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Tailings dam failures in Brazil: River contamination, ecosystem recovery, and institutional responses to the Mariana and Brumadinho disasters

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Mine tailings are wastes from ore extraction and processing, which are frequently stored in hillslopes behind earth dams. Unfortunately, tailings dams have collapsed in a number of places worldwide, literally dumping the waste into nearby rivers as metal-rich debris and mud. The environmental impact of these accidents is systemic and often severe and long-lasting. This study reviewed recent cases from Brazil (the Mariana accident that affected the Doce River and the Brumadinho accident that affected the Paraopeba River), highlighting the impact of large tailings dams' failures on river water quality and implications derived therefrom. The review showed how the Mariana failure affected the entire course of the Doce River, even impacting the estuarine ecosystem for a decade so far; and how physical barriers such as the Igarapé weir helped delaying the propagation of contamination in the Paraopeba River. Invariably, the contamination of river water was characterized by concentrations of metals (e.g. iron, manganese) and turbidity above the legal thresholds and far exceeding the levels observed before the accidents, which in the Brumadinho case, led to the suspension of drinking water supply to the metropolitan region of Belo Horizonte, affecting 2 million people. Besides, bioavailable phases of metals have accumulated in various trophic levels across the food web, threatening human health. The role of storm events in the exacerbation of water quality degradation and the potential impact of floods on the health of riparian forests were also recognized, because contaminated sediments were resuspended during those events and riverbanks were inundated in the sequel. Moreover, contaminated surface water flowing from urban, industrial, and pastureland areas masked the water quality degradation of Paraopeba River caused by the tailings dams' failures, because this water also contained metals and other toxic elements. On the other hand, inflows of sediments and water from tributary rivers helped dilute the contamination in the main watercourses. The time required to bring the river water quality back to safe levels was assessed in some studies, which pointed to 6–8 years in the Brumadinho case and provided no clear timespan for the Mariana case. Dredging of mine waste from the impacted areas was said to accelerate the recovery of Paraopeba river. The reviewed articles suggested some institutional responses, both systemic and specific to tailings dam accidents. The systemic measures comprised reforestation and implementation of best management practices to prevent water erosion and contaminant transport across the river basins, coupled with integration of accountable water quality monitoring in landscape management plans and policies. The specific measures were mostly related with prevention through the design of promptly implementable emergency action plans, coupled with policies capable of making the mining companies pay the recovery costs in a reasonable timeframe, where the affected population has a voice and participates in the compensation process. Overall, the reviewed papers shed light over key issues related to the impacts of large tailings dam accidents on riverine systems in general, in spite of describing two specific cases, leveraging useful insights to the authorities in charge of water security in emergency scenarios.

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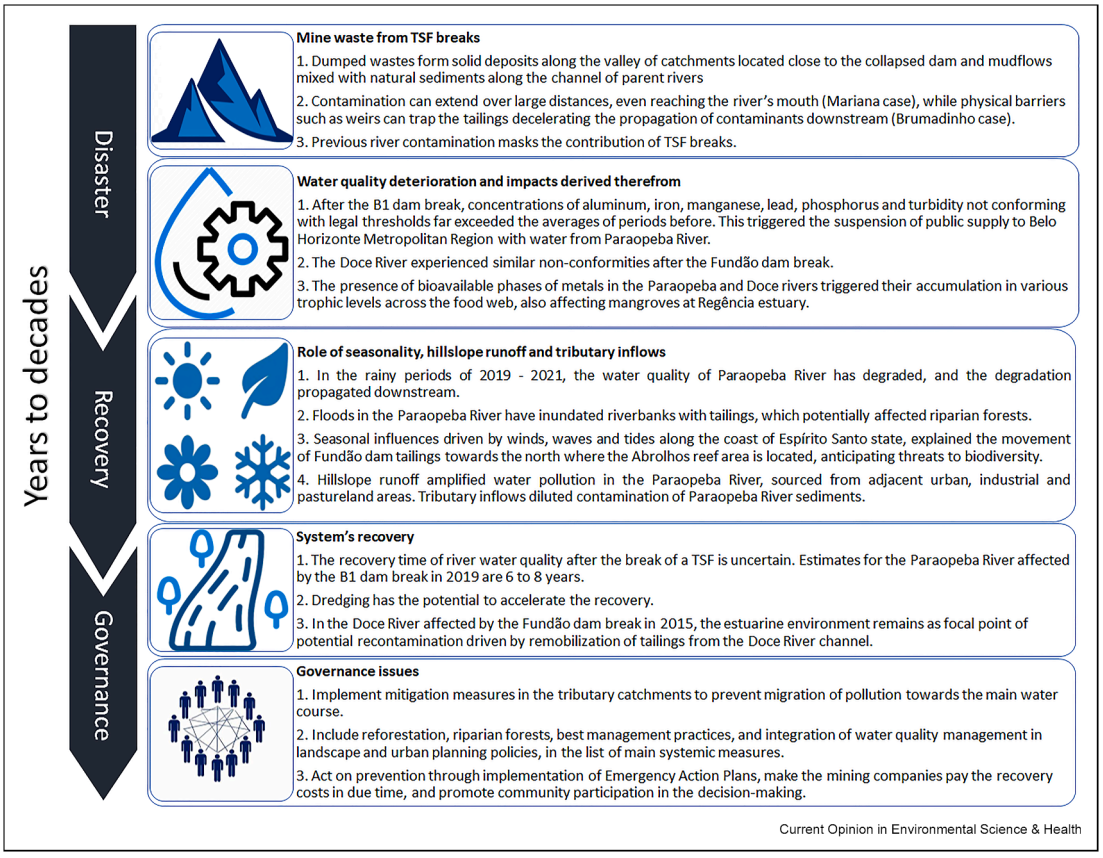
Tailings dams' disasters

The failure of tailings storage facilities (TSFs) is a worldwide problem, with global numbers on magnitude and frequency updated in the work of Rana et al. [1]. According to these authors, the number of TSFs built in the 1965–2020 period was in the range 6810–20,230, while the percentage of TSFs that collapsed in the same period varied from 4.4 to 1.5.%, being associated to 6 deaths per failure, on average. The work of Su et al. [2] covered the China territory and identified 14,217 TSFs with an average failure rate of 1% and a return period of 16 years for failures releasing >1 Mm^3 of mine waste. Brazil has nearly 600 registered TSFs and experienced recent cases of TSF breaks, namely the one that occurred in 2015 in the Mariana municipality and affected the Doce River with approximately 43.7 Mm^3 of mine waste, and the one that occurred just 4 years later in the Brumadinho municipality and contaminated the Paraopeba River with 2.8 Mm^3 of iron- and manganese-rich mud [3].

The causes of a TSF break may be complex, but are frequently related with improper construction/maintenance and/or sitting, as outlined in the work of Karen Hudson–Edwards et al. [4]. For example, the accidents that occurred in Mariana and Brumadinho were both triggered by the tailings' static liquefaction and the earth dam seepage erosion, which, in turn, were induced by improper construction and maintenance of internal drainage systems and promoted by abundant precipitation [3]. The study of Ramon Verdugo describes in detail static liquefaction in the context of earth dam stability [5]. In addition to unsafe construction/maintenance and location in high-precipitation sites, the TSFs, at least in the Brumadinho case, were built on sites with potential geomorphologic instability considering their steep hillslopes and high density of water lines [6]. Irrespective the causes of TSF breaks, the consequences are usually deleterious to the environment. On a global scale, the work of Islam and Murakami [7] assessed the gray water footprint (GWF) to measure the pollution caused by TSF breaks. The authors defined the GWF as '*the volumetric amount of freshwater needed to assimilate the load of pollutants given natural background concentrations and existing water quality standards,*' and estimated an average footprint of 25.5 Mm^3/incident. They also revealed bigger numbers for large failures such as the Mariana disaster, which released 43.7 Mm^3 of tailings into the environment and generated a footprint of 1387.5 Mm^3. This is nearly 10% of Brazilian's gray water footprint related to industry per year (16,000 Mm^3) [8]. In the reminder of this mini-review, a number of topics will be addressed in more detail, namely the spread of mine tailings along the impacted rivers and factors controlling the process; the impact of TSF breaks on water quality, including the legal view and outlines on the involved physical and chemical processes; the exacerbation and dilution roles of extreme hydrologic events and inflows from tributaries, respectively; the attenuation of metal contamination via natural wash-off complemented with mitigating actions like dredging, and finally some governance issues. The main intended contribution was to address the tailings dam failures through the lens of river water quality, namely degradation after the accident and in the years to come, and improvement after the implementation of mitigating measures while considering the diluting roles of natural processes and time. In spite of being a review, i.e. a critical analysis of previously published literature, this study presents a novel view about tailings dams' failures, because it spanned and set a nexus between tailings dam failures, water quality deterioration and corresponding environmental and anthropic drivers, ecosystem recovery, and institutional responses, as clearly stated in the title. To our best knowledge, a thorough and integrated analysis of different but imbricated topics related to tailings dam failures has not been tempted before. The forthcoming descriptions will be restricted to the Mariana and Brumadinho accidents, as they are among the most recent cases worldwide and hence fit the scope of COESH mini-reviews that request addressing cutting-edge research with no more than five years and preferably less than two years. The selection of Mariana and Brumadinho cases also contributes to offering stakeholders, globally, broad tailings management and river restoration strategies, because the studies are among the most documented in the scientific literature. In particular, the Brumadinho case had the contribution of a scientific project called '*ENTIRE - Emergence Analysis of Tailings Impacts for a Restored Aquatic Environment*' led by authors of this revision in coordination with the Minas Gerais Water Resource Management Institute. The relevance of this project relies, among other things, on the accessible database, which was immense. The data were passed to the project by the Vale, S.A., the mining company responsible for the accident, in the course of a judicial compromise signed with the Public Ministry of Minas Gerais. The database comprised millions of entries related to the concentration of contaminants in sediments and water of the Paraopeba River, besides other relevant information on the river basin. A large volume of data and research findings derived therefrom were published in nearly 30 papers since 2021, some of which are cited in the current review. Those studies are landmarks for other similar accidents worldwide, given the spatial (one monitoring station every 10 km) and temporal (daily to weekly analyses from 2019 to 2024) resolution, not always possible to reach in academic studies. A summary of key outcomes retrieved from the revised papers is presented in Figure 1 in the form of a disaster-recovery-governance timeline. The in-depth explanation of all the findings indicated in the figure is detailed in Spread of mine tailings along the impacted

Figure 1



Main outcomes of reviewed studies, presented in the form of a disaster-recovery-governance timeline, which was anticipated in years to decades for the Mariana and Brumadinho accidents that involved the collapse of Fundão and B1 tailings dams and affected the quality of Doce and Paraopeba rivers, respectively.

rivers, Water quality of rivers impacted by tailings mudflows, Role of seasonality, hillslope runoff and tributary inflows, System's recovery, Governance issues.

Spread of mine tailings along the impacted rivers

The failure of a TSF usually occurs in tributary catchments of large rivers. The scenarios created by the failure are usually characterized by blankets of tailings deposited along the tributary stream valleys, accompanied by the dumping of mudflows into the parent's main watercourse. For example, in the Brumadinho accident that occurred in the state of Minas Gerais, Brazil, the failure of B1 dam of Córrego do Feijão mine, owned by Vale, S.A., company released 11.7 Mm^3 of iron- and manganese-rich tailings into the Ferro-Carvão stream. Following the breach, 8.9 Mm^3 of debris and mud formed a deposit along the stream bed and margins of this watercourse, while 2.8 Mm^3 were dumped into the Paraopeba River 10 km downstream [9]. In the Ferro-Carvão stream, the tailings suffered selective transport due to the changes in velocity imposed by topographic (slope) and hydrographic (sinuosity) gradients between the dam site and the Paraopeba. The selective transported ultimately resulted in grain size and chemical differentiation, revealed by fractions richer in clay and manganese close to the Paraopeba, relative to fractions deposited close to the B1 dam that were richer in very fine-grained sand and iron. Besides, the torrent grabbed agricultural soils, bringing significant amounts of phosphorus into the mud that entered the Paraopeba [10].

The 'blanket' and 'dumping' domains of tailings mudflows have been given the names Zone 1 and Zone 2, respectively, in the study of Ghahramani et al. [11] that reviewed various TSF failures. Moreover, a relationship has been set between the volume of tailings released by the failure (V) and the corresponding inundated area (A) along the Zone 1: $A = cV^{2/3}$, where c increases with increasing tailings mobility. A similar relationship could not be set for Zone 2, because many factors affect the transport of tailings in this domain, such as the presence

of physical barriers (dams or weirs). For example, in the Brumadinho accident, mixtures of natural sediments (coarse sands, enriched in quartz and kaolinite) and tailings (clay + silt + very fine-grained sand, enriched in iron and manganese) were trapped behind the small weir of Igarapé, located nearly 40 km downstream of the Ferro-Carvão stream outlet where the mine waste entered the Paraopeba River [12*]. With some surprise, even when the stream discharge was high, the retention affected all grain-size fractions, namely those mostly composed of tailings. This integral retention contributed to decelerating the propagation of iron and manganese loads downstream the weir. The retention was attributed to '*backwater effects, free and submerged hydraulic jumps, bank sedimentation in periods of high flow, and streambed sedimentation controlled by channel sinuosity and tailings density.*'

The tailings in Zone 2 are more prone to settle on the riverbed than the natural sediments, because they are denser. However, as the time passes, both fractions will mix and flow together toward the river's mouth. The study of Kobayashi et al. [13] described the distribution of tailings in sediment cores sampled between the dumping point of the Brumadinho accident (confluence of Ferro-Carvão stream and Paraopeba River) and the Retiro Baixo reservoir, located nearly 240 km downstream. These authors used binary mixing models in the analysis, based on lead isotopes. The end-members in these models were natural sediments and tailings, and the results showed a contribution of tailings to the mixture varying from 80% at the dumping point to less than 5% in the Retiro Baixo reservoir, notably in the upper slices (0−5 cm) of the sampled cores. The results of Kobayashi et al. were in line with the outcomes of other studies, which segmented the Paraopeba River basin after the B1 dam failure into a 'control' sector located upstream the dumping point, an 'anomalous' sector between the dumping point and the Igarapé weir, and a 'natural' sector between the Igarapé weir and the Retiro Baixo reservoir [14]. In the Mariana disaster, no barrier effect was effectively imposed by weirs or dams, because the 43.7 Mm^3 of metal-rich tailings released with the Fundão dam break have traveled 600 km along the Doce River until reaching the river's mouth (Regência estuary in the Espírito Santo state) in just 17 days. The coverage of estuarine sediments by the tailings was observed in cores from mechanical drillings (gravity corer) sampled along the coast to the north, in front, and to the South of Doce River mouth [15]and it was referred to as 'time bomb' in the work of Queiroz et al. [16], mostly because these sediments frequently experience redox conditions that '*favor Fe reduction microbial pathways, which will probably increase the trace metal bioavailability and contamination risk*.' In a later study, Davila et al. [17] argued that past mining and industrial activities, coupled with subsequent recurrent floods, favored the displacement of soils and sediments previously contaminated with heavy metals (e.g. Ba, Cr, Cu, and Zn) and metalloids (As), which eventually reached the estuary, threatening the ecosystem more than the tailings that are much less concentrated in those elements. The authors also noted that the heavy metal concentrations were above the Brazilian Environmental Council thresholds in the soils and sediments not affected by the mudflow, and below those limits in the tailings. The work of Duarte et al. [18] confirmed arsenic levels above the thresholds before the dam disaster, exacerbated by the mudflow-induced remobilization of soils and sediments, while cadmium reached levels above the legal limits after the Fundão dam break. The mineral phases hosting the heavy metals were revealed to be crystalline Fe oxyhydroxides, notably goethite [19]. According to these authors (Camêlo et al.), crystallographic parameters of goethite such as specific surface area and Al substitution imply that it poses no imminent risk to the environment or human health. Highly Al-substituted goethites exhibit elevated chemical stability, resulting in diminished bioreducibility and heavy metal availability. However, their accelerated dissolution in redox-active environments would inevitably trigger the release of associated potentially toxic elements.

Water quality of rivers impacted by tailings mudflows

The interaction between mine tailings and the water column of rivers determines the extent and severity of TSF impacts on the water quality. In a study spanning the 2019−2021 period and focused on the Paraopeba River segment defined between the dumping point of B1-dam tailings (Ferro-Carvão stream outlet) and the Retiro Baixo reservoir located downstream (240 km), Pacheco et al. [20] reported the presence of nonconforming aluminum, iron, manganese, lead, phosphorus and turbidity concentrations, considering the thresholds set on the Brazilian Normative Deliberation COPAM/CERH-MG no. 1. The nonconformities significantly exceeded the averages preceding the B1 dam failure, particularly during the rainy period, unequivocally exposing the TSF impact on the river's water quality. This scenario also triggered the suspension of public supply to the Metropolitan Region of Belo Horizonte (6 million people) with water from this source. In addition, as time has passed, the non-conforming concentrations declined but affected progressively longer stretches within the studied segment. The results obtained by Pacheco et al. were confirmed by Mello et al. in 2024 [21], who also suggested that mining activities licensed after 2019 are likely exacerbating the already fragile situation left by the Brumadinho's accident. The evolution of metal concentrations in river water did not differ much in the Mariana disaster. As per the outcomes of Kütter et al.'s work [22], the concentrations of metal(loid)s in the Doce River, such as Fe, Mn, As, Cu, Ba, Pb, Zn, Cd, Cr, and Ni, were 100 times higher when the dam collapsed (2015) than before the failure, highlighting the TSF impact on the water quality. As with the

Brumadinho's case, these concentrations dropped substantially in the subsequent years and smoothed their contrast across the upper, middle and lower sectors of Doce River. It is worth retrieving from the Kütter et al.'s study that the TSF impact on the Doce River's metal concentrations represented solely 15.89% of river composition variability, the rest being attributed to other sources or processes.

The metals present in rivers usually distribute across the riverbed compartment, the suspension compartment, the dissolved compartment, and the labile compartment. The riverbed comprises clay- to gravel-grainsize fractions, which are transported by the river under the high flows of rainy periods and deposited when the flow decreases. The presence of natural organic matter in the porewater of these sediments fosters a microbial mediated anerobic environment, thereby enhancing metal oxide solubilization. The dissolved metals are transferred and spread into the river column through diffusion and/or advection. The suspension compartment consists of clays to silts that are transported as suspended particles with the river flow. The dissolved compartment represents the metals that were previously present in the adsorbed phase on metal oxide surfaces, which were later released into the river water via desorption or reductive dissolution, when the pH and redox conditions in the aquatic environment allowed metal solubilization. Finally, the labile compartment comprises metals loosely bound to soil particles and, for that reason, potentially bioavailable to aquatic organisms. In the Paraopeba River where the B1-dam tailings were dumped, desorption experiments conducted by Teramoto et al. [23*] revealed that the tailings released small quantities of As, Cu, Al, and Fe into the river water, but large quantities of Mn, and that the amount of metal in solution was constrained by an equilibrium. Besides, the total metal concentrations were higher in the rainy season than in the dry season, while the dissolved and labile fractions were lower in the rainy season. These findings were not surprising because an increased amount of material is transported in suspension during the rainy season, which can increase the total metal concentrations. Moreover, the increased river flow during the rainy season is partly associated with superficial runoff, which dilutes the dissolved and labile metal concentrations. Desorption kinetics modeling was also conducted in the Doce River basin where the Mariana disaster occurred [24], with results also suggesting the preferential release of Mn from the mine waste into the water column, when compared to the releases of Pb, Cu, Al, As, and Fe.

The metals present in the dissolved and labile compartments of rivers can enter the trophic chain and accumulate in the aquatic organisms. This possibility is exacerbated where rivers received spills of metal-rich tailings, as occurred downstream the injection points of Fundão (Carmo River outlet) and B1 (Ferro-Carvão stream outlet) tailings in the Paraopeba and Doce rivers, respectively. In the Paraopeba River, just five days after the B1 dam break, Souza et al. [25] used the *Allium cepa* test to check the potential of metals released from the iron- and manganese-rich tailings into the water column to induce cytogenotoxic effects, with positive results. The potential was confirmed one year after the accident by Parente et al. [26], who reported bioaccumulation of Fe, Mn, Ni, and Zn in fish and an increase of most elements in macrophytes, relating the observations with the Brumadinho tailings spill. The cytogenotoxic potential of water was confirmed in the Doce River by Vergilio et al. [27], who also used *Allium cepa* seeds to perform the analyses. The tests were conducted 15 days and six months after the Mariana accident, representing immediate and medium-to long-term impacts. Besides the *Allium cepa* tests, the authors determined the consequences of metal bioaccumulation in various trophic levels, namely algae, planktonic microcrustaceans, and zebrafish. They detected larger immobility of the microcrustacean *Daphnia similis* closer to the Fundão dam site (Ipatinga −256 km) and accumulation of Al, Fe, Mn, and Zn in the muscle tissue of zebrafish, despite the low mortality levels (<10%). The impact of elevated metal concentrations in the Doce River basin observed after the Fundão dam break has extended to the estuarine mangroves, considering the results of Tognella et al. [28] who noted that some areas in the estuary had higher levels of iron and manganese than before the Mariana's accident.

Role of seasonality, hillslope runoff, and tributary inflows

River flows are contrasting between rainy and dry periods, especially where the annual rainfall occurs in just a few months per year like in the tropical latitudes. As the river flow determines the distribution of sediments among the riverbed and suspension compartments, the aforementioned contrasts may induce very different water quality settings in the high-flow and low-flow periods of rivers. Aligned with this situation, Mendes et al. [29] set up exploratory scenarios based on the results of partial least squares path modeling, separately for the rainy and dry periods of Paraopeba River basin during the 2019−2021 period, i.e. after the B1 dam break that occurred in Brumadinho municipality. The exploratory scenarios included the so-called 'water quality' and 'environmental deterioration' latent variables, defined as follows for the rainy and dry periods: (*a*) rainy period − water quality = (chlorophyll-a × (0.219) + flow rate × (0.554) + total arsenic × (−0.654)); environmental deterioration = (Fe/Al − sediments × (0.903) + average NDVI × (0.253)); (*b*) dry period − water quality = (distance from B1 × (0.863) + dissolved manganese × (−0.138) + total calcium × (0.126)); environmental deterioration = Mn/Al − sediments × (0.953) + average NDVI × (0.173). In the rainy period, the scenario indicated a 'water quality' decline, which propagated over time to regions away from

the Ferro-Carvão stream outlet where the B1 dam tailings have entered the Paraopeba River. Conversely, in the dry period, the spatial distribution of 'water quality' was comparable across the years but revealed an abrupt decrease in the vicinity of the Igarapé weir, located 40 km downstream from the Ferro-Carvão stream outlet, and an abrupt increase downstream, exposing its barrier effect. The spatial and temporal distributions of latent variable 'environmental deterioration' alerted to the potential impacts of iron and manganese on the health of riparian vegetation, aggravated over time and exacerbated in the rainy periods because floods tend to bring and settle down tailings into the riverbanks. The attenuation of iron and manganese concentrations by the Igarapé weir were further investigated by Lima et al. [30], who used the Riverflow 2D software (https://www.hydronia.com/riverflow2d) in the analysis. The modeling results revealed that iron levels dropped from 3062.0 g/yr. km upstream of the weir to 91.4 g/yr. km downstream (33.5-fold decrease) during stream flows typical of 10-year return periods. This drop was caused by backwater effects that reduced flow speeds in the flooded stream banks during the high tides, which made iron-bearing sand particles to settle down. However, the same was not true for manganese, which is more likely present in silt and clay particles. These particles are unaffected by the backwater effects because they are very small and therefore very light. In the Mariana accident that affected the Doce River and especially the Regência estuary, important seasonal influences were driven by winds, waves, and tides along the coast of Espírito Santo state, as per the simulations of Vinzon et al. [31*]. Taken together, these influences explained the movement of tailings toward the north where the Abrolhos reef area is located, anticipating threats to biodiversity.

Assessing the contribution of tailings spills to river water contamination may be a challenge where additional anthropic pressures impact the riverine ecosystem. The Paraopeba and Doce river basins affected by the B1 and Fundão dam breaks adhere to this setup because they are multiple-use and occupation watersheds where urban, industrial, and agricultural activities cumulatively impact the river water quality. Thus, in the Paraopeba River the work of Santos et al. [32] revealed that the B1 dam collapse was the main source of metal contamination along the main water course. On the other hand, urban and industrial discharges affected the tributaries and the main water course with metals, nitrate, and sulfate contamination, which reached the aquatic environment via hillslope runoff. Meanwhile, the presence of neosols in the tributary catchments and the sparse vegetation of urbanized areas promoted riverbank erosion, potentially amplifying aquatic pollution.

The influence of tributary inflows on river water quality adds up to the previously mentioned contributions of seasonality and hillslope runoff. While investigating this effect, Pacheco et al. [33] reported a discharge rate in the Paraopeba River between 500 and 700 m^3/s in January 2020, which caused an abrupt decline in the iron concentrations of sediments, from 100,000 mg/kg to 10,000 mg/kg (ten times less). The drop occurred in the segment most impacted by the B1 dam tailings, called 'anomalous' sector, and located downstream of the outlet of Ferro-Carvão stream. According to the authors, the decline represented a dilution effect driven by the mixture of tailings and clean sediments added by the tributaries Manso River, Betim River, and Sarzedo stream during the event. Subsequently to this work of Pacheco et al., Alonso et al. [34*] estimated the percent contribution of various tributaries to the volume of sediments transported in the Paraopeba River using the SedSAT mixing model (https://www.usgs.gov/software/sediment-source-assessment-tool-sedsat). In the 'anomalous' sector, the Betim River stood out with nearly 35.67% contribution.

System's recovery

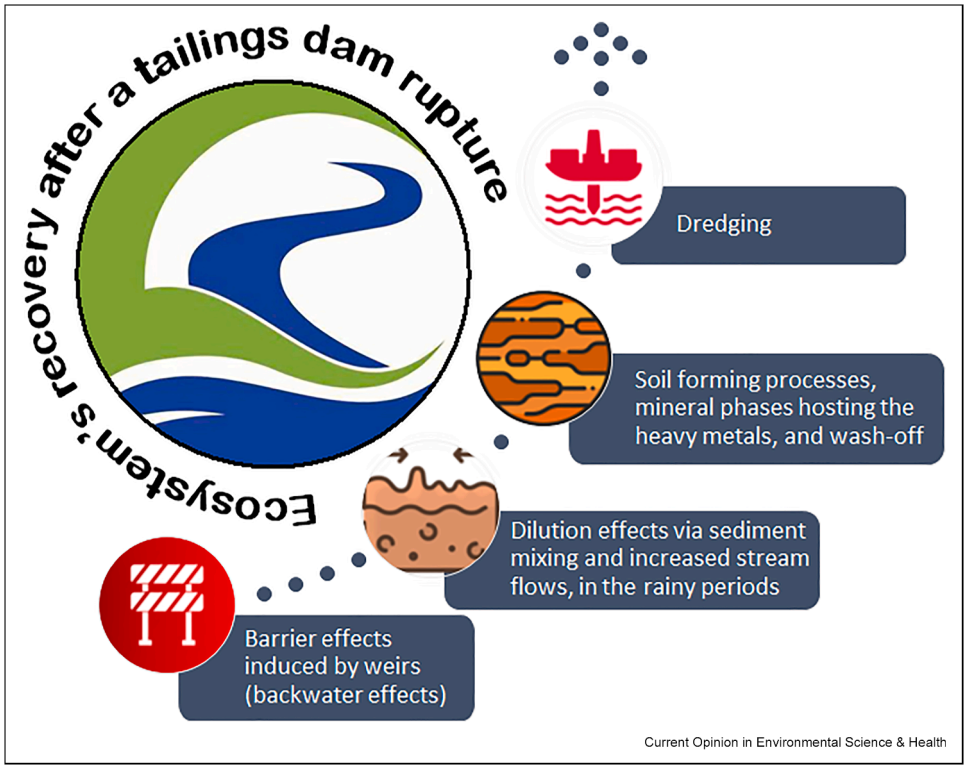
The recovery of a riverine system after the dumping of mine tailings has no fixed time to occur because the timespan depends on the river's resilience and the efficacy of implemented mitigating measures, which in turn depend on the river and the region where its drainage basin has been shaped. In the Paraopeba River, Rolin et al. [35**] determined a period of 6–8 years needed to bring the water quality to a prefailure condition, counted from the B1 dam break that occurred in 25 January 2019. In brief, the authors used artificial intelligence to compare time records of iron and manganese concentrations in water observed under peak flows in points located downstream the dumping point of B1 dam tailings (confluence of Ferro-Carvão stream with Paraopeba River) with homologous records at points located upstream, setting the recovery time when the patterns matched. The work of Terêncio et al. [36] pointed to a potential acceleration of recovery through dredging of tailings near the dumping point (called 'ground zero' in that context) because this action was estimated to reduce iron and manganese concentrations by nearly 30% from upstream to downstream of that point in the rainy period. In the Doce River, a long-term study (six years) conducted by Lopes et al. [37] has shown a gradual decrease in the toxicity index of marine sediment and water samples, corroborated by the presence of sensitive organisms in the environment such as microcrustaceans, copepods, and sea urchins. The estuarine environment, on the other hand, remains as focal point of potential recontamination driven by remobilization of tailings from the Doce River channel, and thereby a place where concerns about environmental impacts stay on the spotlight. The gradual recovery of Doce River estuary was also described from the standpoint of early pedogenesis by Queiroz et al. [38**]. The results revealed an anthropogenic soil developed from the layer of iron-rich tailings within four years after the Fundão dam break.

The soil-forming processes comprised the settlement of crabs and *Eleocharis acutangular* colonies on the bare cover of mud; the incorporation of organic carbon into the soil, with benefits for soil aggregation and melanization processes; the establishment of anoxic conditions driving the reduction and mobilization of iron, succeeded by its reprecipitation in the sandy horizons located below. In some places, the natural recovery of impacted soils was not accomplished. This occurred, for example, in the Ipaba municipality after the Fundão dam break, as described in the study of Fortes et al. [39]. The results exposed a relationship between the inputs of mine waste to the agricultural fields and changes in the sodium, ether-amines (increase), and nitrate (decrease) levels of soils, which inhibited plant growth by osmotic stress and caused severe crop productivity declines in the sequel. In these cases, active mitigation measures were needed to bring the land back to food production, which comprised: (*a*) sediment scraping; (*b*) organic matter amendment; and (*c*) the planting of species able to utilize the nitrogen overload from ether-amines. Figure 2 directs attention to natural and man-related attenuation processes whereby the river system recovers from a tailings dam disaster such as those that occurred in Mariana and Brumadinho. The figure summarizes findings discussed in the previous sections, namely: (a) the retention of mine tailings behind the Igarapé weir, which decelerated the propagation of metals toward downstream sectors of Paraopeba River and opened a time window for dredging the mud; (b) the mixing of tailings with clean sediments from tributaries and from sectors of Paraopeba River located upstream the broken dam; (c) the development of soil from the mud layer in the estuary of Doce River, with subsequent incorporation of organic carbon and mobilization of metals toward deeper horizons; (d) the natural wash-off of metals in suspension or in solution since the accidents, accompanied in the rainy period by metal concentration declines in the water column justified by dilution; and (e) the dredging of tailings from the river channel, which was well documented in the Brumadinho case.

Governance issues

The dumping of mine tailings into rivers generally degrades water quality, but the Mariana and Brumadinho accidents aggravated the deterioration of already poor water quality. In fact, in the Paraopeba River, Pacheco et al. [20] reported noncompliant metal concentrations for the rainy seasons between 2000 and 2018 (i.e. before the B1 dam breach), representing 50% (iron) and 90% (manganese) of all measurements. This is clear evidence that mining and/or other activities in the catchment have previously caused low water quality and that mitigation measures have been absent, inadequate or

Figure 2



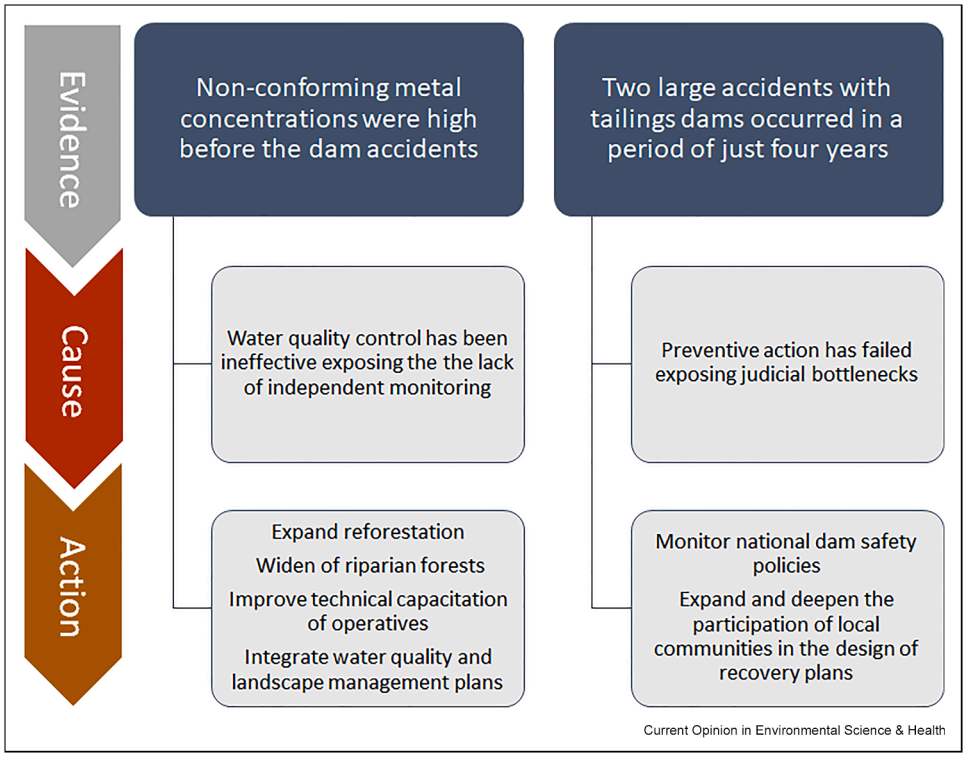
Factors that attenuated contamination in the Paraopeba and Doce Rivers, following the Fundão and B1 dam collapses, and contributed to the system's recovery. Additional explanation in the text.

ineffective. The results of water quality studies in tributaries of Paraopeba River confirmed this prediction. For example, Fernandes et al. [40] as well as Júnior et al. [41] reported cattle grazing, urban sprawl, and mining as focal sources of pollution in the main tributary catchments of the Paraopeba River basin, which were aggravated by deviations of actual from natural (capability) land uses. In the sequel, the authors recommended systemic measures to reduce pollution in the tributary streams, preventing its migration to the main watercourse. The measures comprised reforestation of areas inadequately used for pasture or agriculture, densification and widening of riparian forests along watercourses of urban and agricultural watersheds, technical capacitation of operatives from all activities to promote best management practices, and integration of water quality management into landscape and urban planning policies at all levels of governance. The findings of Fernandes, Júnior, and coworkers were corroborated in the Doce River by Gontijo et al. [42], who revealed water quality losses driven by natural and human factors before the Fundão dam breach at Mariana, namely concentrations of P, Mn and Cu far exceeding the legal thresholds in areas not affected by the accident (e.g. Carmo River close to Mariana municipality).

The systemic measures are capable of leading a contaminated river basin to more pristine conditions in the long term, but they are not devoted to handling emergency scenarios derived from technological disasters. According to Guimarães et al. [43], the best path to address TSF breaks is to act on prevention. Specific measures comprise updating and monitor the full application of national dam safety policies, such as Law no. 14,066/2020 in Brazil. Full application implies, among other things, imposing the preparation and implementation of emergency action plans on mining companies, based on flood studies defined in the Ordinance no. 70,389/2017 as '*studies capable of adequately characterizing the potential impacts arising from the flooding process due to rupture or malfunction of a mining dam*.' An example of such studies was recently published by Medeiros et al. [44]. Besides prevention, the national dam safety policies usually call on mining companies to assume the costs of recovering the impacted areas. For the Brumadinho disaster, Medeiros et al. [45*] used the newly developed EVED methodology (Economic Valuation of Environmental Damages) to estimate R$ 163,641,289.5 of ecosystem services losses, and R$ 571,346,957.9 needed to repair (clean) the affected areas (valley and banks of Ferro-Carvão stream).

An important governance question related with TSF accidents refers to the participation of local communities in the design of recovery plans. As per the assessment of Milanez et al. [46], the cases of

Figure 3



Governance gaps and proposed solutions documented for the Mariana and Brumadinho accidents.

Brumadinho and Mariana came out with disappointing results. In both cases, the judiciary power in charge of leading the process seemed unfamiliar about the way of including people in the decision-making process, which prevented communities from being involved and have their say on the reparations. Because of this and other governance fragilities (e.g. cross-sector partnership barriers), Abreu and Andrade [47] affirmed that '*the Doce river basin's recovery process has taken the form of a wicked industrial disaster, enabling a chain reaction" of increasing wickedness*.' Figure 3 is a boxed summary of governance gaps and proposed solutions that have been highlighted in the reviewed papers for the cases of Mariana and Brumadinho, which included lack of independent monitoring, exclusion of communities, and judicial bottlenecks, among other fragilities. In spite of being documented for two specific cases, the causes of fragility will replicate in other accidents, and hence the proposed solutions can be transposed to them.

Author contributions

The authors participated equally in the tasks necessary to produce the present review. They have read and agreed to publish the current version of the manuscript.

Declaration of competing interest

The authors declare no conflicts of interest. The funders had no role in the design of the study, in writing the manuscript and revising the text, or in the decision to publish it.

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Data availability

No data was used for the research described in the article.

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** of outstanding interest

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