist of members of Environmental Ministry, Federal Government, State of Espírito Santo, State of Minas Gerais, municipalities impacted, the Doce River Hydrograph Basin Committee and Public Defenders of the States. By creating the *Framework Agreement*, public agencies assumed that it is a technical issue to guarantee and protect transindividual rights and interests (Santos and Milanez 2017). These bodies have therefore assigned and restricted decision-making powers to the Renova Foundation, environmental agencies, third-party experts, and the State bureaucracy. The *Framework Agreement* also exempted the Federal government from their responsibility in preventing the disaster (Gonçalves e Silva 2019).

The Renova Foundation started operations on 2 Aug 2016, having responsibility for managing US$6.3 billion and for developing, proposing, enabling and implementing plans, programs, and projects that tackle the above-mentioned environmental priorities. Ultimately, the technical groups discuss and deliver socio-environmental and socioeconomic programs aiming at impact recovery. Both the technical boards and the Renova Foundation respond to the CIF, in a rigid hierarchical structure, and operate according to its ruling (Figure 4a). Nevertheless, a major player does not take part in the *Framework Agreement*. MPF, the Federal Prosecutors' Office, is a separate administration focusing on promoting social justice and democratic rights and is the central institution with legitimacy to homologate agreements and other legal protocols. MPF does not participate of this 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", defining the *Framework Agreement* "unconstitutional in its merits" (MPF 2016b). Also, civil society organisations, scholars, members of the Public Prosecutor's Office and the Public Defender's Office, representatives of social movements and the affected communities sharply criticised the *Framework Agreement* as it did not include the most important stakeholders: the affected communities (Nabuco and Aleixo 2019).

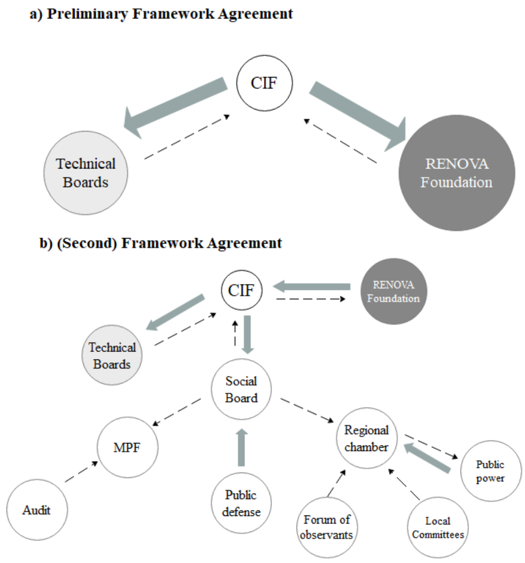

Figure 3. a) Composition of the preliminary Framework agreement and (b) the most recent (second) Framework agreement

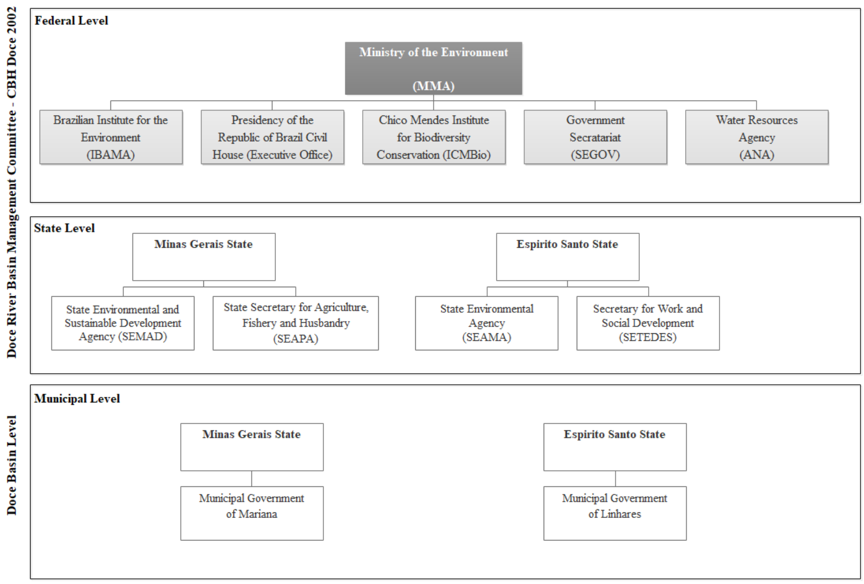

Figure 4. Organogram representing the Inter-Federative Committee (CIF) and its multi-level structure

The *Framework Agreement* aims to provide restoration of environmental damage to the communities affected, including the indigenous. A fund of up to US$ 6.3 billion (20 billion BRL) is available for clean-up costs and recover damages related to the Samarco dam failure. The *Framework Agreement* establishes a public-private governance system to rehabilitate the Doce River Basin with environment-related incentives, constituting the first hybrid governance system in Brazil. According to Muradian and Rival (2012), hybrid regimes are suited to deal with the governance challenges derived from ecosystem services characteristics. The major challenge is the integration of '*regulatory processes, mechanisms and organisations through which political actors influence environmental actions and outcomes*' (Lemos and Agrawal 2006). To evaluate stakeholders' role, a stakeholder analysis was carried out to identify weakness and loss of opportunities to improve governance, according to Brown (2006), which defends a narrative approach to the study of organisations. This approach focuses on stories that underpin our cognitive and emotional lives as agents of memory, emotion, and meaning (Brown 2006). The stakeholders were categorised from the authors' perspectives, constructed by a mix of internal participants that had joined CIF meetings, analysing legal and technical documents, and an empirical explorer group that collected data about geographical changes and post-disaster actions. This vast contextualization allowed comparing how political discussions at CIF's table were being applied in the field. Figure 5 was then generated and is central to understand the reasons why this complex organisation created to manage an environmental disaster has low efficiency although has the power, hegemony and control over the Doce river restoration.

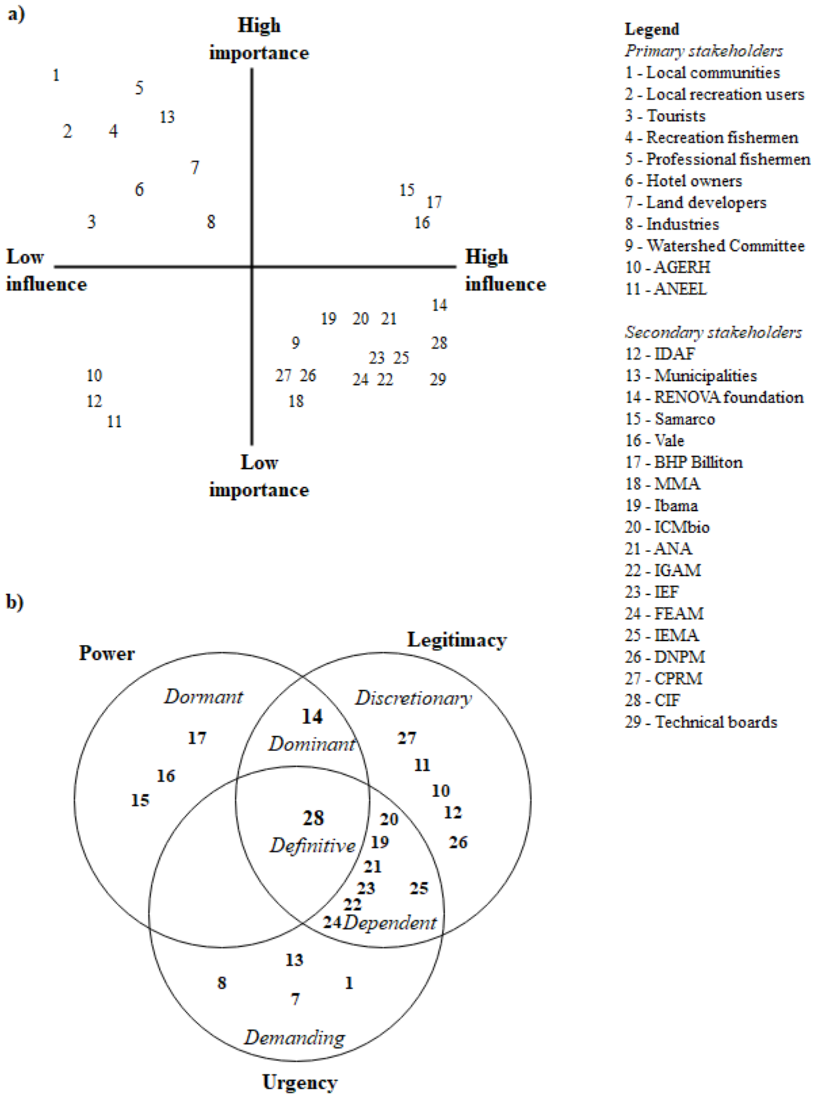

Figure 5. a) Stakeholder level of importance (Brown 2006) concerning impact by the disaster and level of influence on decision-making on the post-disaster actions following the new Framework agreement and b) stakeholder definition (Mitchell et al. 1997).

The stakeholder's analysis generates 29 stakeholders involved in the new *Framework Agreement*, with different degrees of decision-making power (Figure 5a). Brown (2006) defines the importance of these stakeholder groups as for how their livelihoods were (i) impacted by the outcome of decision-making and (ii) their influence over the decision-making process.

Stakeholders were categorised into primary and secondary, depending on decision-making power. The upper left square of Figure 5a describes a stakeholder that is defined as *Demanding* by Mitchell et al. (1997), a group that has no power nor competences but is profoundly impacted by the decision-making process. In the current case, local communities (1) are considered the highest impacted stakeholder, only to be matched by the local professional fisherman (3). Local communities are considered here as the local population living in the river vicinity, but also the indigenous people that live and worship the river. For these people, the Doce constituted water, food, shelter and a belief system. The most impacted and influenced by the disaster, Local communities (1) have the lowest influence over the new governance system. The local professional fishermen (3) have higher influence than (1) 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 scarcity, in terms of degraded land and river, in the absence of natural resources that sustained their business. AGERH (10), ANEEL (11) and IDAF (12) (*Discretionary* stakeholders) are Federal and State institutions that possess both expertise and legislative power but are neither greatly impacted by the disaster nor have significant influence over the decision process. These institutions have little to none representation at the CIF and are not currently included in the watershed recovery, but have legislative power at the State level. Therefore, we consider them as *Discretionary* stakeholders (Mitchell et al. 1997).

Another type of stakeholder is the *Dangerous* type, where regularly NGOs take this role. However, Brazil does not host NGOs with sufficient power to influence the decision process as it is. Therefore, we leave this category blank. The Fundação Renova (14) is the sole stakeholder defined as *Dominant* as it has power with legitimacy to manage the funds that were allocated to the Doce River recovery. The DNPM, the institute supervising tailing dams in Brazil, is indicated as neutral in terms of impact and influence (very close to the origin in Figure 5a and *Discretionary* stakeholder in Figure 5b). The DNPM has all the legitimacy to sanction and stop mining exploitation prior to disaster. Once the tailing dam was ruptured, the DNPM has no competencies relative to ecosystem and environmental restoration. Mitchell (1997) describes the *Dependent* stakeholder as stakeholders who lack power but who have urgent legitimate claims because these stakeholders depend upon others for the power necessary to carry out their will. In this sense, we defined the majority of environmental agencies as dependent (Figure 5b). In the new Framework agreement, these autonomous agencies that generally have the authority to implement directives, supervise and execute sanctions are now dependent on 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 5b). Empirically, the MPF has all the three main attributes as well, but it removed itself from the Framework agreement early in the process.

Samarco (15), Vale (16), and BHP (17) are considered as powerful stakeholders because they have financial capacity and provide the funds that will be used to recover the ecosystem. We consider that they are *Dormant* stakeholders because they lack the urgency to recover the environment. However, this urgency should increase in a post-disaster scenario, mainly by authority imposition – the MPF. Since the MPF has removed itself from the Framework Agreement, the powerful dormant stakeholders will remain as such. The stakeholder analysis suggests that the new *Framework agreement* continues to underrepresent the most impacted stakeholders (Figure 5a, 5b). Being the CIF the *definitive* stakeholder, and the Renova Foundation the *dominant* one, measures should be taken to assure that decision-making is not mainly affected by economic interests but based on the technical and scientific advice provided by the Technical boards (Figure 3a).

The jurisdictions of environmental management systems and water resources management systems in Brazil are separate, and the *Framework Agreement* addresses this divide. Efforts to decentralise decision-making from the CIF and to reduce the industrial ruling should be made. Instead, the watershed ecosystem recovery should be prioritised, and concepts of ecological engineering and ecohydrology should be adopted (McClain and International Association of Hydrological Sciences. 2002; Millenium Ecosystem Assessment 2005). For this to take place, a basin approach should be considered, and for that, the watershed committee (9) should take a central role as *Definitive* stakeholder. This way, environment, energy production, population, sewage treatment, agriculture irrigation, wetland preservation, to mention a few, will be incorporated in decision-making. An instrumental aspect would also to engage indigenous people and make them more representative in the process. The recovery of wetlands along the Doce River is instrumental in support of indigenous people, the Krenak, who support themselves from the river. Also, as the Krenak perceive the Doce River as a deity, working proactively in its recovery would reassure and engage them. For example, the Kagera project, a transboundary watershed between Burundi, Rwanda, Tanzania, and Uganda supported by FAO, can serve as an imprint for the Doce River recovery. Actions portfolio consist of protection of wetlands for water and food supply carried out by local communities in tandem with the technical support. This decentralised approach involves field work and teaching local communities.

The broken policy

With diverse and complex governance, Brazil offers a flexible system that may be considered an advantage when risk (such as disasters) arises (Renn et al. 2011). The new *Framework Agreement* represents a new structure in the national governance paradigm, housing members of different governmental bodies in a 3-axis structure (Figure 3a). Since its inception, several public meetings have taken place to develop the current structure and coordinate with key stakeholders to the Doce River recovery (IBAMA 2018). The *Framework Agreement* developed a regulatory body – CIF –, an independent foundation (Renova Foundation) and technical boards (Figure 4), independent of the established rigid regulatory structure itself. When institutional diversity is taken into account, several benefits can be observed (Renn et al. 2011):

- Increased flow of communication across environmental agencies;
- Reduce bureaucracy;
- Expedite watershed rehabilitation, since communication and decision-making are faster;
- Simplifies decision-making because scientific and technical information is costumed-made;
- Aggregates information to be provided to the public.

The *Framework Agreement* is viewed as a reasonable governance structure for watershed recovery and management. The structure is horizontal, including members from main environmental federal and state agencies; funds are available for ecosystem recovery, and there is sound national and international technical expertise available. Like other hybrid governance systems, it 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).

However, the *Framework Agreement* has proven to be lacklustre, maybe due to its complexity or other factors. As pointed out by Moss and Newig (2010), spatial distance between stakeholders directly influence their level of involvement in collaboration, despite the CIF meetings have been held roughly 1-month apart since its inception (IBAMA 2018). Four years after the disaster, an impact assessment on water quality, aquatic biodiversity and human health is still missing. There was limited knowledge exchange between researchers and local communities for remedy and collective development (de Abreu and de Andrade 2019). A concise environmental monitoring program is being planned and was launched in late 2017 involving academia, technical experts from Government bodies, among others (IBAMA 2017). According to Hardy (2010) this is significant as he found that effective agency-based partnerships are comprised of highly skilled technical experts, government officials, and representatives from regional and state agencies. However, two big *Framework Agreement* caveats consist of:

- The MPF does not participate in the agreement, i.e., the national regulatory body does not partake of the CIF. Therefore, the *Framework Agreement* does not hold juridical 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 organisations be recognised as legitimate.
- The *Framework Agreement* establishes Samarco, the "polluter", as the creator of the Renova Foundation. This point implies a bias towards the management of financial resources, diminishing effective institutional diversity in the decision-making process.

The *Framework Agreement* places itself between markets and hierarchies constituting a hybrid governance structure, similar to the Chesapeake Bay transboundary watershed management (Just and Netanyahu 1998). In this particular case, an agency-based watershed partnership was created that contained over 300 scientists, 22 different state and federal agencies, as well as representatives from the USEPA (Diaz-Kope and Miller-Stevens 2015). In these circumstances, policy decisions regarding restoration and protection of the Chesapeake Bay are made by the members of the Executive Council (governors of Virginia, Maryland, and Pennsylvania; the Mayor of Washington, DC; as well as a representative from the U.S. Environmental Protection Agency (EPA) and the Chair of the Chesapeake Bay Commission") (Chesapeake Bay Program 2009; Diaz-Kope and Miller-Stevens 2015). Policy decisions, however, are taken by the Executive Council, which is comprised of environmental regulators and high-level government representatives and delegations of federal and state agencies (Chesapeake Bay Program 2009). Indeed, decision-making within the Chesapeake Bay Program is complex as the different partners respond to several jurisdictional authorities and are affected differently by watershed issues (e.g. pollution affected both water and air). Therefore, the program incorporates four distinctive decision-making levels that guide governance activities: (a) consensus, (b) unilateral, (c) champion, and (d) voting (Chesapeake Bay Program 2009; Diaz-Kope and Miller-Stevens 2015). Creating levels of decision-making can be the solution to the Doce River *Framework Agreement* delay. By allocating funds and decision-making a restoration and protection group could speed up the process, bypass the CIF centrality (Figure 5b), and empower the "Technical boards" and consequently environmental restoration.

Diversity is key when complex, uncertain, and ambiguous risk problems need to be addressed (Renn et al. 2011). Although diversity is achieved within the *Framework Agreement* constitution, it is evident that the mining industry has strong influence over the Renova Foundation and the overall decision-making process (Figure 5a). The funds have been allocated to the recovery of the Doce River, but the actions taken so far are not effective for the recovery of the river. As Muradian and Rival (2012) stated, without appropriate incentives or local engagement in rulemaking, there is abundant evidence that state policies might be ineffective. The economic influence of the private sector over Governments must then be addressed. In Brazil, political campaigns could be financed by private companies up to a limit of 2% of their gross annual revenue. Specifically, a company that bills two billion USD a year may donate up to three million USD to a given political party. This practice of "lending money", which ended in 2015, may have undermined the integrity of political decision-making. Politicians have been criticised because they focused on the companies' growth to the detriment of the protection of the population and the environment (Westra et al. 2013). Since 2015, by electoral reform, donations by private companies to political parties are prohibited. In the aftermath of the Fundão failure, several close collaborations between the mining industry and politicians were disclosed, some related to bribery, exposing powerful alliances between industry and politicians (Lyra 2019).

However, industries were given flexibility throughout the years, including the compliance with international regulations such as safety and security (e.g. US Occupational Safety and Health Administration OSHA). Brazil mining activities are spread out, with over 3000 listed tailing ponds). Currently, there are a considerable amount of dams at risk of rupture in Brazil (DNPM 2016). Basin vulnerability was defined based on tailing dams risk assessment and its size and on socio-economic data regarding indigenous people representation, GDP, administration improbity. High-risk mining industries should supervise and regulate locally but should respond to national governmental bodies, where contingency plans are instrumental in preventing and minimising environmental impacts along the entire fluvial-estuarine-marine continuum, and policy-making need to focus more on prevention at source (Lu et al. 2015).

When we consider dam failure risk alone, Brazil has considerable basin resilience-based merely on its basin sizes (Lacerda et al. 2002). Indeed, when we add a social dimension because of local policies to watersheds to basin vulnerability given by risk of dam failure, we see that basins with medium vulnerability rise from two to seven (Figure 6). Policy and its social impacts do add to the risk of watershed management in case of dam failure. In the case of the Doce River, collaboration between the different layers of federal and state government, academia, industry and local communities, including indigenous people, is essential to recuperate the basin. Given the scale of mining operations in the Iron Quadrangle, monitoring, contingency plans, and legislative reinforcement need to be of the same scale, if we are not to have a similar event soon. However, we alert to the fact that there are other basins in Brazil in danger of dam failure, and that current local policies would result in the same type of disaster management. Forcing industries to implement contingency plans for possible dam failures now may mitigate uncertainty in the future (like the Canadian Directive 085).

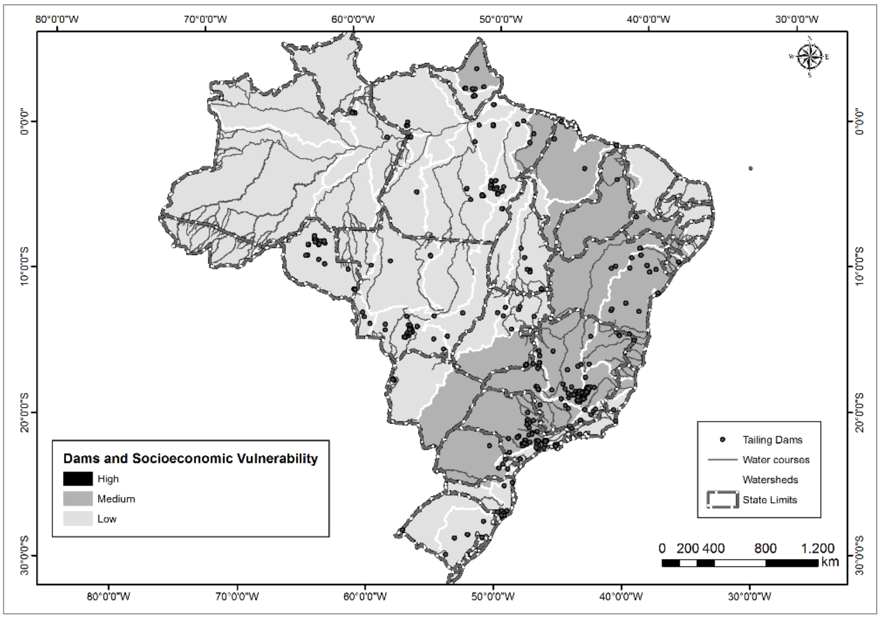

Figure 6. Basin vulnerability based on dam risk failure assessed by DNPM (DNPM 2016), combined with the ratings attributed to basin size, and socioeconomic data.

The *Framework Agreement* created in 2018 has yet to prove to be effective, as the affected communities face serious obstacles to have their voice heard in both CIF and Renova Foundation, as well as to have access to equitable remedies (Nabuco and Aleixo 2019). The affected communities should be able to freely choose assistance committees (including legal counselling), to have representatives with the capacity to influence remedy programs in the decision-making bodies within Renova Foundation and CIF, and have the power to decide on the remedial measures tailored to their needs (Nabuco and Aleixo 2019). For example, the indigenous communities of the Krenak, Tupiniquim, and Guarani; the 'quilombolas', and the artisanal fishermen still lack access to inherent human rights such as water, work, wealth, and an adequate standard of living and health (Gonçalves e Silva 2019). Other issues, such as transparent and trustworthy systems of monitoring, control and disclosure of results, are also not implemented (Santos and Milanez 2017). Also, the predominance of Executive Branch agencies in the CIF compromises the monitoring activity, as they currently do not have the capacity for effective enforcement of the regulations (Santos and Milanez 2017).

If we need to single out the main reason why the *Framework Agreement* is on a standstill, we would have to address the stakeholder analysis (Figure 5b). The CIF is the *Definitive* stakeholder, the single entity that has effective power over decision-making in this governance system. Concentrating decision-making power in one single entity is the principle of classical governance systems (Hammer et al. 2011; Lemos and Agrawal 2006; Milas and Latif 2000; Muradian and Rival 2012). The new *Framework agreement* (Figure 3b) introduces social stakeholders and both federal and state environmental agencies. However, it is our understanding that the hierarchy does not change. According to Muradian and Rival (2012), solving the problems posed by ecosystem services usually requires that we move from thinking in terms of single, ideal managerial approaches to combining governance structures, scales, and tools. If we want the *Framework Agreement* to be successful, governance requires to be misplaced from a single centre of power (McGinnis 2000). Similar to the Chesapeake Bay program, the *Framework Agreement* should adopt distinctive decision-making levels that guide governance activities (Chesapeake Bay Program 2009). Moreover, since most Brazilian watersheds are transboundary, we urge the central government to initiate and implement, a priori, a similar type of Framework Agreement to each national watershed (especially the ones highlighted with medium vulnerability in Figure 6). More policy guidelines for disaster management can be found in, e.g. PEDRR (2011); Schoenberger (2016).

A second massive disaster in the same region has recently occurred. On 25 Jan 2019, tailings from a dam in Vale's Córrego do Feijão mine (Belo Horizonte, Minas Gerais) released 12 million m^3 of iron tailings to the Paraopeba River (Freitas et al. 2019). This rupture had a lower volume of tailings released (and lower environmental impact when compared to Fundão Disaster), but higher loss in human lives (almost 300 fatalities) and it is considered a large-scale work accident (the largest in Brazil) (Almeida et al. 2019). The slurry released travelled approximately 7 km downhill until reaching Rio Paraopeba, thereby destroying a bridge of the mine's railway branch, and spreading to Vila Ferteco local community, near the town of Brumadinho. The company responsible for this disaster is one of the owners of Fundão tailings dam. This second disaster highlights two things: (i) the new governance adopted – the *Framework Agreement* – does not successfully reach the mining companies and their responsibility for the state of their tailing ponds; and (ii) the urgency of restructuring the Brazilian Environmental Policy System. The *Framework Agreement* is temporary and was created outside of the environmental system with the sole goal of accelerating the watershed recovery process. During the four years between the two disasters, no other actions were carried out to better appropriate responsibilities in the mining industry. As a result of this oversight, another 300 hundred human lives were lost. How many more?

Final Remarks

Resource-based countries, such as Canada, Russia, China, Australia, and Brazil, rely heavily on mining activities to support their economy, and they will continue to exploit natural resources in the future (Montesanti 2014). Currently, in Brazil, integrated state participation regarding industrial resource exploitation is inexistent. The new Framework agreement constitutes the first hybrid governance system in Brazil and presents limitations regarding stakeholder engagement and empowerment. Based on basin vulnerability, we can predict that the Doce River and "Costeira do Norte Oriental" are potential watersheds to undergo new tailing dam rupture in the future and require special judicial and environmental audit to these basins. In principle, the Framework Agreement in place would be diverse and well-structured system to oversee ecosystems recovery. However, efforts to decentralise decision-making and minimise the industrial biases should be made. According to the Brazilian law, and the polluters-pay principle, *"the person exploiting mineral resources must recover the degraded environment, in accordance to the technical solution required by the competent public authority"* (Article 225, 2, Brazilian Constitution). To this day, no concrete action-plan, goals and recovery targets have been established.

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List of Abbreviations

FUNAI - National Indian Foundation (Fundação Nacional do Índio)
Samarco - Samarco Mineração S.A., mining industry co-owned by VALE and BHP Billiton
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-Federative Committee (Comitê Inter-Federativo)
RENOVA Foundation - Foundation managing the new Framework Agreement
MPF – Federal Prosecutors' Office (Ministério Público Federal)

References

Almeida I M , Jackson Filho J M ., Vilela R A G (2019) Reasons for investigating the organizational dynamics of the Vale tailings dam disaster in Brumadinho, Minas Gerais State, Brazil. Cad Saude Publica. doi: 10.1590/0102-311X00027319

Alves RH, Rietzler A C (2015) Toxic effects of arsenic on *Eisenia andrei* exposed to soils surrounding gold mining operations. Rev Bras Cienc Solo 39: 682–691.

ANA (2015) Noticia da Agência Nacional de Águas. http://www2.ana.gov.br/Paginas/imprensa/noticia.aspx?id_noticia=12271. Accessed 22 August 2017

ANA (2017) Sewage Atlas. http://atlasesgotos.ana.gov.br/. Accessed 17 October 2017

Anton A, Cebrian J, Heck K L et al (2011) Decoupled effects (positive to negative) of nutrient enrichment on ecosystem services. Ecol Appl 21(3): 991–1009

Armada C A S (2019) The environmental disasters of mariana and brumadinho and the brazilian social environmental law state. SSRN. doi: 10.2139/ssrn.3442624

Biermann F, Bai X, Bondre N et al (2016) Down to Earth: Contextualizing the Anthropocene. Glob Environ Chang 39: 341–350.

Boger D V (2013) Rheology of slurries and environmental impacts in the mining industry. Annu Rev Chem Biomol Eng 4:239–257

Bourcy S C, Weeks R E (2000) Stream morphology and habitat restoration of Pinto Creek, Gila County, Arizona, In:Proceedings of the Seventh International Conference on Tailings and Mine Waste 2000, Fort Collins, Colorado, USA. Balkema, Rotterdam, pp. 467–475

Bridge G (2004) Contested terrain: Mining and the environment. Annu Rev Environ Resour 29:205–259

Brown A D (2006) A narrative approach to collective identities. J Manag Stud 43:731–753

Cambridge M, Shaw D (2019) Preliminary reflections on the failure of the Brumadinho tailings dam in January 2019. Dams and Reservoirs 29:113-123.

Chesapeake Bay Program (2009) Summary Report to the Chesapeake Executive Council. 2009 State of the Chesapeake Bay Program

Chiaretti D (2017) Reconstrução após desastre da Samarco esbarra em entraves. Valor Econômico. https://valor.globo.com/brasil/coluna/reconstrucao-apos-desastre-da-samarco-esbarra-em-entraves.ghtml. Accessed 15 October 2018

Costa A T (2001) Geoquímica das águas e dos sedimentos da bacia do Rio Gualaxo do Norte, Leste-Sudeste do quadrilátero ferrífero (MG): Estudo de uma área afetada por atividades de extração mineral. Dissertation, Universidade Federal de Ouro Preto

Costanza, R, d'Arge R, de Groot R et al (1997) The value of the world's ecosystem services and natural capital. Nature 387:253–260

CPRM (2015) Portal CPRM - Serviço Geológico do Brasil. http://www.cprm.gov.br/. Accessed 22 August 2015 de Abreu M C ., de Andrade R D J C (2019) Dealing with wicked problems in socio-ecological systems affected by industrial disasters: A framework for collaborative and adaptive governance. Sci Total Environment. doi:10.1016/j.scitotenv.2019.133700

Davies M P (2002) Tailings impoundment failures: Are geotechnical engineers listening? Geotechn News 20(3):31-36

Diaz-Kope L, Miller-Stevens K (2015) Rethinking a typology of watershed partnerships: A governance perspective. Public Work Manag Policy 20:29–48

DNPM (2016) Classificação de Barragens de Mineração. http://www.dnpm.gov.br/assuntos/barragens/cadastro-nacional-de-barragens_2016-_atualizacao_campanha. Accessed on 25 March 2018

Eckersley R (2004) Green State. Rethinking Democracy and Sovereignty. MIT Press, Cambridge.

Escobar H (2015) Natural disasters. Mud tsunami wreaks ecological havoc in Brazil. Science 350: 1138–1139

Foley J, Defries R, Asner G P et al (2005) Global consequences of land use. Science 309: 570–4.

Fourie A B, Papageorfiou G, Blight G E (2000) Static liquefaction as an explanation for two catastrophic tailings dam failures in South Africa. In: Proceedings of the Seventh International Conference on Tailings and Mine Waste 2000, Fort Collins, Colorado, USA,. Balkema, Rotterdam, pp. 149–158.

Freitas M B, Rodrigues S C A (2014) As consequências do processo de desterritorialização da pesca artesanal na Baía de Sepetiba (RJ, Brasil): Um olhar sobre as questões de saúde do trabalhador e o ambiente. Cien Saude Colet 19: 4001–4009.

Freitas C M, Barcellos C, Asmus C I R F et al (2019) Da Samarco em Mariana à Vale em Brumadinho: Desastres em barragens de mineração e saúde coletiva. . Cad Saude Publica. doi:10.1590/0102-311X00052519

Fundação Renova (2019) Dados da Reparação - Terra e Água, https://www.fundacaorenova.org/dadosdareparacao/terra-e-agua/. Acessed on 24 October 2019

Garcia L C, Ribeiro D B, de Oliveira Roque F et al (2017) Brazil's worst mining disaster: Corporations must be compelled to pay the actual environmental costs. Ecol Appl 27: 5–9

Gonçalves e Silva T V (2019) The Mariana dam disaster in Brazil: Open issues about corporate accountability under international human rights law. Educamazônia 1:35-53

Gomes L E de O, Correa L B, Sá F et al (2017) The impacts of the Samarco mine tailing spill on the Rio Doce estuary, Eastern Brazil. Mar Pollut Bull 120: 28–36.

Grangeia C, Ávila P, Matias M et al (2011) Mine tailings integrated investigations: The case of Rio tailings (Panasqueira Mine, Central Portugal). Eng Geol 123: 359–372

Guedes G R, Simão A B, Dias C A et al (2015) Risco de adoecimento por exposição às águas do Rio Doce: Um estudo sobre a percepção da população de Tumiritinga, Minas Gerais, Brasil. Cad Saude Publica 31: 1257–1268

Hammer M, Balfors B, Mörtberg U et al (2011) Governance of water resources in the phase of change: A case study of the implementation of the EU Water Framework Directive in Sweden. Ambio 40: 210–20

Hardy S D (2010) Governments, group membership, and watershed partnerships. Soc Nat Resour 23:587–603.

Hatje V, Pedreira R M A , de Rezende C E et al (2017) The environmental impacts of one of the largest tailing dam failures worldwide. Sci Rep. doi:10.1038/s41598-017-11143-x

Herard D (2010) The Hungarian Toxic Red Sludge Spill and Determining Public Accountability. Dissertation. Florida International University

IBAMA (2018) CIF Meetings. http://www.ibama.gov.br/cif/pautas-das-reunioes. Accessed 24 August 2018

IBAMA (2017) Bacia do Rio Doce recebe rede para monitorar qualidade da água http://www.ibama.gov.br/noticias/422-2017/1154-bacia-do-rio-doce-recebe-rede-para-monitorar-qualidade-da-agua. Accessed 25 October 2017

IBAMA (2016a) Technical report PAR. 02024.000023/2016-47 NUGEO/RO/IBAMA.
IBAMA (2016b) Rupture of the Fundão Dam: Documents related to the Samarco disaster in Mariana/MG. http://www.ibama.gov.br/informes/rompimento-da-barragem-de-fundao#pareceres. Accessed 25 October 2017
IBGE (2017) Pesquisa Nacional por Amostra de Domicílios 2015. https://www.ibge.gov.br/estatisticas/sociais/educacao/9127-pesquisa-nacional-por-amostra-de-domicilios.html. Accessed 25 October 2017
IBGE (2016) Mudancas na cobertura e uso da terra 2000-2014. Rio de Janeiro.
IEMA (2017) IEMA - Informativo Rio Doce. https://iema.es.gov.br/informativo-rio-doce. Accessed 17 October 2017
IEMA (2015) Grupo de Técnico de Enfrentamento da Crise Ambiental do Rio Doce. Processo nº 72423994. Cariacica
Just R E, Netanyahu S (1998) Conflict and Cooperation on Trans-Boundary Water Resources. Springer US.
Kossoff D, Dubbin W E, Alfredsson M et al (2014) Mine tailings dams: Characteristics, failure, environmental impacts, and remediation. Appl Geochem 51: 229–245
Lacerda L D, Kremer H H, Kjerve B et al (2002) South American Basins: LOICZ global change assessment and synthesis of river catchment - coastal sea interaction and human dimensions. Texel.
Lemos M C, Agrawal A (2006) Environmental governance. Annu Rev Environ Resour 31:297–325.
Lima A T, Mitchell K, O'Connell et al (2016) The legacy of surface mining: Remediation, restoration, reclamation and rehabilitation. Environ Sci Policy doi:10.1016/j.envsci.2016.07.011
Lu Y, Song S, Wang R et al (2015) Impacts of soil and water pollution on food safety and health risks in China. Environ Int 77:5–15
Lyra M G (2019) Challenging extractivism: Activism over the aftermath of the Fundão disaster. Extract Indust Soc 6: 897-905
McClain M E (2002) The ecohydrology of South American rivers and wetlands. International Association of Hydrological Sciences. IAHS Special Publication no. 6
McGinnis M D (2000) Polycentric games and institutions: Readings from the Workshop in Political Theory and Policy Analysis. University of Michigan Press
Medeiros A O, Kohler L M, Hamdan J S et al (2008) Diversity and antifungal susceptibility of yeasts from tropical freshwater environments in Southeastern Brazil. Water Res 42:3921–3929
Meira R M S A , Peixoto A L, Coelho M A Net al (2016) Brazil's mining code under attack: Giant mining companies impose unprecedented risk to biodiversity. Biodivers Conserv 25:407–409
Milas S, Latif J (2000) The political economy of complex emergency and recovery in northern Ethiopia. Disasters 24: 363–379.
Millenium Ecosystem Assessment (2005) Ecosystems and Human Well-being: Wetlands and Water Synthesis. World Resources Institute, Washington, DC.
Miranda L S, Marques A C (2016) Hidden impacts of the Samarco mining waste dam collapse to Brazilian marine fauna - An example from the staurozoans (Cnidaria). Biota Neotrop doi:10.1590/1676-0611-BN-2016-0169
Mitchell R K, Agle B R, Wood DJ (1997) Toward a theory of stakeholder identification and salience: defining the principle of who and what really counts. Acad Manag Rev 22:853–886
MMSD (2002) Breaking New Ground: Mining, Minerals and Sustainable Development, Final Report - Minerals and Sustainable Development Project. London
Montesanti S (2014) Policy: Count the social cost of oil sands too. Nature 513:172–172

Morgenstern N R, Vick S G, Viotti C B (2016) Fundão Tailings Dam Review Panel: Report on the Immediate Causes of the Failure of the Fundão Dam.
Moss T, Newig J (2010) Multilevel water governance and problems of scale: Setting the stage for a broader debate. Environ Manage 46:1–6
MPF (2016a) Procedimento Investigatório Criminal (PIC) - MPF n.º 1.22.000.003490/2015-78. Brasilia.
MPF (2016b) Acão Civil Pública 155M com pedido de liminar inaudita altera PARS.
MPMC (2015) Post event environmental impact assessment report – Key finding report.
Muradian R, Rival L (2012) Between markets and hierarchies: The challenge of governing ecosystem services. Ecosyst Serv 1:93–100
Nabuco J, Aleixo L (2019) Rights holders' participation and access to remedies: Lessons learned from the Doce River dam disaster. Business Human Rights J, 4:147-153
Nazareno A G, Vitule J R S (2016) Pollution: Too many mining disasters in Brazil. Nature 531:580–580
Nobre C A, Marengo J A, Seluchi M E et al (2016) Some characteristics and impacts of the drought and water crisis in Southeastern Brazil during 2014 and 2015. J Water Resour Prot 8:252–262
Oliveira E N de, Knoppers B A, Lorenzzetti J A et al (2012) A satellite view of riverine turbidity plumes on the NE-E Brazilian coastal zone. Brazilian J Oceanogr 60:283–298
Oliveira K S S, Quaresma V da S (2017) Temporal variability in the suspended sediment load and streamflow of the Doce River. J South Am Earth Sci 78: 101–115
Pain D J, Meharg A, Sinclair G et al (2003) Levels of cadmium and zinc in soil and plants following the toxic spill from a pyrite mine, Aznalcollar, Spain. Ambio 32:52–57
PEDRR (2011)"Managing watersheds for urban resilience." Partnership for Environment and Disaster Risk Reduction (PEDRR). Policy Brief Presented at the Global Platform for Disaster Risk Reduction, Roundtable on "Managing Watersheds for Urban Resilience", Geneva, Switzerland
Petticrew E L, Albers S J, Baldwin S A et al (2015). The impact of a catastrophic mine tailings impoundment spill into one of North America's largest fjord lakes: Quesnel Lake, British Columbia, Canada. Geophys Res Lett 42:3347–3355
Pires J M M, Lena J C de, Machado C C et al (2003) Potencial poluidor de resíduo sólido da Samarco Mineração: Estudo de caso da barragem de Germano. Rev Árvore 27:393–397. doi:10.1590/S0100-67622003000300017
Renn O, Klinke A, van Asselt M (2011) Coping with complexity, uncertainty and ambiguity in risk governance: A Synthesis. Ambio 40:231–246
Ribeiro R A, Lemos-Filho J P, Ramos A C S et al (2011) Phylogeography of the endangered rosewood *Dalbergia nigra* (Fabaceae): insights into the evolutionary history and conservation of the Brazilian Atlantic Forest. Heredity 106:46–57. doi:10.1038/hdy.2010.64
Rico M, Benito G, Salgueiro A R et al (2008) Reported tailings dam failures. J Hazard Mater 152:846–852
Rodrigues A S de L, Malafaia G, Costa AT et al (2014) Iron ore mining promotes iron enrichment in sediments of the Gualaxo do Norte River basin, Minas Gerais State, Brazil. Environ Earth Sci 71:4177–4186
Rodrigues L (2017). Governo de Minas autoriza pesca de algumas espécies na bacia do Rio Doce | Agência Brasil - Últimas notícias do Brasil e do mundo. Agencia Bras. http://agenciabrasil.ebc.com.br/geral/noticia/2017-05/governo-de-minas-autoriza-pesca-de-algumas-especies-na-bacia-do-rio-doce. Accessed 17 October 2017
Rooney R C, Bayley S E, Schindler D W (2012) Oil sands mining and reclamation cause massive loss of peatland and stored carbon. Proc Natl Acad Sci USA 109:4933–493
Samarco (2014) Relatório Anual de Sustentabilidade da Samarco SA. Belo Horizonte|Ouro Preto|Germano|Matipó|Vitória|Ubu|Muniz Freire|Amsterdam|Hong Kong

Samarco (2008) Relatório Anual de Sustentabilidade da Samarco SA 2008
Santolin C V A, Ciminelli V S T, Nascentes C C et al (2015) Distribution and environmental impact evaluation of metals in sediments from the Doce River Basin, Brazil. Environ Earth Sci 74:1235–1248
Santos R S P, Milanez B (2017) The construction of the disaster and the privatization of mining regulation: Reflections on the tragedy of the Rio Doce basin, Brazil. Vibrant: Virtual Brazilian Anthropology, doi: 10.1590/1809-43412017v14n2p127
Schoenberger E (2016) Environmentally sustainable mining: The case of tailings storage facilities. Resou. Policy 49:119–128
Segura F R, Nunes E A, Paniz F P et al (2016) Potential risks of the residue from Samarco's mine dam burst (Bento Rodrigues, Brazil). Environ Pollut. doi:10.1016/j.envpol.2016.08.005
Tuck C A (2015) USGS Minerals Information: Iron Ore https://minerals.usgs.gov/minerals/pubs/commodity/iron_ore/. Accessed 12 August 2017
UNEP/OCHA (2000) Cyanide spill at Baia Mare, Romania, UNEP/OCHA Assessment Mission, UNEP/Office for the Co-ordination of Humanitarian Affairs.
Van Niekerk H J, Viljoen M J (2005) Causes and consequences of the Merriespruit and other tailings-dam failures. L Degrad Dev 16:201–212
Vick S G (1997) Failure of the Omai tailings dam: Closure. Geotech News 15(1):49–55
Westra L, Taylor P, Michelot A (2013) Confronting Ecological and Economic Collapse : Ecological Integrity for Law, Policy and Human Rights. Taylor & Francis Group.
World Bank (2017). DataBank http://databank.worldbank.org/data/home.aspx. Accessed 2 August 2017
Zhang R, Cuartas L A, de Castro Carvalho L V et al (2018) Season-based rainfall-runoff modelling using the probability-distributed model (PDM) for large basins in southeastern Brazil. Hydrol Process 32:2217–2230.