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FERNANDA SOARES NEREU

IMPACTOS DOS ACIDENTES EM BARRAGENS DE REJEITO DE MINERAÇÃO: UMA REVISÃO HISTÓRICA

SALVADOR
Setembro 2017

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IMPACTOS DOS ACIDENTES EM BARRAGENS DE REJEITO DE MINERAÇÃO: UMA REVISÃO HISTÓRICA

Este manuscrito representa o trabalho de graduação do Curso de Graduação em Oceanografia, Instituto de Geociências, Universidade Federal da Bahia, como requisito parcial para obtenção do grau de Bacharel em Oceanografia. Este trabalho é apresentado na forma de um manuscrito que será submetido para a revista Journal of Hazardous Materials.

Orientador: Profa. Dra. Vanessa Hatje

SALVADOR
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APRESENTAÇÃO

Este trabalho é apresentado na forma de um manuscrito que será submetido para a revista Journal of Hazardous Materials.

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ABSTRACT

The aim of this study is to critically analyse the data of accidents with mining tailing dams, acquired from 148 scientific articles, 11 technical reports, and 4 databases available online (Supplementary Material). The aspects addressed here involve the main causes, ores, type and magnitude of the socioeconomic and environmental impacts. Reports on dam accidents date from 1626, with 1994 being the year with the largest number of accidents. At the end of 2015, the Mariana accident, in Brazil, stood out as the incident with the largest volume of tailings released ever registered. More than half of the reported accidents were related to human error (59%), while natural processes (32%) were reported as the second most important cause of accidents. From the 60's, a substantial increase in the number of events happened, especially with Cu and Au or several combinations of ores. The largest amount of accidents occurred in the Americas (51.1%), where The United States and Chile were the countries with more occurrences. About 31% of the incidents reported deaths and a wide number of homeless people as a result of the accident. Among the countries with accidents, all of them have legislation regulating the mining activities. Mineral exploration is indispensable for the global economy, thus new technologies are constantly under development to improve the extraction efficiency and minimize associated environmental impacts. However, there is an imminent need for greater control of the operations of dams and better use of tailings generated. Recycling of tailing is an essential step to be incorporated in the life cycle of the mined ores. Preventive actions, despite corrective actions, are more effective and less costly for the environment and for society. Therefore, better practices, higher low enforcements together with preventive actions are necessary to reduce the number of accidents.

Keywords: accidents, tailing dams, mining, tailing, impacts

1. Introduction

Mining is one of the oldest and most important socio-economic activities in the history of mankind. It produces raw material for a diverse set of products and services largely employed by the modern society (Coetzee & van Staden 2011; Edraki et al. 2014; Lana 2015). In 2014, only in Brazil, the product of mineral extractive industry came to 80,2 billion US dollars (Departamento Nacional de Produção Mineral 2015) .

It has been suggested that mining is especially beneficial to the economy of developing and emerging countries (Candia et al. 2009). These activities in emerging countries with significant territorial areas and high population density, such as the BRICs (Brazil, Russia, India, China), are driven by the high demand of mineral production associated to the world high growth rate and development of new technologies (Tobergte & Curtis 2013). Most of the product of the mining industry comes from developed countries, but, in general, it’s concentrated in South Africa, Australia, Brazil, Chile, USA, Canada, China and Russia (Calaes 2010).

Mining activities in developed and developing countries faces similar challenges. The mining process consists, basically, of four steps: exploration, mining, ore processing and metallurgical process. Each of those processes result in a myriad of anthropogenic footprints due to the landscape alteration for mining and storage areas, high demand of water and energy and waste produced. Acid drainage, for instance, resulting from the oxidation of sulphide minerals during the mining of gold, nickel, copper, among others metals (C.Singer & Stumm 1970) causes the deterioration of superficial waters and aquifers (Valente et al. 2016; Akcil & Koldas 2006; Nicholson et al. 1990; Mirlean et al. 2001; Gazea et al. 1996; Grande et al. 2005; Huang et al. 2010). Besides, the extraction and use of chemical and physical methods to separate metals from impurities produce large amount of tailings, which are a mix of crushed rocks and mill processing fluids that possess a high potential to cause contamination (Kossoff et al. 2014). It has been suggested that mining activities produce more hazardous wastes than any other economic sector (Finnie et al. 2009; International Commission on Large Dams - ICOLD 1996).

Globally, it has been estimated that more than 10 billion tonnes of tailing wastes are produced every year (CRC CARE n.d.). The tailings can represent up to 97-99% of the total ore processed, leaving only 1-3% of the amount of concentrate produced (Adiansyah et al. 2015). To store enormous amount of tailing wastes produced annually worldwide, several dams of various designs and capabilities have been constructed.

Tailing dams are structures build to last forever. They are usually located in the vicinity of the mining area to store the solid and liquid waste formed during the ore processing (Zandarín et al. 2009). Nevertheless, tailing dams are more vulnerable and prone to accidents than other retention structures due to several characteristics (Rico, Benito & Díez-Herrero 2008), including: i) embayment formed by local materials derived from mining operations; ii) raising of the dam in multi-stage, according to the increase of the solid material stored and effluent released; iii) lack of regulations on dam design criteria; iv) lack of dam stability requirements regarding continuous monitoring and control during construction and operation, and v) high maintenance costs after the closure of the mining activities. Other elements that make these structures a risk are the poor quality of construction and maintenance, the high percentage of water produced in the slurry, and proximity to aquatic ecosystems (Adiansyah et al. 2015; Jeyapalan et al. 1983; Melorose et al. 2015).

One of the ecosystems most affected by mining activities is the water bodies (Carpenter et al. 2009; Mcintyre et al. 2014). For a long period of time mine tailings were discharged directly in rivers and lakes (Terezinha Costa et al. 2006; Ferraço 2016; Wei et al. 2013; Macklin et al. 2006; Rodrigues et al. 2014; Huang et al. 2010). Although representing less than 1% of the total mines in the world, direct discharge of mining effluents is still present (Franks et al. 2011; Wang et al. 2014), especially in Asia and Europe (Adiansyah et al. 2015).

Mining tailings dam failures represent around three-quarters of the accidents with environmental impacts related to mining (Anon 2002). Kossoff and collaborators (2014) (Kossoff et al. 2014) suggested that these dams should be located distant from water bodies, because in the case of failure and evasion of the wastes, the associated socioeconomic and environmental impacts are potentially high (Chambers & Higman 2011). Although mining is an inevitable environmentally disruptive activity (Schoenberger 2016), environmental disasters should not be. Accidents frequently result from poor tailing management, and the public concern on the risk and potential impacts of tailings has been growing, resulting in a high demand for more sustainable environments practices including incentives to recycle tailings (Park et al. 2015).

Over hundreds of years, many accidents involving mining tailings dams were recorded and their impacts studied at some extent. This paper aims to critically analyse accidents in tailings dams reported in the literature. The occurrence, causes and most importantly the impacts (*i.e.,* social, environmental and economic) associated with dam accidents worldwide are addressed. Despite the public concern on the risks of mining activities (operation, maintenance and closure), and technological advances in the mining activities, tailing dam failures are remarkably more frequent than one would expect if technological advances were followed by good practices in accident prevention and evaluation of potential risks. Moreover, despite the severe consequences associated to dam failures, the impacts associated with tailing spills are still poorly documented and monitored after accidents and require not only more attention from all stockholders, but also better tailing management practices in the mining industry.

2. Methodology

After a detailed literature review, a database was constructed with the available information regarding accidents with mine tailing dams around the world. Scientific literature was searched through academic platforms such as Google Scholar, Web of Science, Science Direct and Brazilian CAPES database, between the months of July of 2016 to July to 2017. Literature was also searched using Google and Safari to find technical reports, non-indexed publications, databases of tailing dam failures (*e.g.*, Wise Uranium Project, ICOLD, tailings.info), among others. The keywords used for the literature survey include: tailing dam failure, mining tailing, tailing dam accidents, mining legislation, mining laws, acts of mining, tailing, mining impacts and contamination, mining tailings impacts and contamination. In a second stage of literature research the location and the date of accidents were used as keywords.

The information gathered was assembled into a database that included the location of the accident, date, causes, types of ores associated, volume released, characteristics of the dam, environmental and socioeconomic impacts reported and mining legislation in each country (Supplementary Material Table S1). The database was carefully evaluated and the information collected was verified with the largest number of scientific articles and data available on the literature, composing a robust panorama of the tailing dam failures. Hundred forty-eight articles and 15 non-indexed documents (which includes webpages and reports) composed the database. Only the accidents with a minimum amount of information characterizing the incident (*i.e.,* volume released, location, and date of occurrence), which could be confirmed in the literature, were included in this review. Several other accidents have been reported for hydroelectric and water supply dams, however, they have not been included in this study due to the potential differences in the nature of the environmental and socio-economic impacts associated.

3. Results

A total of 141 accidents with mining tailing dams were reported in the literature for the period between 1626 and 2017 (Supplementary Material Table S1). This figure diverged from the number of accidents documented previously, *i.e.*, 147 accidents (Rico, Benito, Salgueiro, et al. 2008), 107 (Wise Uranium Project 2017), 228 (Bowker & Chambers 2015) and 232

(Tailings.info n.d.). The discrepancy between the previously reported numbers and the data presented here results from the fact that only accidents involving ore tailing dams, with minimum key information to characterize each case study, were included.

The distribution of tailing dam accidents by continents indicated that majority of accidents occurred in the Americas (71 incidents, 50% of the total). Forty-five accidents (32% of the total) reported in North America (USA, Canada and Mexico), and 26 accidents (18% of the total) in South America (Bolivia, Brazil, Chile, Guiana and Peru). This ranking is followed by Asia (30 accidents, 21%), Europe (29 accidents, approximately 21%), Oceania (6 accidents, 4%) and Africa (5 accidents, approximately 4%). Among the accidents in the North America, the USA stands out with 26% of the occurrences, followed by Canada (4.2%), and Mexico (1.4%). In the South America, Chile had the largest number of accidents (9%), then Brazil (5%), Peru (3%), Bolivia (1.4%) and Guiana (0.7%). In the Asia, 11% of the accidents occurred in China, 6.3% in the Philippines, 2% in Japan and 0.7% in Myanmar, Israel and in Indonesia, each. In Europe, the United Kingdom presented the highest number of cases 4%, followed by Bulgaria and Russia (3% each), and Romania (2%), Spain (1,4%) and Hungary (1.4%), while Sweden, Armenia, France, Germany, Italy, Macedonia, Finland and the former Yugoslavia presented 0.7% of accidents each. In Oceania, 5 accidents were reported for Australia (3%) and one in New Zealand (1%). There were only few records of accidents/information from individual countries in Africa - only 2 (1.4% each) were reported for South Africa and Zambia, and 1 (0.7%) accident in Zimbabwe.

The temporal evolution of the number of accidents (Fig. 1) displays a gradual increase since the first case reported (1626) until 1995, when the number of events reached a peak. This peak is due to the occurrence of 9 accidents in 1994 in America (1 in Brazil and 5 in the USA), Oceania (Australia, 1), Africa (South Africa, 1) and Asia (China, 1). From 1996 to the present date, a decreasing trend was observed in the number of accidents.

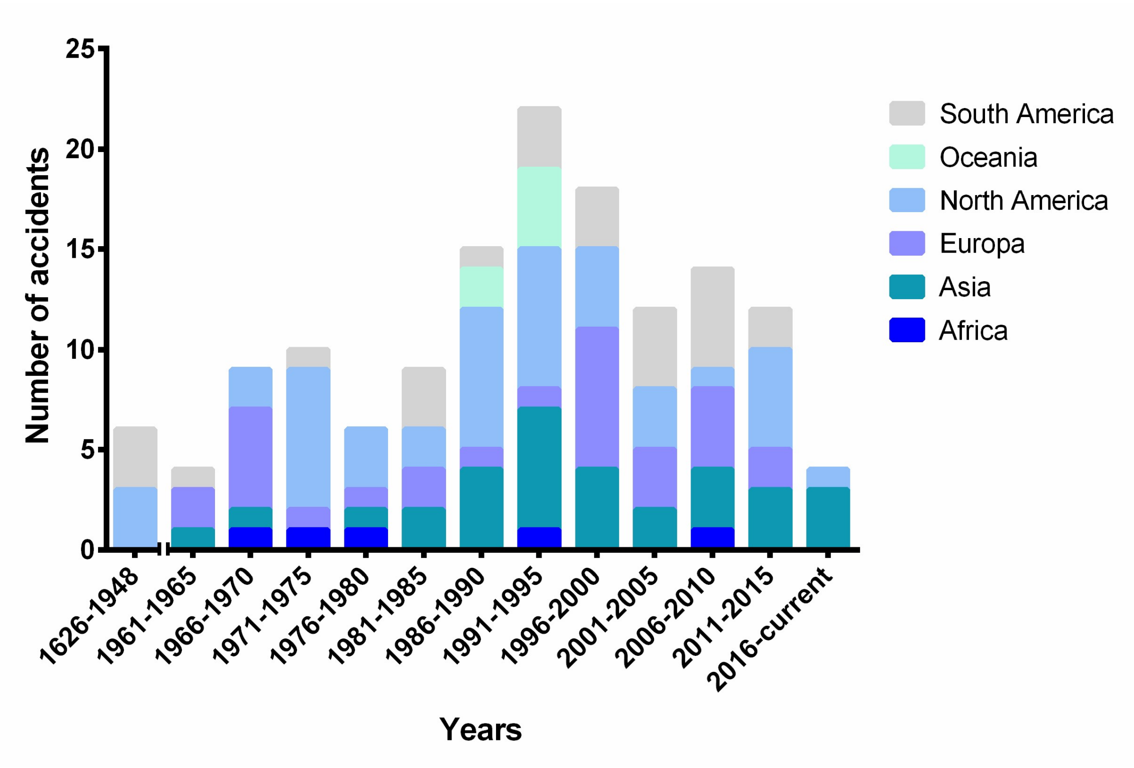

Fig. 1. Distribution of the number of accidents with mining tailing dams between 1626 and 2017. The data was grouped in quinquennium to assist the visualization of temporal trends, except for the first period, which encompassed 322 years, due to the small number of occurrences.

Among the reported accidents, a large number was related to Cu (20%), Au (13%), phosphate (11%), coal (10%) and Fe (6%) mining (Fig. 2). The mining of Al, F, Hg, Ni, sand, limestone, cyanide, fluorite, gypsum, jade, mica and platinum is related to 1 accident for each ore, and hence are not represented in Fig. 2.

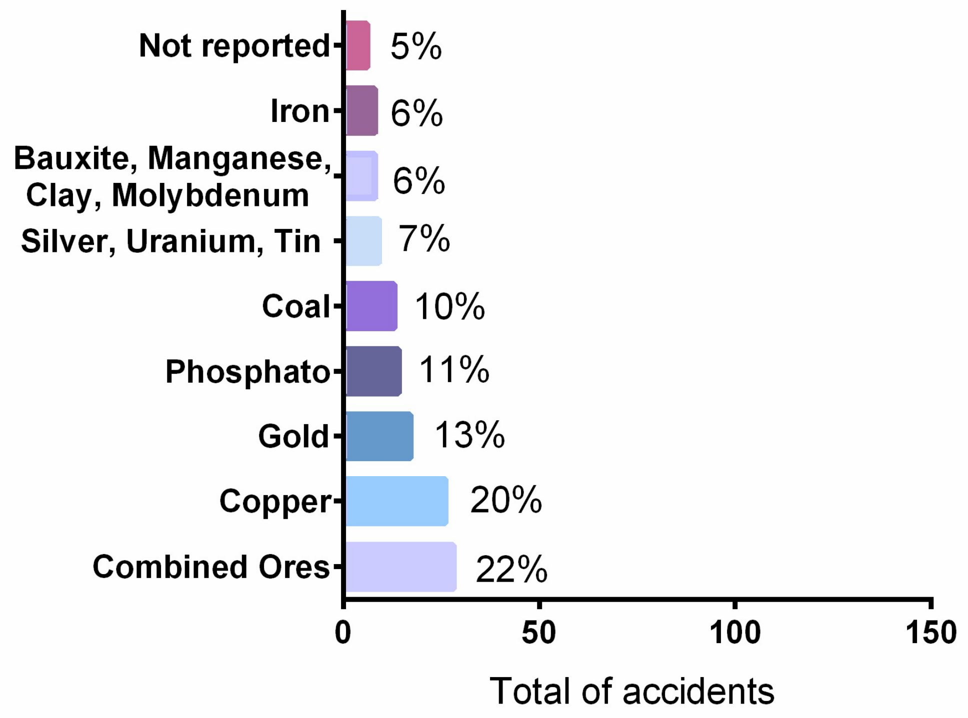

Fig. 2. Percentage of accidents in mining tailing dams involving the main ores extracted.

The tailings dams from the extraction of combined ores represented the major number of accidents reported in the literature (22% of the total). Among those, the extraction of combined of Pb and Zn stood out with 21% of accidents, followed Ag, Cu, Pb and Zn combined (Table 1). Each of the other combined ores represented less than 7% of the accidents.

The reported causes of dam failures were grouped in five categories (Fig. 3). Human errors, divided in poor management and dam design and construction problems, were identified as the main causes of the accidents. Among the 58% of accidents related to human error, 35% happened due to a failure in the structure (*e.g.,* dam placement and construction, structures under erosion or with infiltration problems, foundations, slope instability of the dam structure, and leakages) and 23% occurred due to poor maintenance of the dam complex (*e.g.,* lack of monitoring, overtopping and overflow, management operations, among others).

The second most important cause of accidents, representing 33% of the data, was related to natural/meteorological factors, such as earthquakes, torrential rains that cause the overflow of materials or rupture of the dam due to the increase of the weight of the material accumulated, and landslide (Bowker & Chambers 2015; Kossoff et al. 2014; Wise Uranium Project 2017). Among the remaining accidents, 7% of the cases have unknown causes and 2% have not had their causes reported by the companies or responsible bodies.

Table 1. Number of accidents with tailings from the extraction of combined ores

Combined ores	**Number of occurrences**	**%**
Pb and Zn	6	21
Ag, Cu, Pb and Zn	3	11
Au and Cu	2	6,7
Bauxite and Fe	2	6,7
Sn and W	2	6,7
Ag, Pb, S and Zn	1	4
Sand and gravel	1	4
Agility and Aerolite	1	4
Hg and coal	1	4
Au and Ag	1	4
Au, Pb e Zn	1	4
Clinochlore and nitratine	1	4
Cu and Mo	1	4
Cu and U	1	4
Cu, Ag, Au and Fe	1	4
Fe and Mo	1	4
Ag, Hs, and S	1	4
Total	27	100

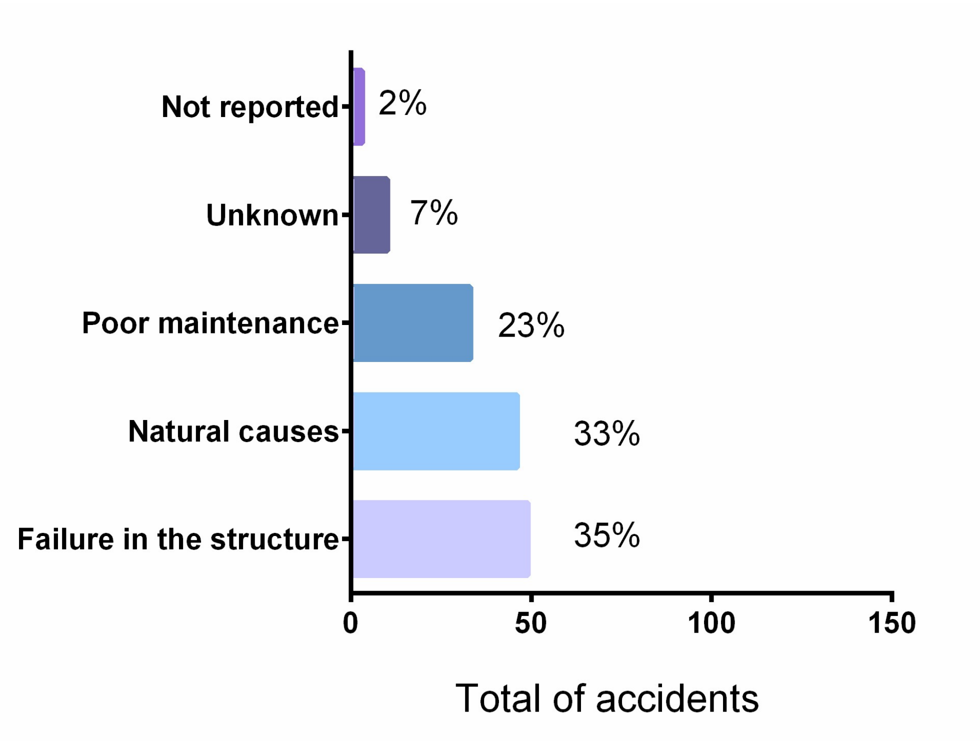

Fig. 3. Distribution, in percentage, of the main causes of accidents with mining tailing dams.

Several accidents reported the volume of the tailings spill during the rupture of the dam and the distance that these tailings travelled. It was observed that most of the accidents releasing less than 10^7 m^3 of tailings did not travelled more than 200 km after the breaching of the dam (Fig. 4). Although the larger spills seem to travel further than small spills, no clear trend was observed, and a large variability in the data was observed (it was found a positive correlation $r = 0.65$, but $p>0.05$). The furthest distance travelled by a tailings spill was registered in the accident of the Samarco Mining spread over more than 650 km from the tailing dam to the Atlantic Ocean (Fernandes et al. 2016; Hatje 2016; Hatje et al. 2017) .

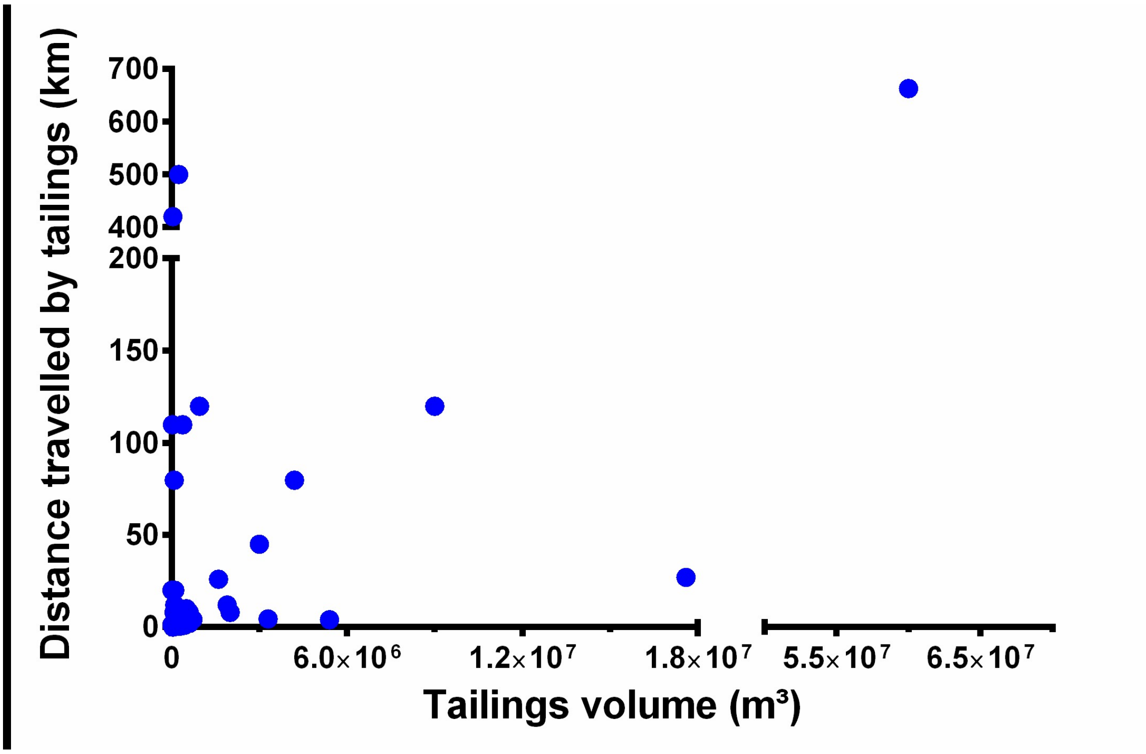

Fig. 4. The relation between the volume of tailings spills and the distance travelled by the tailings.

A number of environmental impacts have been related as a consequence of dam failures. A large range of negative impacts have been described, including: i) impacts on the water bodies, such as contamination of rivers, marine waters, and groundwater, ii) impacts on soil, floodplains, and sediments, causing problems of sedimentation, erosion, contamination and/or loss of crop areas, iii) changes in the growth, diversity, ecological services provided by different environments, mortality or contamination of the local biota, and iv) dimension of the impacted area. A surprising result was the low percentage of studies (97 accidents, 69%) that reported any environmental impact associated to tailing dams. For the accidents which environmental impacts were not reported, it was either not possible to unveil if there were no negative environmental impacts or the occurrence of the adverse effects were not evaluated.

Out of the total number of failure cases where environmental impacts were reported (Fig. 5), 61% (44 cases) of the accidents occurred in the Americas, of which 36% (26) in North America, and 25%(18) in South America (Guiana, Brazil, Chile, Bolivia and Peru). There were a relatively large number of accidents (17 cases) for which no adverse effects were reported and 6% (4) reported no environmental damages in North America. Europe presented the second highest percentage of accidents (83%, 24 cases) for which adverse environmental effects have been described. Asia had 29 accidents, of which 48% (14 cases) reported environmental impacts, and 45% (13 cases) did not report data regarding any type of impacts. For Oceania, 50% (3 cases) of the accidents presented negative impacts. Out of the accidents reported for Africa, only 1 case out of 5 (20%) did not report environmental impacts.

Among the environmental impacts reported in the literature (Fig. 5), the impairment of water bodies (80 cases) was the most frequent. Most of the damage to biota was reported in America and Asia. In Europe, only the accident in Spain (Aznalcóllar) reported impacts on the biological communities (Madejón et al. 2002; Gallart et al. 1999; López-Pamo et al. 1999; Madejón et al. 2003; Martín Peinado et al. 2015). No impacts in biological communities were reported for Africa and Oceania. Among all reported cases, only 9 described negative environmental impacts in sediments.

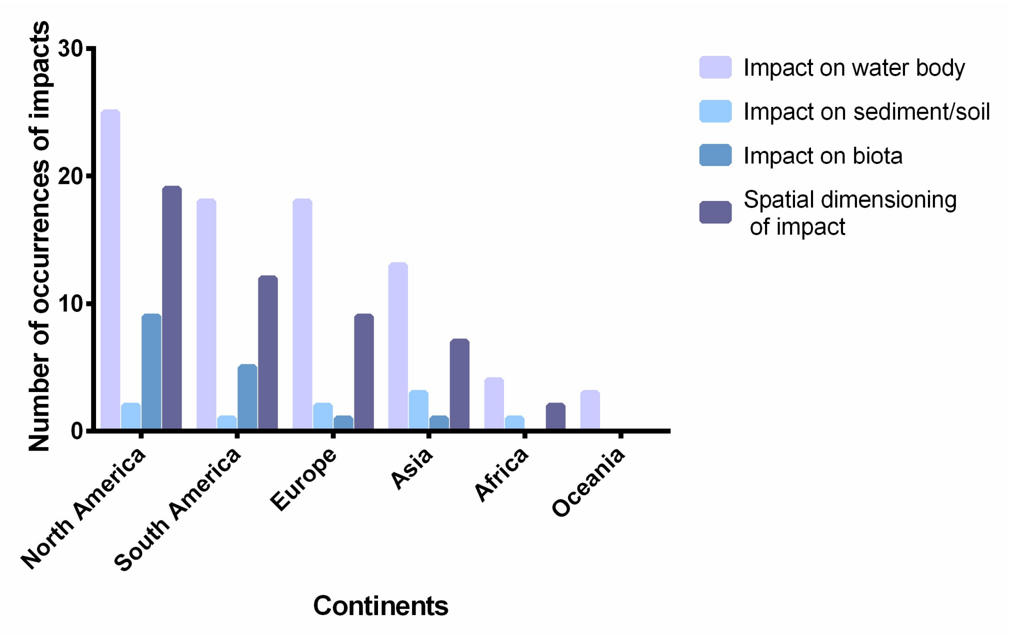

Fig. 5. Distribution of reported types of environmental impacts due to dam failures. The spatial dimension of impact refers to the number of accidents that reported the distance reached by the tailing spill.

Several studies in North America (19 cases), South America (12 cases), Europe (9 cases), Asia (7 cases) and Africa (2 cases) reported the size of the impacted area, which was described as the distance travelled by tailings after a dam failure.

Among the most serious risks of dam failures are the social negative impacts. About 31% of the accidents on this study (44 cases) reported human deaths. The number of fatalities varied between 1, for accidents in Ages (USA), Arcturus (Zimbabwe), Karamken (Russia) and

Mochikoshi nº1 (Japan) (Bowker & Chambers 2015; Rico, Benito, Salgueiro, et al. 2008), to 4,000 in the accident in the Potosí (Bolivia) (Kossoff et al. 2014).

Among the social negative impacts, the number of people that became homeless after dam accidents deserves attention. Although the number of people that loses their home when their communities are flooded by tailing spills is very variable (Table S1), this figure reached up to 13,970 inhabitants in Yunnan Province accident in 1962 (Wei et al. 2013). Large accidents such as the Samarco spill (Hatje 2016; Fernandes et al. 2016; Jacobi, Pedro Roberto e Cibim 2015; Owen & Kemp 2016; Zhouri et al. 2016; Hatje et al. 2017)reported also several other social impacts such as loss access to clean water (10 cases), crop production areas (7 cases), lost of hydroelectric power (1 case), and fishing resources (12 case).

Economic losses, which include the destruction of roads, bridges, private and public properties, monuments, crop areas, cultural and ethnic heritages are also reported (Table S1). Regarding specific values of economic losses few cases reported it. Among those, a total of 152 million of euros were spent in Aznalcóllar (1998), of which 147 million was dedicated to remediate environmental and agricultural losses and 5 million for social-economic losses (Rico, Benito & Díez-Herrero 2008). Apart from Europe and in terms of direct losses, 80 million US dollars were spent in the Philippines (1996) (Bowker & Chambers 2015), about 13 million and 1.6 million US dollars in China, in 2008 and 1985, respectively. And 15 million US dollars in Guyana (1995) (Vick 1996). Besides, toxic mud covered large crop areas (2557 ha) and natural parks (2656 ha) in the Aznalcóllar disaster (Grimalt et al. 1999). Another example was the Samarco's dam, where the tailings travelled downstream through 41 municipalities, affecting more than one million people (Fernandes et al. 2016). During the accident of El Porco in 1996, tailings travelled in the Pilcomayo river, exposing indigenous populations in Bolivia, Paraguay and Argentina, who relied on the river for drinking water and fishing (Macklin et al. 2006). However, 54% (76 cases) of the incidents did not report adverse effects from a socio-economic point of view. For the accidents that socio-economic impacts were reported, there are mostly records of the number of deaths and missing people.

All countries that had accidents with tailing dams present legislation regarding implementation, inspection, operation and/or licensing of mining activity. Nonetheless, the details of such legislation are very difficult to acquire and most of them are not promptly available in the literature.

4. Discussion

Despite the improvements in public awareness, safety and management practices, and the technological revolution, large accidents with mining tailing dams are still recurrent. The critical analysis of accidents with mining dams is thus essential to understand the causes, impacts, and context of its occurrence, and to subsidize actions of management, prevention, and mitigation of associated socio-environmental impacts.

The evolution of the number of accidents in the 20th century indicates that only a small number of accidents were recorded prior to the 60's. This low record is more likely associated to the lack of documentation on dam operations and accidents (Chambers & Higman 2011) in comparison to the absence of failures and spills. In Europe, for instance, such events only started to be recorded recently in 2003 by the Major Accident Hazard Bureau (Rico, Benito, Salgueiro, et al. 2008).

The high demand for metals and minerals after the World War II intensified mining activities (Azam & Li 2010). From the 1960s, the development of newly independent countries in Africa and Asia promoted a second boom in the exploration of natural resources (Davies 2002). These were followed by an increasing trend in the number of accidents, reaching a peak in mid 1990s (Davies & Martin 2009; Chambers & Higman 2011; Wise Uranium Project 2017). This trend is exemplified by the Au production in USA that grew between 1980-2000, reaching a peak in 1996 (US Geological Survey 2006; World n.d.). The same trend was observed in South Africa, Australia and China that together are the largest producers of gold in the world (Anon n.d.; Kumah 2006). Moreover, this trend can also be observed for copper, lead, nickel, bauxite and zinc (Fig. 6) (Anon n.d.).

In addition, the strong decrease in the price of the gold (~27.1%) in the USA, also impacted the mining industry (US Geological Survey 2006). The market crisis promoted a bankruptcy of several businesses between 2000 and 2002, which directly affects the distribution of net yields within a company, especially in risk management and mitigation (Finnie et al. 2009). In other words, when considering that the relationship between demand and price is directly proportional, and that companies need more income to develop better risk remediation methodologies, the lower the price of the gold, the lesser is the investment on preventing possible accidents that could cause environmental impacts. Furthermore, the decline of traditional producers can also cause the emergence of other countries such as Peru, China, Indonesia, Russia, etc (Finnie et al. 2009).

Once tailing dams are constructed to last forever, the aging of the structures demands increasing maintenance with time. The lack of good monitoring and safeguarding of these dams are the main reasons for the relatively high number of accidents still occurring in the 21st century (Pisaniello et al. 2015). The increase in the value of ores, such as gold, from 2010 also contributed to this scenario (Anon n.d.). The spatial distribution of the recorded accidents indicated that most of them occurred in the USA, possibly due to the high demand for natural resources between the 1960s and 1970s (MacGregor 1986). As the USA have large mineral deposits of Au, coal, clay, Cu, among others, large investments are made upon the mining industry (IBRAM 2014). As a result, the mineral prices and consequently the production of them suffer from fluctuations depending on the market situation. The gold production, has demonstrated since 2001 a quick response to the rising of oil prices, international tension and high demand from India and China. In other words, the more a mineral is required and produced, the higher is the risk of accidents with tailing dams.

There is an association between the number of accidents and the ores mined worldwide (Fig. 2). Among the reported tailing accidents, Cu mining presented the major number. The largest Cu producers are Chile, Peru, China and the USA (Tobergte & Curtis 2013), which corroborates that the high demand is related to more accidents, for most of these countries. This relationship can also be applied in the United Kingdom, the country with the highest number of incidents in Europe, with 5 out of 6 occurrences in between the decades of 60-70 (Fig. 6).

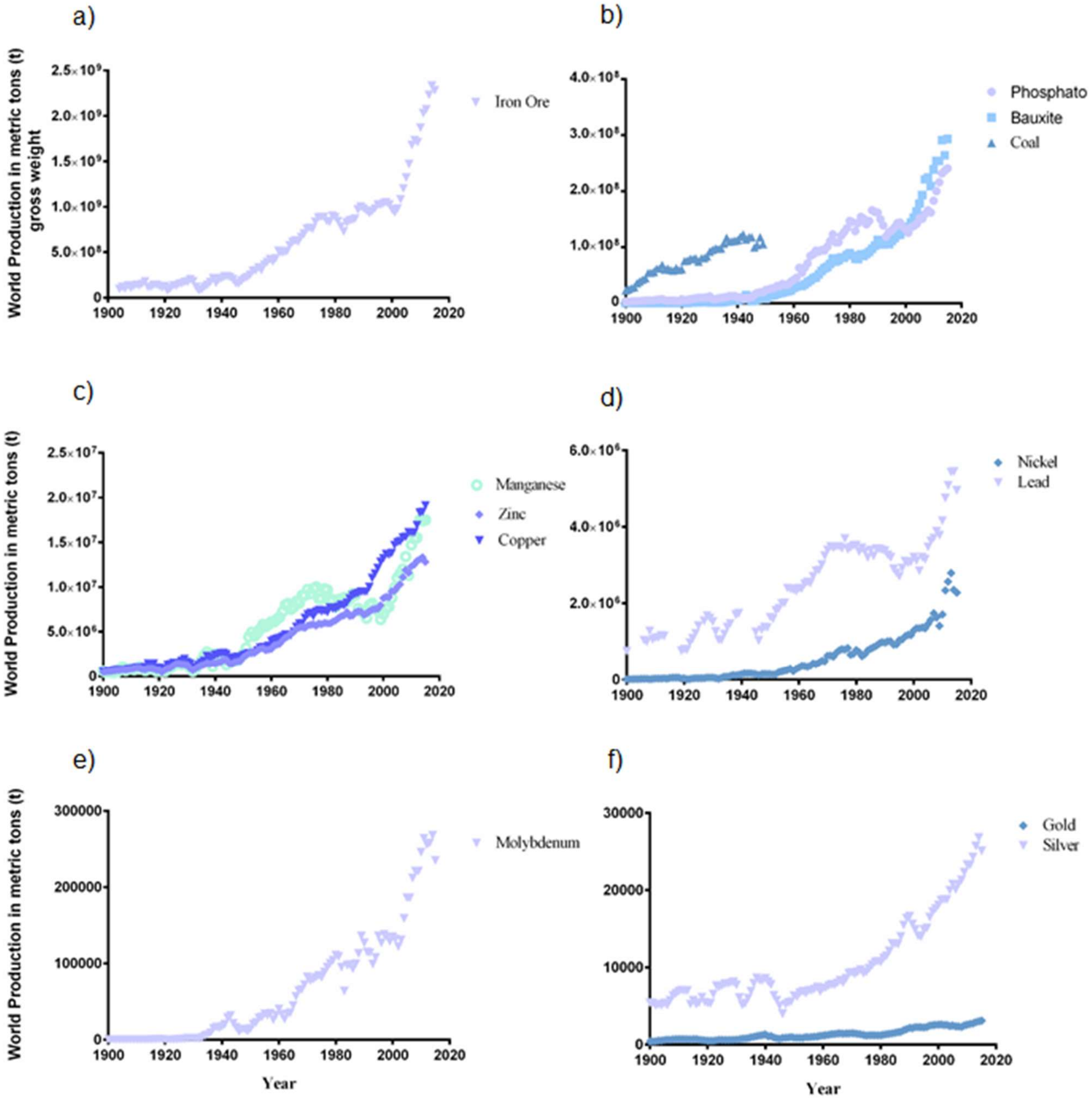

Fig. 6. World ores production in metric tons (t) through the years [Iron ore (a), Phosphate, bauxite and coal (b), Manganese, zinc and copper (c), Nickel and lead (d), Molybdenum (e), Gold and silver (f)]. Graphs created with data from: USGS – Science for a changing world (World n.d.).

Chile has the second highest number of accidents in America, but this high figure is mostly related to natural causes. Chile is located between two tectonic plates (Nazca and South American), in a region of high geological instability subject to frequent earthquakes (Assad n.d.). In 1965, one earthquake collapsed six large dams and several smaller dams in Valparaiso (El Copper dam) (Kossoff et al. 2014).

Brazil presented the third highest record of accidents in America. Unlike Chile, Brazil is in a region with relatively stable tectonics. Despite of the fact that small-scale seismic shocks were registered prior to the Samarco dam failure, the causes of accidents in Brazil are mostly related to poor maintenance and lack of preventive measures, suggesting that most accidents could have been avoided. Strong Federal funds restrictions were translated in budgets cuts of more than 20% in 2015, leading to serious difficulties in the routine inspection of dams alongside the Brazilian territory (Ferraço 2016). Although the largest tailing dam accident in Brazil occurred during this period, the limited resources intended to promote law enforcement in dam operations are not necessarily the main reason of dam failures. On the other hand, it points out that many enterprises, such as mining and dam operations lack environmental responsibility in many cases.

Asia ranked second among the continents in number of accidents, with China in first place regarding to the number of occurrences. The oldest event in China dates back to the 60’s. Until the early 90’s, tailings generated by small and medium-sized mining companies in China were not adequately discarded, increasing the risks associated with their activity (Wei et al. 2013). Still according to these authors, from the 2000s to the present day, mining grew along with China's economy. In addition, Yu & Chen (2011) (Yu & Chen 2013) showed that a seasonal intensification in coal mining production is directly related to the increase in the number of accidents in observed for mining in China.

The high demand to produce high-technology products and clean energy technologies require large amounts of a critical commodity: rare earth elements (REE). The global market of REE-based products is estimated to be worth 1.5–2 trillion US dollars, based on trade information and REE contents of manufactured goods (Tukker 2014). China controls the world mine production and exportation of REEs. The high demands of REE worldwide are causing concern, once even more environmentally conscious and progressive countries like Greenland are loosening regulations to allow mining of REEs (Dutta et al. 2016). The large demands for REE suggests that there is a prominent risk of high potential impacts associated to the mining of these commodities and hence ways to combat the environmental impacts need to be implemented in short time scales (Filella & Rodríguez-murillo 2017).

In Oceania, all reported accidents occurred between the 80’s and 90’s, and were associated with high demand for Au, U and Cu (IBRAM 2014; Calaes 2010). The value of Au in 1993 presented a peak (Anon n.d.) and it was related to the number of accidents. According to Davies and Martin (2009) (Davies & Martin 2009), the peaks in ore prices generally last about two years and are responsible for the rapid increase in the exploitation of ores. The rush and pressure imposed by the market can lead to an increase in the number of accidents after a relatively short period of the mining boom. In Africa, Fourie and collaborators (2001) (Fourie et al. 2001) reported that the Merriespruit dam failure, in South Africa, was positively relevant for the development of an effective dam operation system, as well as boosted efforts to correct potential system failures. This system, according to the former author, has supported the efficient operation of dozens of tailings dams at this site.

Mining activities produce several environmental pressures that cause impacts in terrestrial and aquatic ecossystems. These impacts include changes in landscape, generation of solid and liquid effluents, erosion, contamination of soil and groundwater, degradation of ecosystems compromising ecological services, among others (Bian et al. 2010). Moreover, the mining activities require the construction of dams to retain the large volumes of the tailings produced. The breakage of such structures have a high potential to be a source of severe socio-economical and ecological impacts. For example, the water leaked from this structures are toxic, and normally possess heavy metals that bioacummulate (Coelho et al. 2011; Madejón et al. 2002). These compounds can get trapped into the sediments and be released to the ecossystem, frequently resulting in long-term and slow contamination (Huang et al. 2010; Concas et al. 2006; Favas et al. 2011). On the other hand, these metals can be released even without a spill, during the mining process of gold, that uses mercury for its amalgamation (Macklin et al. 2006; Rösner & van Schalkwyk 2000). Furthermore, the acidic drainage of mines reduce the pH releasing metals that were in the sediment (Kempton et al. 2010), once the solubility of some metals can be described as amphoteric, which means it has a tendency to dissolve as cations at low pH (Cravotta III 2008; Huang et al. 2010).

Still about the potential bioaccumulation of contaminants, it depends on the physical and chemical properties of the water body, alongside with the species of the metal, once there are a variety of species in the aqueous environment and with different toxicities and potential for bioaccumulation. This process is controlled by the pH, oxidation – reduction potential, composition of the sediment, among others factors (Warren & Haak 2001). Moreover, species that comprise more than one oxidation state in natural waters are more mobile and reactive (Ahmann et al. 1997; G. E. Brown et al. 1999; D. A. Brown et al. 1999; Ledin & Pedersen 1996; Lin 2000; Nordstrom 1999; Warren & Haak 2001).

Mining tailings, even if not toxic, causes soil degradation when deposited. The deposition of the tailings interferes with the infiltration of water, affecting the conditions of germination and development of plants (Adler Miserendino et al. 2013). Contamination of soil and sediments can cause severe chronic problems in water, sediments and for aquatic organisms. The mobilization of contaminants from river basins affected by tailing spills along time may affect human health through water contamination and consumption of fish and shellfish enriched in toxic metals (Coelho et al. 2011; Fernandes et al. 2016; Ruhl et al. 2009). Benito and collaborators (2001) (Benito et al. 2001) suggested, as a short and medium term mitigation method, the recovery and use of riparian vegetation in order to prevent the diffusion of mining tailings and to protect the soil from erosion, once it works as a natural trap for sediments.

Some metals, such as iron, copper, lead, mercury and nickel, can cause DNA damage and lipid peroxidation, by producing reactive oxygen species (Stohs & Bagchi 1995). The oxidation of these metals generally involve symptoms of neurotoxicity and hepatoxicity, although some metals are essential for metabolic systems (*e.g.* iron, zinc, copper, manganese, nickel, molybdenum). Problems involving contamination occurs when they are above natural levels, exceeding environmental quality criteria due to anthropogenic activities such as mining.

Chambers and Highman (2011) (Chambers & Higman 2011) pointed out that the risk assessments for the construction of tailing dams is often focused on the potential for loss of life and damage to existing infrastructure, while long-term environmental impacts and clean up measures are frequently disregarded. The insufficient environmental control over the years in the mining history was initially justified by the shortage of understanding of the severity of environmental impacts and the lack of available technology to prevent and control environmental damages in the past (Coelho et al. 2011). Environmental considerations have become increasingly important in tailing dam projects (Davies 2002), although not always incorporated in most developing countries mining operations, where, in fact, there are a still large number of artisanal clandestine operations (Terezinha Costa et al. 2006; Lana 2015; Hatje et al. 2017). Emergency plans and remediation initiatives after accidents need to be incorporated into the financial statements and the feasibility assessments of environmental risks evaluations (Finnie et al. 2009).

The environmental impacts on water bodies are the most recurrent adverse effect reported in the literature. Its consequences are easily and promptly detected, once water bodies, after accidents, work as important pathways to transport tailings. In short terms, tailing dam accidents can contaminate superficial and groundwater although in a medium and long term (years to centuries), contaminant concentrations tend to decrease and accumulate in sediments (Kossoff et al. 2014; Driussi & Jansz 2006). Bird et al. (2008) (Bird et al. 2008) reported that after 4 months of the Novat-Rosu dam accident in the municipality of Maramures in Romania, the Novat river was recovered. It was pointed out that this rapid recovery was due to the restoration of the dam, reducing the concentration of metals, and the dilution caused by the input of clean water of the tributaries of the river Novat. The same authors also reported that, in general, the recovery time of the rivers is controlled by its flow and the amount of tailing that accumulated in the sediments and floodbanks. However, this is not expected to occur in all cases. The King River in Australia, for example, had been contaminated with acidic drainage until 1994 and it is predicted to continue to be polluted for the next 600 years (Fergusson 2014). Another example is the Tui river in New Zealand, which still contains a significant level of metals even 26 years later than contaminants stopped to be added to the system (Sabti et al. 2000). The dimension of the damages caused by dam failures is variable since factors such as retention by other dams, avoiding impacts outside the dam area (Bowker & Chambers 2015), dilution and haulage of tailings through rivers and their tributaries (Bird et al. 2010; Bowker & Chambers 2015; Wise Uranium Project 2017), and absence of containment measures, cause tailings to travel long distance, even if the tailing spill was not large.

Among the most recent accidents, is worth mentioning the 2015 failure of a large dam operated by the multinational mining companies BHP Billiton Ltd and Vale SA in Minas Gerais, Brazil. It was followed by an enormous tailing spill, considered as the largest environmental disaster of this kind of recent times (Marta-Almeida et al. 2016) releasing more than 32 million m³ of Fe-ore tailings into the environment (Wise Uranium Project 2017). The tailings reached more than 650 km, contaminating sediments and waters (Hatje et al. 2017), affecting more than 1460 ha of vegetation, killing entire fish populations by burying or gill clogging (Fernandes et al. 2016). Over 20 billion dollars were estimated as environmental and material losses. A recent study suggested that low-intensity seismic shocks (4.9 and 4.0 on the richter scale), which were recorded at the time of the accident, are one of the potential causes or factors that contributed to the dam collapse (Agurto-Detzel et al. 2016). Structural problems in the dam have already been detected prior the accident, such as defective structures, deficiency in the drainage system, inefficient monitoring, high rate of annual dam increase, silting of dams (Pimentel 2016), although there have not yet been official reports proving any of these hypotheses.

Freitas and collaborators (2016) (Freitas et al. 2015) reported several environmental impacts of the dam accident in Mariana, Brazil, including: i) the long period (hundreds of years) for soil recovery in Barra Longa, ii) increase in erosive processes, iii) silting of rivers, iv) loss of Atlantic rainforest, v) impact on the Doce river food chain, and v) changes in river course and river dynamics. Hatje et al. (2017) (Hatje et al. 2017) reported that the large amount of tailings deposited in the bay is a concern not only in terms of the amount of material deposited in the Doce River basin, but the potential long term release of metals (*e.g.,* Fe) associated to them. Heavy rains can mobilize tailing material, producing high loads of suspended materials and contaminants that may be available to the biota.

According to Grimalt et al. (1999) (Grimalt et al. 1999), after the accident in Aznalcóllar, Spain, legal actions were implemented in the area for the banning of agricultural activities. These included sowing, irrigation, harvesting, pruning, soil treatment, grazing, and transit over the affected soil. Fishing and shellfish harvesting were also halted. Prohibition of these activities has also been extended to commercialization. Bird hunting near Donana Park was also banned as a precautionary measure to avoid metal ingestion. The affected land was not considered suitable for all future agricultural activities. Thus, the Government of Andalusia has initiated a procedure for the mandatory purchase of all polluted areas.

The spill in El Porco, Bolivia in 1996, travelled 300 km of the Pilaya river that became a source of Pb for at least for two years after the accident (Bird et al. 2008). Although Hudson-Edwards et al. (Hudson-edwards et al. 2003) suggested that the continued contamination of river sediments was due to the impacts of the ongoing mining activity as well as the long-lasting influence of the El Porco spill.

The most recent accident, in Israel in June 2017, has not yet defined causes, however it already shows its environment impacts on the region. The spill of 100,000 m³ of acidic water, enriched in contaminants, travelled 20 km (Udasin 2017). Several birds and foxes have already been found dead as a consequence of the toxic slurry. It was known before that only 26 individuals of the ibexes' species lived in the region before the spill, and at least 8 has been already found dead (Lidman 2017). It is expected the impairment of ecological services as a possible long term impact of this accident, and also that several years will be necessary until the potential recovery of this system can be evaluated (Reuters 2017).

Despite the few examples cited here, it is clear that the impacts on soil and biota described in the literature are sparse and superficial, showing that there are important gaps in impact assessments and post-accident studies related to tailing dam accidents. This context hinders the developments of emergency plans, and also indicates the banalization of environmental consequences, which are frequently ignored.

As it has just been showed, despite the fact that there were few reports of environmental impacts related to mining dam accidents, it's well known in the literature the effects on biota related to the mining activity. According to (Littlepage et al. 1982), the impacts of mine-mill discharge in the marine environment can be grouped in relation to: i) the tailing slurry's chemical composition and chemical behaviour; (ii) the submerged tailing flow's physical behaviour; and (iii) the changes in the receiving ecosystem.

As reported by (Nicolaidou et al. 1989) and (Lancellotti & Stotz 2004), for example, mining waste has indirect impacts on the benthic assemblage, by changing the particle size distribution of the sediments and consequently increasing the instability of the environment. Besides, it can affect these organisms directly causing its deaths (Carter 1975). Another example of problems related to mining discharges is the turbidity, that reduces the light penetration, decreasing benthic species richness and diversity (Fariña & Castilla 2001; Burd 2002).

In order to reduce the environmental risks, mining dams must be well designed, managed, monitored, and located away from water resources. In addition, all dams should have well-defined emergency and mitigation plans for potential accidents. Furthermore, the construction of dams in areas ecologically vulnerable and or important aesthetical, cultural or of ecological value must be forbidden. The larger the amount of water in the tailings the greater the potential risk. To avoid such hazards, there are techniques using vacuum or pressure that filter the water of the slurry, leaving 70-80% of solids, compared to the 30-50% obtained by the conventional storage system, and making it easier to handle (Schoenberger 2016; Edraki et al. 2014; Driussi & Jansz 2006). This technique decreases the water loss to the environment, apart from reducing the possibility of chemical reactions to occur during storage. Furthermore, this process creates a tailing more stable and in an inert form, besides, the water reclaimed can also be recycled (Franks et al. 2011). Recycling the tailings is also possible by reprocessing or re-mining the waste to extract the maximum of metals, or using it to create bricks, floor tiles, cement and other useful products, for example (Lottermoser 2011). Although recycling the tailings is an expensive process, it is the way to achieve the sustainability in the mining industry (Bian et al. 2010), and reduce the impacts generated by the accidents.

The modernization of the techniques for dam constructions, the development and implementation of new technologies, associated to better management practices and the improvement of environmental regulations have been claimed as the main reasons for the decline of accidents from the late 1990s (Azam & Li 2010; Davies et al. 2002; Bowker & Chambers 2015; Gomes et al. 2016).

Societal impacts (*e.g.,* number of deaths or people affected by tailing accidents) were rarely reported, clearly indicating a lack of concern regarding the well-being of the potential affected population. Considering the importance of impacts and their awareness, this high number of missing information is alarming. The negative social effects associated to dam failures, regardless of being of short of long-term, are in most cases not dealt with the required attention, which can also lead to irreversible damages (*e.g.,* losses of crop areas and cultural and ethnic heritage). The number of dead (at least 17), wounded and homeless (158 houses destroyed) in Samarco accident, for instance, clearly demonstrates how destructive an accident of this kind can be (Fernandes et al. 2016; Freitas et al. 2015; Zhouri et al. 2016; Jacobi, Pedro Roberto e Cibim 2015).

In the international scenario, most countries have laws that deal with dams in a generic way, adopting measures that address mining tailing dams and dams for the containment of floods, hydroelectric power generation similarly. This is the case of Finland, Germany, and Italy, for instance. However, the legislative system of Austria and the Netherlands, for example, is more specific; different directives are adopted for each type of dam (ICOLD European Club 2014), which is advantageous, once problems associated with different types of dams are distinct and require specific actions.

According to the report of the International Commission on Large Dams (Norstedt 2012), supervision of mining activities in countries differs greatly. For example, the UK and Sweden delegate supervision of dams to local and regional authorities, respectively. In many cases, however, the responsibility for dam safety (*i.e.,* ensuring that there is no disruption in the structure, compromising the installation) is not a priority of the inspection. Some countries, such as France and Netherlands, for example, include risk assessments in their legislation (Norstedt 2012).

In Brazil, the safety of dams and measures to prevent accidents is the responsibility of the Ministry of National Integration together with the National Water Agency (Superintendência de Planejamento de Recursos Hídricos - SPR/Ministério de Meio Ambiente 2017) and with the Secretariat of Water Infrastructure. The national dam registry came from a partnership between Itaipu Binacional and the Brazilian Committee of Dams (CBDB) (Anon 2017) in 2012 and gathers data on the characteristics of the dam, as well as photos, notes, and records of accidents with dams. However, the access to this database is restricted to CBDB members only. Environmental licensing is one of the most important requirements for the implementation of mining activities in Brazil. Nonetheless, the most recently approval of Federal Bills, such as PEC 65/2012 and Bill 2.946/2015 for example, has made this issue more flexible, contributing to a possible expansion of the over exploitation of natural resources. If these are implemented, they will represent a large step backwards for the protection of the environment and promotion of sustainable practices.

Another very concerning aspect that contributes to the increase of risks of dam failures and thus the socio-economic and environmental impacts of dam failures is the lack of effective supervision of the mining operations (Zhouri et al. 2016). Dam structures need constant maintenance, once one of the major cause of the accidents are related to it. In emerging or developing countries, the price of the mineral commodities is lower than in the countries that follow the rules to environment protection, turning these countries into a more attractive place to invest, but also increasing the risk of accidents (Calaes 2010). The responsible body for the prevention work, which means ensuring that the companies are regarding the prevention of accidents, not only remediating it, is the Federal Government, since the Federal Constitution foresees as the competence of the Union the planning and promotion of permanent defence against public calamities and also provides for the organization of the National System of Civil Defence.

5. Conclusions

Dam accidents represent an extra pressure of the mining activities in addition to the well-studied acid drainage and landscape alteration. These accidents are mostly caused by poor management and/or dam structural or operational problems associated to human errors and negligence. As a result, they produce impacts on water bodies, soil and biota, which potentially leads to social and economic negative impacts.

A decrease in the number of accidents with mining tailings dams was observed after the 2000s. However, large-scale accidents are still a contemporaneous issue. Most of the mining dam accidents occurred in developing countries, in dams with combined ore tailings, with the largest amount of accidents occurring in the USA. It was alarming to observe that most reported studies did not quantify and qualify the impacts associated to accidents. The results indicated that once risk assessments and impacts evaluation still do not play a major role in the mining industry there are no signs of investments in preventing accidents and mitigating risks.

The relationship between the mining industry and modern society has proved viable over the years through the development of technologies. However, the increasing demands for mineral, especially for high-tech products require technological development of more efficient methods for mining, recycling the wastes, prevention measures and surveillance to reduce the number of accidents and impacts, since the costs for remediation are much higher than mitigation plans.

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