

Tailings storage facilities, failures and disaster risk

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Abstract

Mining generates 13 billion tonnes per year of potentially toxic wet slurry waste, called tailings, commonly deposited in tailings storage facilities (TSF). Since 1915, 257 TSF failures have occurred, releasing a total of ~250 million m³ of tailings, destroying areas up to ~5,000 km², killing an estimated 2,650 people and impacting ~317,000 people through displacement, property damage, and risks to livelihoods and health. In this Review, we provide an interdisciplinary approach to understanding the causes, effects and response to TSF failures, applying a disaster risk reduction framework. TSF failures can occur owing to earthquakes, overtopping, weak foundations and liquefaction, among other mechanisms. The severities and volumes of TSF failures have increased since the year 2000, owing to increasing mine waste generation from the exploitation of larger, lower-grade deposits. Despite the increasingly severe impacts, the mining industry has been hesitant to use the term ‘disaster’ to analyse TSF failure, presumably to avoid liability. TSF failures should be considered as disasters when they cause severe disruption to the functioning of ecological and social systems. Future research should build on attempts to link tailings facility locations to situated risk factors by improving spatial and time series analysis, reducing reliance on corporate disclosures, and increasing the visibility of priority locations and patterns of concern.

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Introduction

Mining produces huge volumes of waste, as the minerals of economic interest can comprise less than a few percent of the mined ore. Mining wastes include billions of tonnes per year of discarded waste rock¹, up to 13 billion tonnes per year of tailings^{2,3} (the wet slurry waste generated during mineral processing), slags, ash and other wastes generated after refining, upgrading and use. Tailings are made of ground-up rock and water, sometimes contain leftover processing chemicals and fluids, and are often toxic, radioactive and/or corrosive⁴. Such tailings can be stored in a tailings storage facility (TSF) but these can and do fail, with severe environmental, health and financial consequences (Fig. 1). For example, a reported 257 TSF failures have occurred since 1915 (refs. 5–8), which released ~250 million m³ of tailings⁹ and destroyed over 5,300 km of river channels and 4,950 km² of floodplains and coastal areas⁵. An estimated 2,650 people have died from TSF failures, and 317,000 people have been affected by displacement, property damage, and risks to livelihoods and to health⁵ (Fig. 1). Inundated areas pose serious risks to agricultural and ecosystem health through land contamination and loss of habitat^{10,11} (Fig. 1). Even protected conservation areas (PAs) are affected, as 9% of TSFs are located within a PA (with half of these facilities established after the PA was designated) and another 20% are situated within 5 km of a PA¹². Estimates of the financial implications of the social and environmental impacts of major TSF failures range between US\$750 million and US\$56 billion (ref. 13).

Since the early 2000s, the global transition to renewable energy and pursuit of net zero CO₂ emissions has been driving substantial increases in demand for metals and minerals, which is increasing mine waste generation as larger deposits of lower grade material are exploited. For example, the mining of metals commonly used in batteries, such as Cu, Li, Mn and Ni, could generate up to 2 trillion tonnes of tailings and waste rock between 2020 and 2050 (ref. 1). The additional tailings storage costs for these four metals alone could amount to US\$1.6 trillion (ref. 1) and place greater pressure on land and water resources^{14,15}. These increasing volumes of tailings are already causing a notable increase in both the number and severity of TSF failures. For example, the TSF failures that occurred since the year 2000 account for more than half of the released volume of tailings ever recorded¹³, and the two largest (by volume) TSF failures (Mount Polley, Canada and Fundão, Brazil) have occurred since 2014 (ref. 16). Tailings management is therefore a major global safety and sustainability challenge^{17,18}, and improvements in reporting standards, policy and disaster risk reduction strategies are urgently needed.

Three of the most serious TSF failures include Mount Polley, Canada (2014), Fundão, Brazil (2015), and Brumhadinho, Brazil (2019)¹⁶. The Fundão and Mount Polley TSF failures caused widespread environmental damage through release of the largest volumes of tailings recorded to date (32 million m³ and 25 million m³, respectively^{19,20}), with Fundão resulting in 19 deaths²¹. A smaller volume of tailings was released at Brumhadinho (12 million m³ (refs. 22,23)), but the death toll was greater, with 270 people killed, and the damage to mining infrastructure and ecosystems was as severe as at Fundão and Mount Polley²⁴. These three TSF failures, and particularly Brumhadinho, led to the formation of the Investor Mining and Tailings Safety Initiative²⁵ comprising 112 institutional investors, who requested TSF information from 726 publicly listed extraction companies to determine their environmental and social risks²⁶. This work led to the Global Tailings Review²⁷ and, on 5 August 2020, publication of the first Global Industry Standard on Tailings Management (GISTM)²⁸, a voluntary standard that requires operators to prioritize, and be responsible for, the safety of

TSFs throughout their life cycles. The introduction of the GISTM is an important policy development, but without a backing institution or a process for driving adoption and implementation, and with the large number of historical and operating TSFs, substantial risks remain.

This Review explores TSF failures and their impacts, with the aim of highlighting preventative and management strategies, as well as themes for future research. We make a clear distinction between TSF failures and disasters (see Glossary) and argue that prevention of TSF disasters requires paying closer attention to factors that go beyond the physical mechanisms that induce mechanical instability. We also discuss how TSF failures can be analysed as disasters when they cause adverse impacts and result in material disruption to social, environmental and economic systems^{28,29}. We highlight how TSF failure rates and sizes might change in the future, that they can be best prevented through management and policy, and that circular economy offers a new way to reduce tailings generation through large-volume by-products. Global co-operation to practice mining responsibly is necessary to prevent TSF failures and disasters and protect people and the planet.

Tailings storage and failures

Despite information gaps in several mining jurisdictions, ~25,000 TSFs have been geo-located, including active, inactive, closed and abandoned facilities³⁰. Of these, it is estimated that ~3,400 are active². TSFs are intended to hold tailings indefinitely, but as many as 10% of all sampled TSFs, and 18% of sampled active upstream-type facilities, have reported notable stability concerns at some point in their history². This section provides an overview of how tailings are stored and how TSF failures occur.

Storage facilities

Mining produces multiple types of waste which can be divided broadly into four categories, including the overburden soil and rock that cover the ore, the waste rock that falls below the profitable grade, spent heap leach pads, and tailings that result from the mineral extraction process^{31,32}. Tailings typically result from a rock crushing process which generates particle sizes that are small enough (<1 mm) to be amenable to hydraulic deposition^{31,33,34}. They are composed of particulate matter and processing water, and can contain potentially toxic, corrosive and/or radioactive components⁴.

A range of tailings storage options are available¹⁸. Direct disposal of tailings into water bodies such as rivers, lakes and seas^{31,35} remains in use, although it is often associated with severe environmental damage and securing a permit for this type of strategy remains difficult in most jurisdictions³⁵. More commonly, tailings are deposited in a designated TSF. The TSF can consist of a natural or mined-out pit or an on-surface impoundment with a dam^{2,31,33} (Fig. 2a). Additionally, the backfilling of mined-out voids with tailings is required in some underground mining methods³⁶. Placing the tailings back underground increases the costs of any attempt to further reprocess the tailings and this can limit the adoption of void backfilling as a tailings disposal strategy³³.

On-surface tailings dams vary according to the topographic setting, and can be built across valleys, on the side of hills, or as a ring-dike in flat areas (Fig. 2b). Dams can be further subdivided into single-raise and progressively raised types (Fig. 2c). Single-raised dams are built to their full height in a single construction phase that is completed before tailings deposition begins³⁷. Conversely, in progressively raised dams, which are much more common², the retaining dam grows concurrently with mining to accommodate tailings as they are generated. The construction of progressively raised dams can extend over several

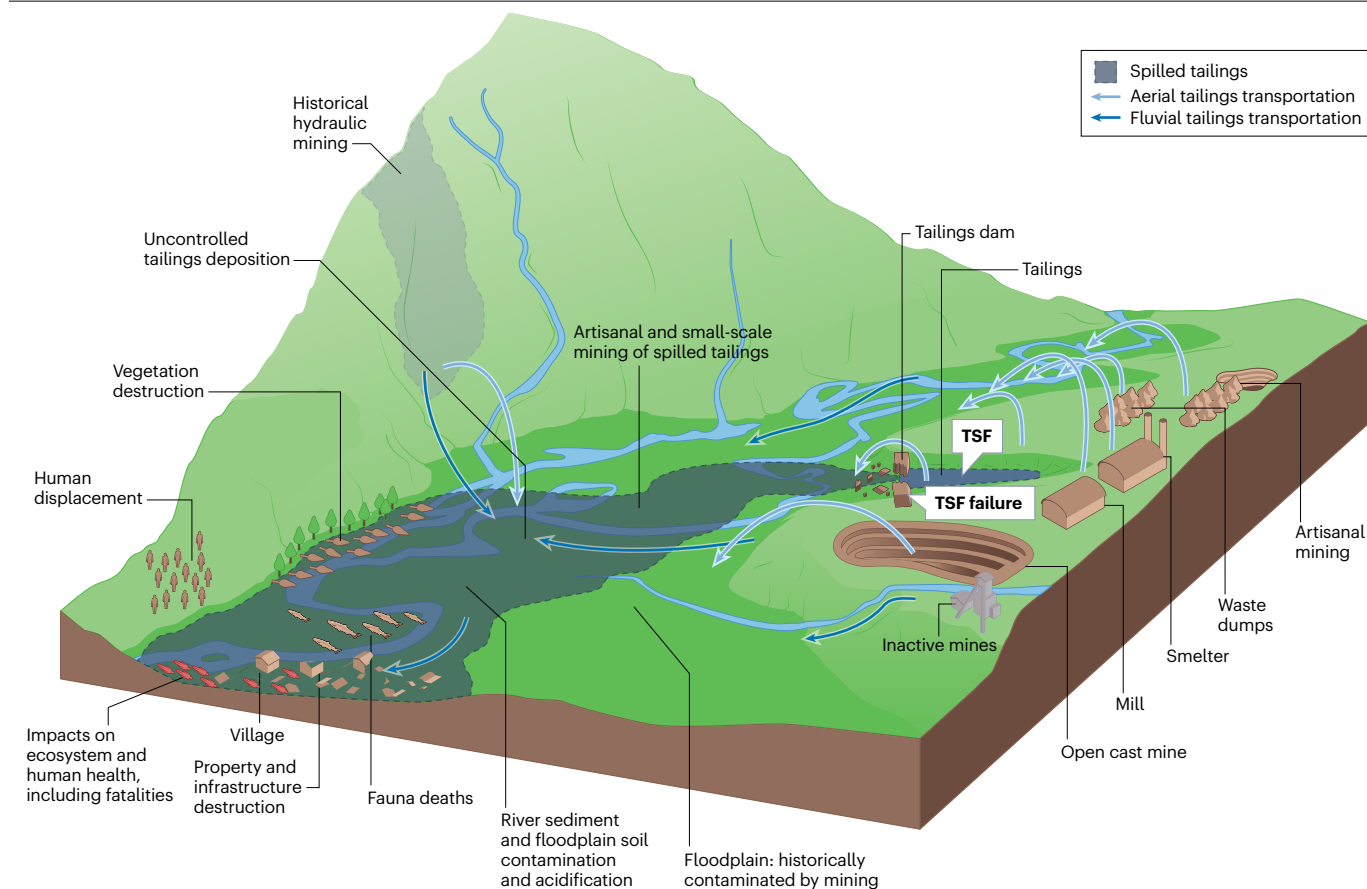


Fig. 1 | Effects of TSF failures and disasters, and other mining activities on river catchments. Failure of tailings storage facilities (TSFs) cause uncontrolled tailings deposition and sediment contamination for tens to hundreds of kilometres downstream. Tailings deposition can cause fatalities and destruction of vegetation, property and infrastructure. Soil contamination causes fauna

deaths and impacts on human and ecosystem health. Mining activities, such as open-cast, hydraulic and artisanal mining can cause contamination of rivers and flood plains through aerial and fluvial transportation of tailings¹⁷⁷. Understanding the impacts of, and recovery from, TSF failures and disasters requires a catchment-system approach.

years and even decades and this poses challenges to ensuring uninterrupted adherence to the best available practice (BAP) and continuous documentation of the construction process^{2,38}.

As progressively raised dams grow, their crest can move towards the deposited tailings (upstream construction), remain equidistant from them (centreline construction), or move away from them (downstream construction) (Fig. 2d). Upstream construction is generally regarded as the least stable construction method because it involves building lifts on previously deposited tailings, as opposed to on other dam segments^{2,39}. Concerns around the stability of upstream construction have led to their being banned in countries with high rainfall or seismicity such as Brazil, Chile, Ecuador and Peru³⁹. Dams can have distinct internal zones (such as a core with filters and rockfill), similar to water-retaining dams, or they can be largely homogeneous and made of tailings themselves (self-raised dams) or alternative materials (Fig. 2e).

Tailings can be dewatered to different degrees before being transported to the TSF (Fig. 2f). Dewatering improves mechanical properties but makes sulfidic tailings prone to oxidation processes that can promote acid and metalliferous drainage, unless the tailings have undergone desulfurization before dewatering. The degree of dewatering also impacts how the tailings are deposited in TSFs (Fig. 2g). Conventionally

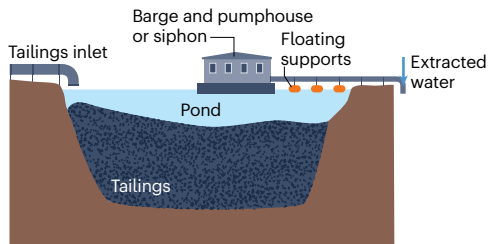
dewatered tailings are deposited from the perimeter of the TSF and flow towards its interior wherein a pond forms. Deposition options include paddocking, in which the tailings slurry is deposited into enclosed areas (paddocks), around the perimeter of the TSF to raise the dam or into the TSF interior when the dam is not being raised. The tailings slurry can also be released from spigots positioned along the dam perimeter. Hydrocyclones are used to separate the tailings slurry into a coarse fraction used to build the dam and a fine fraction conducted into the TSF. Thickened tailings are generally discharged at a point (for example, central thickened discharge, Fig. 2f) or along a line close to the centre of the TSF from where they flow towards the perimeter.

In 2021, information disclosed by multiple mining companies from around the world enabled the compilation of a public database containing details of 1,743 TSFs including active and inactive facilities². Although incomplete, the database provided insights into the prevalence and geographic distribution of different types of TSFs. For instance, although upstream dams were the most common types of TSF constructed during the twentieth century, downstream dams were the most popular alternative between 2010 and 2020. The drop in popularity of upstream dam construction probably reflects concerns around their mechanical stability. Analysis of the disclosures revealed that active upstream facilities

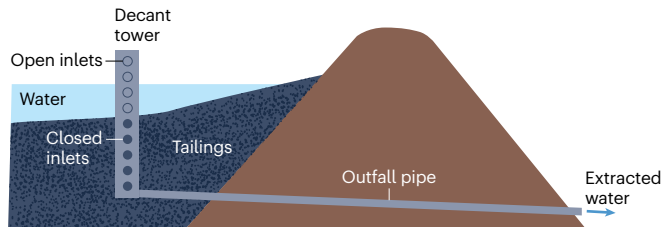
Review article

a Retaining structure and drainage methods

In-pit disposal with pump or siphon

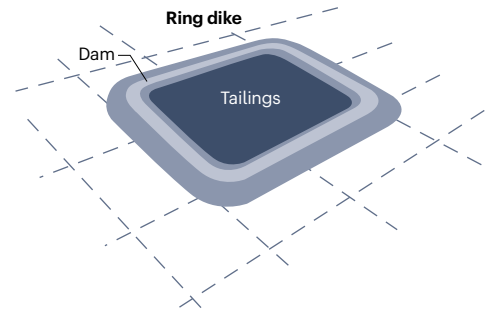
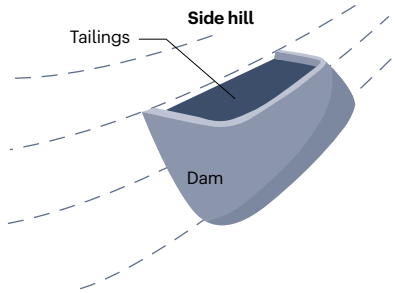
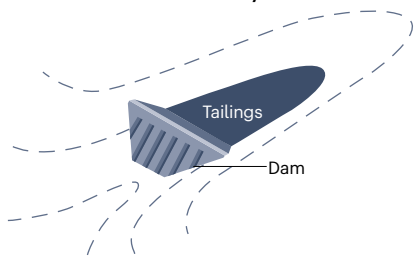


Retaining dam with decant tower



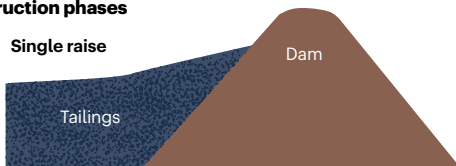
b Topographic configuration

Cross valley

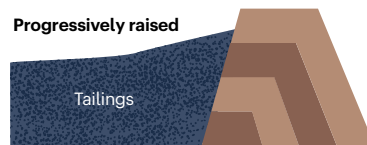


c Number of construction phases

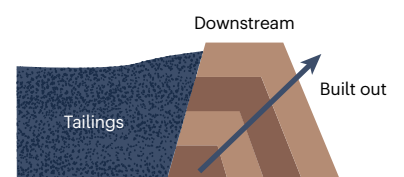
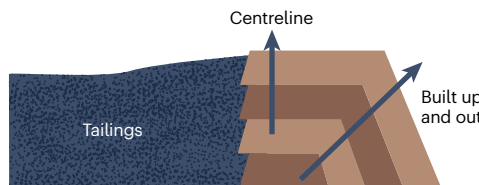
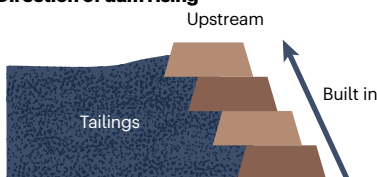
Single raise



Progressively raised

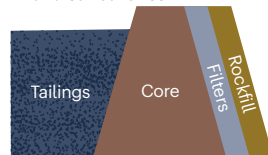


d Direction of dam rising

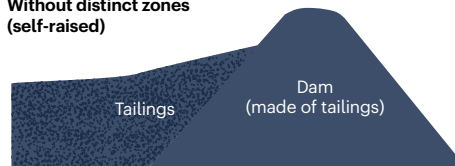


e Internal structure of dam

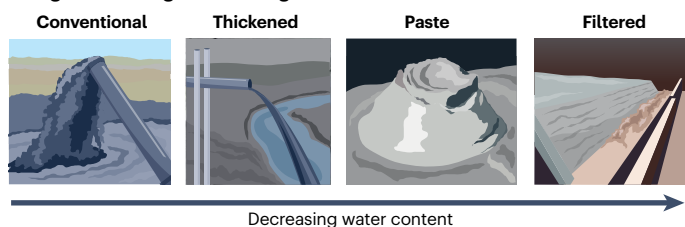
With distinct zones



Without distinct zones (self-raised)



f Degree of tailings dewatering



g Tailings of deposition strategies

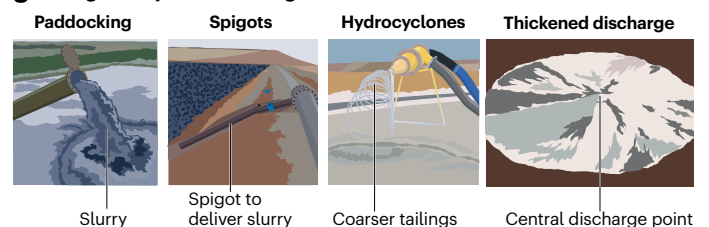


Fig. 2 | Classification of tailings storage facilities (TSFs). **a**, The retaining structure can consist of an artificial or natural pit, or a dam. Pumps and/or siphons are used to drain ponded water from in-pit or dammed TSFs, and decant towers are used to drain ponded water from dammed TSFs¹⁷⁸. **b**, The topographic configuration of the TSF is a function of the terrain. Cross valley and side hill configurations are common in mountainous areas whereas ring dikes are common in flat areas¹⁷⁹. **c**, The dam can be built in a single raise, such as a water-retention dam, or progressively as the mine produces more tailings.

d, Progressively raised dams can be built in the upstream, centreline or downstream directions, or a combination thereof. **e**, Dams can have distinct internal zones or they can be largely homogeneous made of tailings themselves or alternative materials. **f**, Tailings can be dewatered to different degrees before being transported to the TSF, with conventional tailings being the most water-rich, and thickened, paste and filtered less so. **g**, Deposition of tailings in TSFs can be done by paddocking, spigots, hydrocyclones or central deposition of thickened tailings. TSFs can vary markedly from one facility to another.

reported the highest incidence of stability issues with the elevated risk persisting even when those facilities were built in high governance settings². Of the 1,743 TSFs in the database, North America hosts 29% and Europe only 3%. Africa, Asia, Oceania and South America all have a similar share of 17% or 18% (ref. 2). The new database does not quantify or characterize the number or type of human settlements downstream from TSFs, or the social and economic conditions of areas where TSFs are situated⁴⁰. This information is essential for calculating human exposure and vulnerability to TSF failures. The absence of this information is a major impediment to understanding disaster risk in this field⁴¹.

Failures and disasters

Broadly speaking, any engineering structure can be considered to have failed when it is no longer fit to fulfil the purpose for which it was built. In the case of TSFs, that purpose is to contain the tailings without harming the environment. Accordingly, uncontrolled releases of tailings or contaminated water constitute a TSF failure. The uncontrolled release of tailings generally follows a breach of the dam (for example, during the Val di Stava fluorite TSF failure in 1985, Italy; Box 1) or other physical barrier (for example, a concrete plug during the Tapien pit TSF failure³¹) whereas the release of contaminated water can occur without a breach, such as by water seeping under or through the dam or pit wall. Although the uncontrolled release of tailings from a dam breach tends to be visually more dramatic than the seepage of contaminated water, both types of failures can lead to disasters.

In this Review, we distinguish between TSF failures and disasters as follows: TSF failures generate disasters when they result in disruption to social, environmental and economic systems to such an extent that the affected entity (household, community, town, ecosystem) is unable to recover by its own means. When TSF failures result in disaster, they tend to have large-scale, long-term impacts that can span generations or into perpetuity^{6,10,23,40,42}.

The breach of a dam wall occurs owing to physical mechanisms that include slope instability triggered by static or dynamic loads, internal or external erosion, weak foundation layers, dam overtopping, failure of appurtenant structures, and mine subsidence⁶ (Fig. 3). Dam breaches triggered by overtopping, static loading and earthquakes are the most common and they jointly account for 52% of all TSF failures (Fig. 3). Many dam breaches that lead to TSF failures have multiple precursors and causes (Box 1). The geotechnical stability of tailings is intimately related to the tendency of their interparticle voids to either decrease or increase their volume when sheared. However, methods to assess the volume change tendencies of tailings still involve considerable uncertainty⁴³.

Analysis of TSF failures by engineers and environmental scientists often focuses on the physical mechanisms of the failure, the chemical properties of processed waste, and associated failure scenarios^{44–46}. Understanding these aspects is essential, but they are insufficient for preventing the reoccurrence of TSF disasters. Human factors contribute substantially to bringing about failures and disasters⁴⁷. Human

factors involve decision making processes as well as the organizational, regulatory and industry context within which a TSF operates^{45,48–50}. For example, normalization of deviations from adequate engineering performance⁵¹, conflicts between production and safety^{49,50}, operation of isolated business units that hinder the internal auditing of TSF management, difficulties for safety concerns to reach upper management, remuneration incentives that favour short-term production over safety^{49,50} and a company culture that perceives regulatory compliance as an end, rather than as a means^{49,52,53}. Differences and disparities between developing and developed countries must be accounted for wherein implementation and enforcement of standards and regulations can vary^{47,54}. Some suggest that physical mechanisms can often account for ‘what’ happened, whereas human factors can help to explain ‘why’ it happened⁵⁵.

Adoption of BAPs aims to address both the physical mechanisms and human factors that result in TSF failures and disasters. BAP should include the characterization of the in-situ soils, sediments, rocks, hydrogeology, weather and seismicity, designs that account for the life cycle of the TSF including post-closure, strict adherence to good construction practices, constant monitoring of construction quality and indicators of potential failure mechanisms, information disclosure practices, and corporate structures that promote good communication, accountability and a balanced consideration of safety and production^{28,33,34}. BAP also includes explicitly accounting for the effect of climate change in the design and management of TSFs. For instance, the GISTM prescribes that the knowledge base of a TSF should capture uncertainties owing to climate change²⁸. In particular, climate change directly impacts the water management considerations that have to be made during design, operation, and closure of a TSF⁵⁶. The literature now includes multiple examples of how climate change considerations are incorporated into TSF management^{57,58}. Water management implications can be estimated using downscaled general circulation models together with precipitation runoff models calibrated with site-specific measurements^{56,57}. However, the climate change scenario that will eventually materialize is highly uncertain and adaptability of TSF design and management plans to this scenario remains an important requirement⁵⁶. The onus is now on industry and regulators to progressively transfer this knowledge into BAP.

It is impossible to guarantee that BAP will be static or that it will be consistently implemented throughout the lifespan of a TSF. Accordingly, dam breach analyses, which estimate the characteristics of the debris and liquid flow that would ensue should a breach occur, are also an important aspect of TSF management^{28,59}. BAP for dam breach analyses, however, remains contested, even in jurisdictions with considerable experience in TSF failure⁶⁰. Disaster prevention and mitigation also requires a consequence-based approach in which governance and design parameters depend on examining a range of worst-case scenarios²⁸. This approach is not applied consistently across the industry.

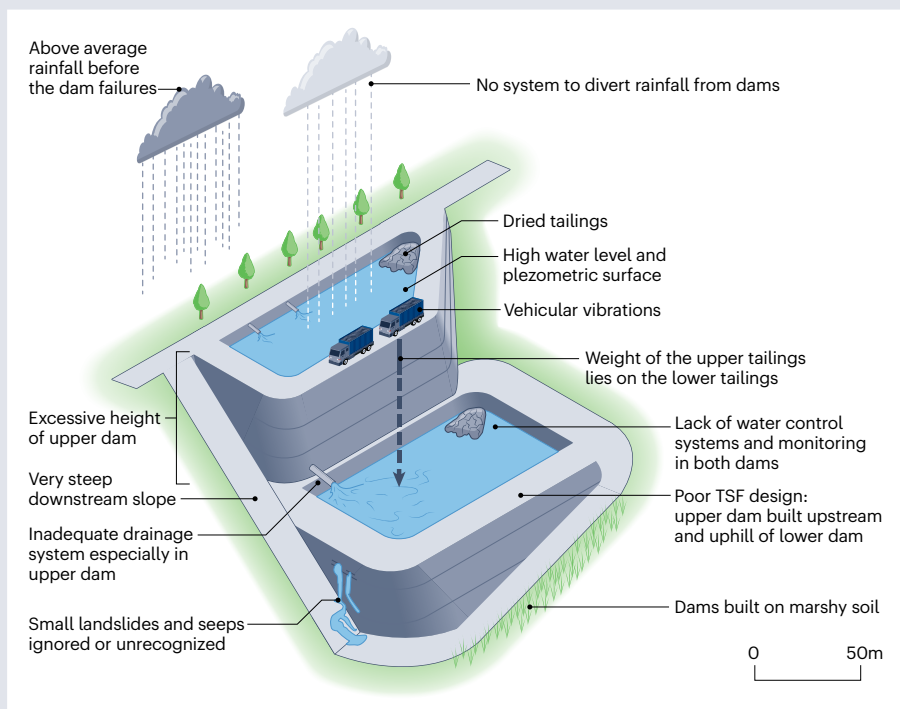
Contemporary disaster science views TSF failures as extensions of the social, cultural, economic, and political systems within which they

Box 1 | Multiple precursors and causes of the Val di Stava TSF disaster, Italy, 1985

On 19 July 1985, two tailings storage facilities (TSFs) storing fluorite tailings from the Prealpi Mineraria Mine in the Dolomite Mountains of Italy failed¹⁸⁶. Around 185,000m³ of tailings flowed at around 90 km h⁻¹ along 4.2 km of Stava Creek^{187,188}, inundating the villages of Stava and Tesero¹⁸⁹. Two hundred and sixty-eight people were killed, 53 houses, 3 hotels, 8 bridges and 6 industrial buildings were destroyed and hundreds of trees were uprooted¹⁸⁹. The cost of the damage was estimated to be around €133 million (ref. 190). Recovery operations began immediately after the disaster and continued for 15 years, involving reclamation of the affected areas, extensive rebuilding, and distribution of relief and reconstruction funds to families and property owners¹⁹¹.

Although the overall cause of the Stava disaster was attributed to the instability of the two TSFs, there were many reasons for this, and precursors to the failure itself (see the figure). The design of the dams was poor: they were built without geotechnical site investigations on marshy glaciofluvial soils on a slope with an average inclination of 25°, and they had inadequate drainage systems, no water control measures and no monitoring systems^{191,192}. Rainwater, groundwater and slope runoff were not diverted from the TSF. These factors, together with high rainfall preceding the failure, resulted in high water levels and piezometric surfaces¹⁸⁸. The height of the dams was also excessive, with the upper dam reaching 34 m (ref. 193). Leaks and requests from local communities for dam investigations were ignored¹⁹³.

The Stava TSF disaster is not alone in having multiple causes and precursors. The Fundão TSF failure has been attributed to seismic



shocks, liquefaction and poor technical and managerial practices and governance¹⁹⁴. The Aznalcóllar TSF failure has been blamed on inadequate design, brittle foundation marls¹⁹⁵ and high liquid pore pressures¹⁹⁶. To prevent TSF failures and disasters, it is necessary to build a clear and integrated understanding of all their causes and the sequence in which they occur. Building this integrated understanding of TSF failure precursors would include extending the analytical frame to the institutional systems and structures that enable disaster patterns to persist after policy and standards have been widely endorsed.

Figure adapted from ref. 197, Springer Nature Ltd.

occur, rather than isolated physical events^{40,61,62}. The search for deeper explanations for disastrous outcomes incorporates a focus on human exposure and vulnerability in hazardous situations⁶³. In contemporary disaster science, vulnerability is regarded as more critical to understanding the root causes of a disaster than hazards, to the extent that hazards are merely triggers against which disasters unfold⁶⁴. Using this approach, the Fundão failure has been understood as a function of a corrupt political and economic system interacting with deeply embedded vulnerabilities in the host context, such as poverty, inequality, and social exclusion⁴². This analysis brings into frame the broader systems and structures that create the underlying conditions for industrial disasters to occur^{42,52,53}. Although the adoption of disaster science to investigate TSF failures holds much potential for better apprehending the causes and consequences, it is not common industry practice.

TSF failures have multiple causes, often acting simultaneously (Box 1), which include decisions about placement and design relative

to the host context. These decisions are inherently cross-disciplinary given that the TSF placement and design must consider geological and geotechnical stability, rainfall, flood occurrence, population, land use and – beyond these factors – an assurance that construction and management of the facility are appropriate. The impacts of a TSF failure involve further interdisciplinary consideration, given the full range of social, environmental and economic factors that are drawn into a TSF disaster footprint.

Impacts of TSF disasters

The environmental, ecosystem, human health and socioeconomic impacts associated with TSF disasters can be geographically extensive and long term. This section presents an overview of the nature of these impacts, contrasting them with those of chronic mine waste discharges, particularly related to historical (legacy) mining, and emphasizing inherent socioeconomic tensions.

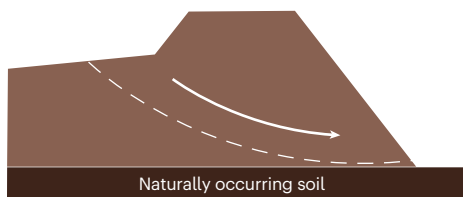
Contamination from mining activities

Past and present mining activities can contaminate sediment and water in river systems with potentially toxic and radioactive elements through acute failures of TSF¹⁷, and by continual chronic discharge of tailings and other mine wastes⁶⁵. Before humans began to mine and process earth materials, element concentrations in rivers were controlled by natural

weathering processes, but as mining began, these concentrations were augmented by the disposal of liquid and solid mine wastes, usually into the nearest watercourse. Although metal mining contamination began more than 7,000 years ago, severe contamination of catchments did not begin in most countries until the Industrial Revolution at the end of the eighteenth century^{65–69}.

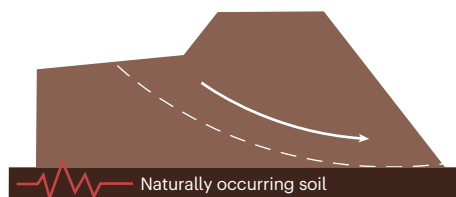
a Slope instability (17%)

Instability caused by static loads

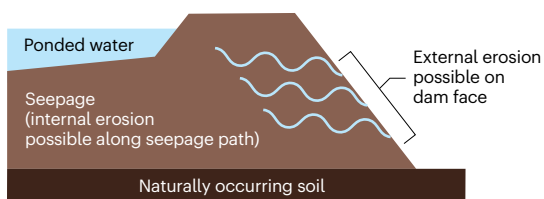


b Earthquake (16%)

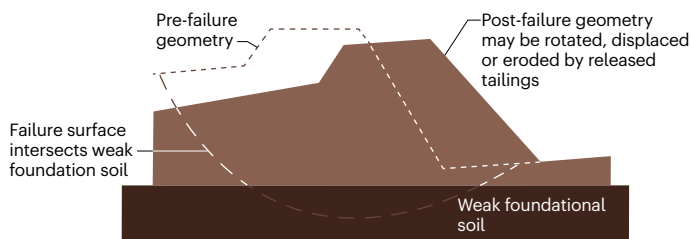
Instability caused by dynamic or seismic loads



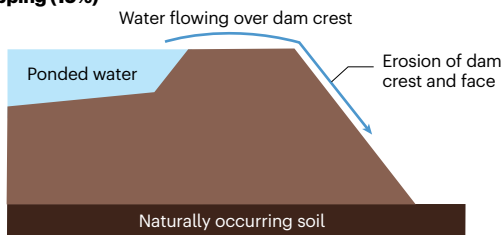
c Seepage (9%)



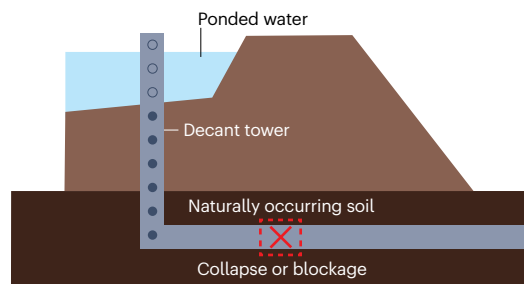
d Weak foundation (7%)



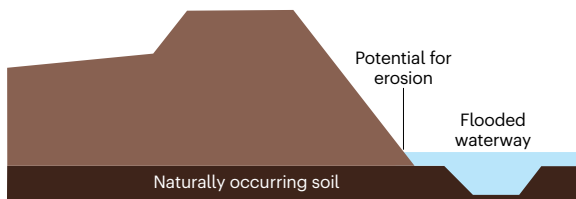
e Overtopping (19%)



f Collapse of structural elements (8%)



g Erosion by nearby waterways (4%)



h Mine subsidence (1%)

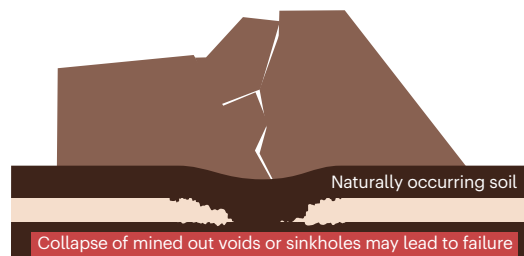


Fig. 3 | Tailings storage facility (TSF) failure mechanisms. A range of mechanisms can cause TSF failure. Percentages in parentheses in the figure indicate prevalence of the mechanism based on the analysis of 339 incidents¹⁸⁰. The mechanisms for 19% of the incidents were unknown. **a**, Slope instability caused by static loads: for example, Brumhadinho, Brazil, 2019 (ref. 23). **b**, Failure owing to seismic action: El Cobre Old Dam, Chile, 1965 (ref. 181), and Mochikoshi Dykes 1 and 2, Japan, 1978 (ref. 182). **c**, Seepage through the dam leading to internal or external erosion: Bafokeng, South Africa, 1974 (ref. 33), and Southern Clay, USA, 1989 (ref. 6). **d**, Weak foundational soils: Aznalcóllar,

Spain, 1998 (ref. 85), and Mount Polley, Canada, 2014 (ref. 45). **e**, Excess of ponded water overtopping the dam: Merriespruit, South Africa, 1994 (ref. 33), and Baia Mare and Baia Borşa, Romania, January and March 2000 (ref. 77). **f**, Structural inadequacies of appurtenant structures: Fundão, Brazil, 2015 (ref. 183), and Tapian Pit, Philippines, 1996 (ref. 31). **g**, Flooded nearby waterways generating external erosion: Pinchi Lake, Canada, 1971 (ref. 6), and Pico de São Luís, Brazil, 1986 (ref. 6). **h**, Subsidence of mined out voids: Inez, Martin County, Kentucky, USA, 2000 (ref. 109), and Mufulira, Zambia, 1970 (ref. 6). Safe management of a TSF requires active monitoring against all credible failure mechanisms.

In the first industrial nations, such as the UK, poor recovery efficiencies of the valuable components (normally metals), and the lack of environmental legislation, led to severe and widespread river contamination, most notably in the second half of the nineteenth century^{65,70}. Although discharge of mining wastes decreased in the first half of the twentieth century owing to improved processing methods and declining output, it has been estimated that approximately 4,500 km of river channels and approximately 1,500 km² of the floodplains of the UK remain severely contaminated with metal and metalloid concentrations at toxicological levels⁵.

In both North and South America, and in Oceania, legacy contamination from unregulated precious metal mining in the late sixteenth to the early twentieth century^{71–73} has a substantially greater impact on contemporary river channels and floodplains than present-day mining activities⁵. Because of climate change related increases in the frequency and severity of flooding, remobilization of sediment-associated metals and metalloids from river channels and floodplain affected by historical mining is becoming an emerging issue of concern for both ecosystem and human health^{70,74–76}.

For small failures (<100,000 m³), tailings rich events have a much shorter runoff distance (<10 km) than contaminated water (<100 km), but the supernatant water is diluted quickly (days to weeks). However, for large events (>1,000,000 m³), there is much less difference between the two. Impacts related to water contamination are temporally very short compared to the long-lasting tailings rich events. The impacts of solids-rich TSF failures typically last longer (years to decades) than those of water-rich failures (weeks to years). Remediation activities are useful in reducing both the spatial and temporal extent of the consequences of TSF failures (Fig. 4).

Environmental and ecosystem impacts

TSF failures cause erosion, sedimentation and destruction of downstream channel and floodplain environments. They can add to the

contamination burden by instantaneously releasing large volumes of contaminant-bearing supernatant and solids into river systems^{17,77–79}, and wherein there is a history of mining activity within a catchment, by remobilizing contaminated alluvium⁶⁶. Element concentrations (for example, As, Cd, Cu, Fe, Pb, Sb and Zn) in affected waters, soils and sediment can exceed background concentrations by several orders of magnitude¹⁷, especially in the areas closest to the TSF failures⁸⁰. Potentially toxic concentrations of metals and metalloids in these soils and sediment persist in catchments for thousands of years and can be mobilized and redeposited downstream especially during high magnitude flow events^{66,81} (Fig. 5a,b). By contrast, dissolved aqueous contaminants generally decrease relatively soon (days to several months) after TSF failures owing to dilution⁷⁷ or sorption onto primary or secondary minerals⁸².

Not all TSF failures cause contamination because not all tailings contain high concentrations of potentially toxic metals and metalloids¹⁷. The 2014 Mount Polley, Canada, TSF failure, for example, had considerably higher physical impacts on Hazeltine Creek and Quesnel Lake than chemical impacts owing to low metal and metalloid concentrations in the tailings¹⁹. Only Cu and V were slightly enriched in affected waters and river sediments, and their concentrations were naturally attenuated through dilution and mineral weathering^{19,83}. Contamination following TSF failures occurs when tailings minerals that contain toxic elements are deposited and weathered. Highly reactive minerals such as pyrite and arsenopyrite readily break down, potentially releasing As, Co and others, and generating acid and metalliferous drainage owing to release of protons and sulfate⁸². Less reactive tailings minerals such as magnetite, which can contain Cr, Ga, Mn and V, are more resistant to weathering, but they can release these elements during chemical reactions such as reductive dissolution⁸⁴.

Industry recognized methods for systematically evaluating the environmental and ecosystem impacts of TSF failures do not exist. The assessments are site-specific, varying in time and numbers of

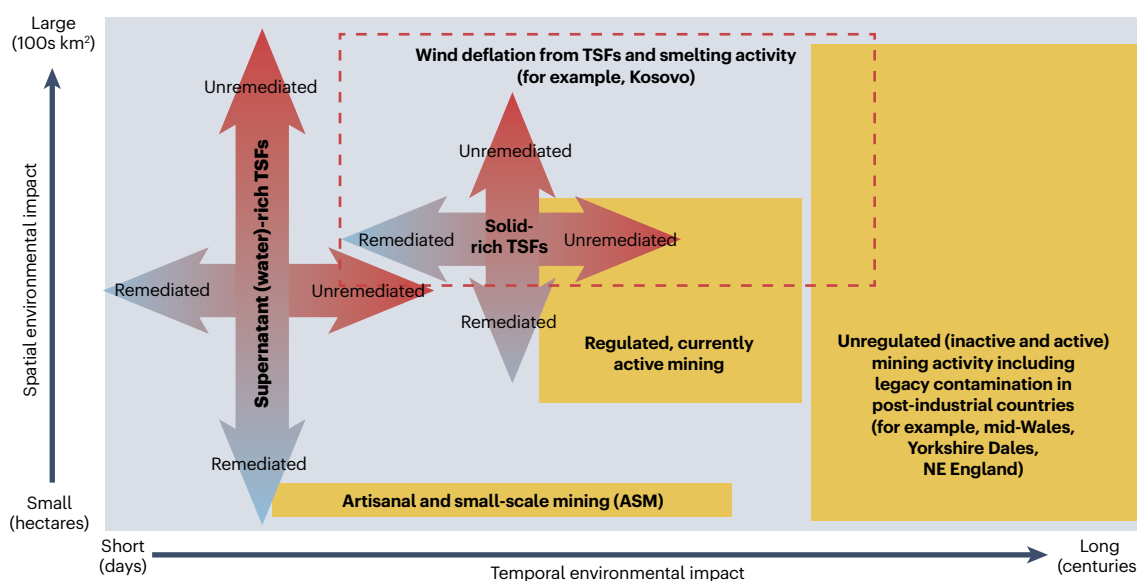


Fig. 4 | Impacts of tailings storage facility (TSF) failures and other mining activities. Typical spatial and temporal environmental impacts of TSF failures (both supernatant (water)-rich and solids-rich, wherein the blue arrows indicate remediated TSF failures and the red arrows indicate unremediated TSF failures).

The impacts of past and present metal mining operations (yellow boxes) and atmospheric dispersal from TSF deflation and smelting activity (red dashed box) are also shown for comparison.

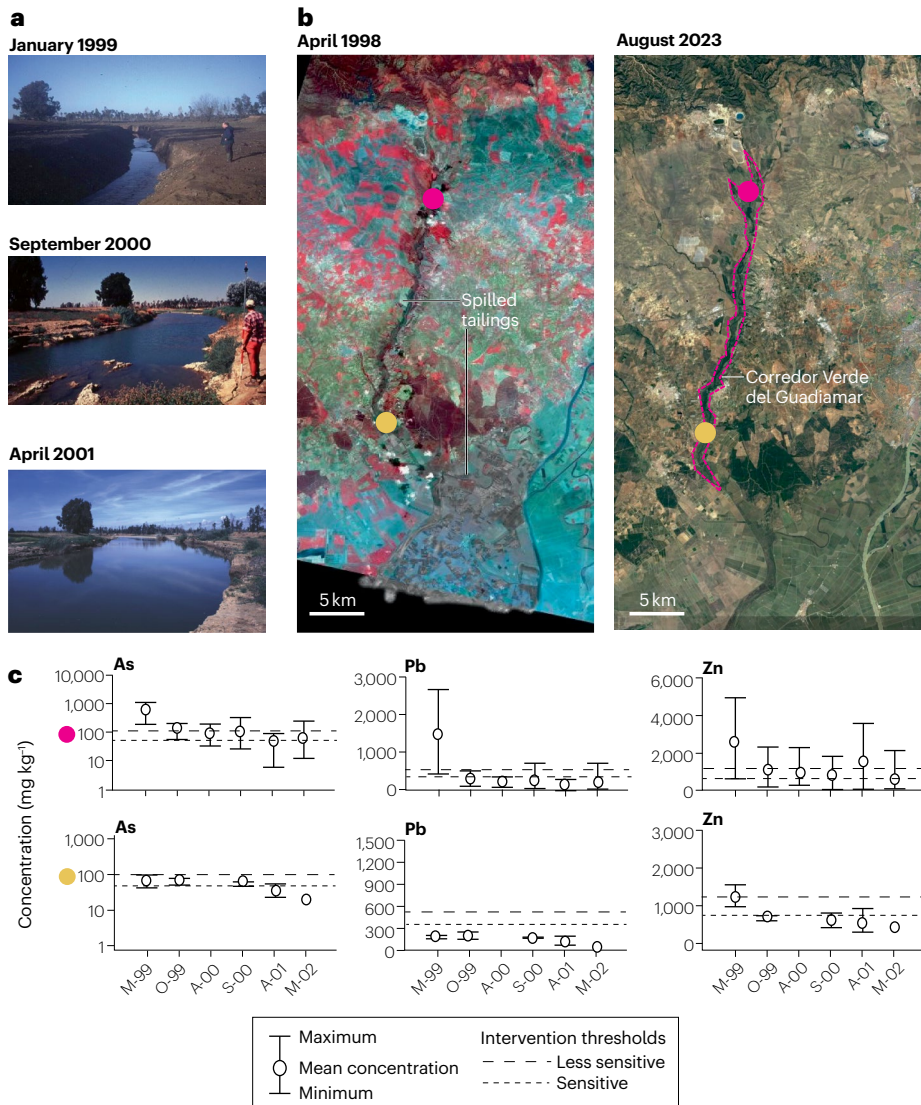


Fig. 5 | Catchment impacts and transformation after the 1998 Aznalcóllar TSF failure, Spain. **a**, Photos of the Guadiamar floodplain following the removal of spilled tailings and vegetation in January 1999, followed by flooding in September 2000 and April 2001 that caused channel widening and remobilization of historically contaminated alluvium. **b**, A SPOT satellite image from April 1998 showing the Guadiamar catchment covered in grey tailings (left panel) and a Google Earth image from August 2023 of the catchment showing the limits of the Corredor Verde del Guadiamar (magenta line) that was created following the TSF failure and remedial operations (right panel). Magenta-coloured and yellow-coloured circles show upstream and downstream reaches, respectively, that were sampled between 1999 and 2002. **c**, Changes in sediment-borne As, Pb and Zn concentrations from the locations of the magenta-coloured and yellow-coloured circles between May 1999 (M-99) and May 2002 (M-22). Sensitive and less-sensitive intervention thresholds are shown by the short-dashed and long-dashed lines, respectively. In all cases, the concentrations declined over the 3 years, mainly owing to dilution by clean sediment. Although unremediated TDF failures can have some of the largest spatial impacts, their temporal impacts are not as long as those from unregulated and legacy mining impacts. Panel **c** adapted with permission from ref. 128, Elsevier.

impacts examined. They are often carried out as part of academic studies, many of which are summarized in this Review. In the short term, they include quantitative analysis of the numbers of organisms and humans killed, infrastructure destroyed and land affected by the failure itself. The short-term (days to months) impacts of TSF failure on ecosystems and agricultural lands can be devastating¹⁷. All fish and shellfish in the Guadiamar basin were killed by deposition of tailings following the 1998 Aznalcóllar, Spain, failure⁸⁵, and 1,240 tonnes of fish died following cyanide and metal releases from the 2000 Baia Mare and Novaț-Roșu TSF failure in Romania⁸⁶. The 2019 Brumhadinho, Brazil, TSF failure caused increases in the amount and abundance of antimicrobial resistance genes in affected soils, sediments and water <30 days after the event⁸⁷. The 2015 Fundão, Brazil, TSF failure caused a loss of 460 ha of Atlantic forest (a biodiversity hot spot) extending up to 74 km from the dam⁸⁸, and severe damage to at least 1,500 ha of natural reserves and Krenak Indigenous land⁸⁹. The 2018 collapse of tailings dam number 2 at Huancapátí, Peru, released 80,000 m³ of tailings that severely contaminated crops, as did the

1998 Aznalcóllar, Spain, TSF failure, which resulted in contamination of ~2,600 ha of agricultural land and destruction of its agricultural products⁸⁵.

Longer-term impact analysis involves monitoring changes in organism numbers and diversity and contaminant uptake, patterns of water and soil contamination (Fig. 5c) and documenting altered river channel and floodplain dynamics. Chronic effects on ecosystems can last for years or even decades¹⁷. For example, reduced diversity of microbial communities in riparian, wetland, fresh and saline waters^{90,91}, and shifts in these communities towards those existing in the spilled tailings^{91,92}, occurred within 3 years of the 2014 Mount Polley, Canada, and 2015 Fundão, Brazil, TSF failures. Four and a half years after 1998 Aznalcóllar, Spain, TSF disaster, freshwater fish populations were shown to be recovering, mainly in reaches furthest downstream of the TSF rather than near it⁹³. Chronic impacts for freshwater and estuarine fish affected by other TSF failures include metal accumulation in the liver and muscle⁹⁴ causing organ damage⁹⁵ and changes in the composition of fish assemblages⁹⁶.

Human health impacts

Rapidly moving tailings slurry waves released during many TSF failures (for example, Val di Stava, 1985, Italy, Brumhadinho, 2019, Brazil) have engulfed and killed many people. In addition to these deaths, the physical and mental health of populations affected can be compromised by the stress of displacement, loss of livelihood, environmental degradation⁹⁷, cultural impacts and community disruption^{46,98}. In the case of the 2019 Brumadinho, Brazil, TSF failure, the forensic work associated with recovering and identifying victims added further distress to families⁹⁹.

After these shocks, adverse impacts on human health can continue from sub-lethal, but long-term, effects of exposure to metals and metalloids directly from the contamination¹⁰⁰ and potentially from subsequent biogeochemical concentration¹⁰¹. The health hazard might be from direct exposure to toxins through skin contact, accidental ingestion, inhalation of contaminated dust¹⁰², consumption of contaminated water^{16,103} and from indirect exposure by eating food^{17,104,105}. Partitioning of exposure among these routes is challenging as it varies by metal and metalloid, cohorts within the exposed community, land use and food sources, and tends to be highly variable within and between spills. A scenario modelled with the Geo-Environmental Risk Assessment System, tier 1 simulation^{106,107} showed that around 10% of the metal and metalloid burden for As, Cd and Pb arose from crops grown on contaminated land, with most of the remainder being direct exposure from soil ingestion and groundwater consumption. The model did not account for contamination from animal food sources. Post-TSF failure measurements of contaminants in humans and the wider environment at Potosí, 1626, Bolivia¹⁰⁸, Church Rock, 1979, USA¹⁰⁹, Aznalcóllar, 1998, Spain⁸⁰, Ajka, 2010, Hungary¹¹⁰ have revealed concentrations well above national safety guidelines^{17,77,103}.

The effects of tailings contamination can continue to be a health hazard for many human lifetimes, depending on the volume and dispersal of contamination, population exposed and the success and speed of any remediation. The use of Disability Adjusted Life Years (DALYs) for quantitative health impacts assessment of environmental pollution cumulative over time, such as that arising from TSF failures, offers promise but the methodology requires development¹¹¹. In the future, DALYs could be combined with other environmental risk modelling, such as loss of ecosystem services¹¹², to quantify the full human cost of TSF failures and, in turn, provide an improved estimate of the value of remediation. However, the huge financial price and technical challenge of remediation efforts for large-volume contamination events can make conceptually 'ideal' remediation efforts unrealistic^{17,107}, despite the benefits, leaving long-term consequences for health. This human cost will be amplified in low-income countries and communities where the burden of poor health is already high and where stretched health services will be challenged to respond.

Socioeconomic impacts

Socioeconomic impacts of TSF disasters are multi-faceted. The most obvious negative impacts are recorded in the form of human deaths and injury, destruction of property and livelihoods, loss of economic activity and public revenue owing to suspension or closure of mines, general disruption of infrastructure and amenity, litigation through criminal and civil proceedings, fines and penalties, and reputational damage to the mining industry and affiliated sectors (such as regulators, financiers and insurers)^{19,23,44,113}. Cultural identity loss, recognition of affected Indigenous communities⁹⁸ and impacts on ecological tourism¹¹⁴ are additional factors that warrant exploration but are often overlooked.

Disaster events of the speed and scale witnessed at Mount Polley, Canada, 2014, Fundão, Brazil, 2015, and Brumadinho, Brazil, 2019, have driven calls for new standards and regulations^{115,116}. These exercises draw, in an ad-hoc fashion, on the resources of state, corporate and civil society actors to develop new regulatory propositions, such as the GISTM²⁸. Although industry promotes these efforts as addressing root cause and meeting stakeholder expectations, they can fail to drive the necessary change, in part owing to a lack of jurisdiction in which to apply new regimes, a lag time in their implementation and the absence of oversight and enforcement³⁹.

Another way of measuring these disasters in socioeconomic terms is to account for the inherent tension that forms between governments and citizens over the approval and permitting of hazardous industrial projects. This tension is sometimes described as contributing to political instability, with the net effect being a gradual erosion of trust between affected people and their governing institutions¹¹⁷. That major institutions of all persuasions have demonstrated an inability to effectively govern the sector's approach to waste generation, storage, and disaster risk management, amplifies these tensions. Each successive failure diminishes public confidence in both the industry and the affiliated sectors.

The underlying need for mined materials¹¹⁸, and the increasing transaction costs surrounding the building of hazardous TSFs, might not be a deterrent to their construction (in the case of green fields or expansions) or improvement (in the case of brownfields projects). Where mining projects are deemed essential, any increased transaction costs might result in projects cutting more corners to bring their cost of production to within what the market will offer¹¹⁹. This cost-cutting is an important consideration given that individual mining projects and corporations do not set the price for mined commodities, but rather depend on the market to establish prices¹²⁰.

The GISTM embeds a suggestion that mining companies ought to share more information about potential failure scenarios. This is problematic for companies because the likelihood of disasters occurring is low in most instances, whereas the likelihood of negative impacts from disclosures is uncertain. For example, if a company suggests through its disclosures that an area is a potential inundation zone, the property values in those areas could diminish, as has been in the case with housing markets in many disaster affected areas¹²¹. There is a risk that disclosures in areas with extreme consequence facilities could result in major downward adjustments across segments of housing markets in areas exposed to greater risk¹²². The greater the potential for inundation, the higher the potential for deflation within the housing sector with pronounced demographic and socioeconomic effects^{123–125}. This challenge of responding to the 'disclosure deficit' is a concern amongst proponents but is not yet featuring in academic or policy literature and there is no immediate clarity on the role that other institutional actors such as banks or insurers might play in mitigating adverse knock-on effects given their collateral interests in commercial and residential property, and resource sectors⁴¹. The perverse effects associated with the introduction of new standards is an area ripe for further research.

The impacts of TSF disasters are wide-ranging, affecting ecosystems, human health, socioeconomic structures and the wider environment around and downstream of mines. Development of industry-wide standards has the potential to reduce the numbers of such failures or, if they do occur, their impacts, but these must be implemented with due consideration to all of their potential socioeconomic impacts.

Table 1 | Remediation, responses and residual hazards in river systems impacted by TSF failures

	Transformed systems	Untransformed systems
Typical remediation strategies	Large-scale physical remediation by removal of tailings River channel engineering, often in the absence of hydraulic design criteria Seeding and tree planting, phytoremediation	Limited or no physical remediation Water management strategies used to dilute dissolved metal(loid) and cyanide concentrations, aiming to reduce risk to ecosystem and human health
Primary (short-term) responses and impacts	Rapid channel adjustments, driven by flood events, especially proximal to TSF River bank and bed erosion leads to channel widening and bed incision	No physical channel alteration Spatial concentration of dissolved metals, metalloids and compounds (cyanide) declines in response to aqueous dilution Aquatic fauna deaths
Secondary (medium-term) responses and impacts	At more distal sites, rapid in-channel and overbank sedimentation occurs, driven by high rates of sediment supply from upstream (derived from upstream channel expansion and surface runoff from stripped floodplain surfaces) Fine-grained sediments are often contaminated and can impact in-channel, riparian zone and floodplain ecosystem health	Recovery of fish stocks via migration from unimpacted tributaries and other refugia
Tertiary (long-term) responses and impacts	Catchment-wide stabilization of channels by vegetation growth and greater hydromorphic stability	Typically long-term responses and impacts are limited
Residual hazard	Floods remobilizing contaminated channel and floodplain sediments and dispersing them downstream	Metal and metalloid accumulation in aquatic fauna, and potential genetic damage, caused by acute and chronic exposure to contaminated TSF supernatant
Case study examples	Aznalcóllar, Spain (1998) ⁸⁰ Mount Polley, Canada (2014) ^{19,83} Fundão, Brazil (2015) ²¹	Baie Mare, Romania (2000) ⁷⁷ Novaț Roșu, Romania (2000) ⁷⁸ Akja, Hungary (2010) ¹¹⁰

Summary of typical remediation strategies, temporal and spatial responses, and residual hazards in river systems impacted by TSF failures. The responses and impacts are related to the catchment and river systems after the initial remediation efforts. TSF, tailings storage facility.

Recovery after disasters

A variety of natural, engineering and management approaches can be applied to aid environmental, ecosystem and socioeconomic recovery of affected catchments following TSF disasters. This section explores these approaches and discusses their outcomes, benefits and limitations.

Environmental recovery

The long-term environmental impacts of historical metal mining are well documented⁶⁶ compared to relatively few data on the recovery periods of river systems impacted by TSF failures. However, recovery from TSF failures tends to be in the order of decades to centuries. The responses to TSF failures disasters varies greatly worldwide depending on environmental regulations and funding available, as well as the type of river and catchment affected and the regional population density.

In some cases, no remediation was undertaken (Table 1) and the river system recovered naturally by dilution of contaminated waters and sediments from uncontaminated tributaries (for example, Baia Mare, Romania, January 2000 (ref. 77) and Novaț-Roșu, Romania, March 2000 (ref. 78)), although sediment associated contaminant element concentrations remained elevated above EU environmental threshold levels for over 3 years after the disaster⁷⁸.

In other cases, especially where extensive areas of the valley floor were covered with tailings layers from centimetres to metres thick, environmental restoration was undertaken to aid the recovery (Table 1). After the Aznalcóllar failure in 1998, Spain, the spilled tailings were largely removed from the rivers and floodplains⁸⁰. River channels and valley floors were entirely terraformed and re-engineered following the 2014 Mount Polley failure, Canada¹⁹ and affected river

systems were chemically treated after the 2010 Akja, Hungary failure¹¹⁰. Restoration operations such as these are costly, generally take between 1 and 5 years to implement and are often not completely effective in removing all the tailings from the catchment or achieving full system recovery. In addition, river channel and floodplain engineering can cause inadvertent secondary remobilization of contaminated sediment in river systems previously affected by historical metal mining¹²⁶, which must be taken into account when planning and carrying out remediation efforts.

Example remediation efforts following TSF failures

The TSF failures of Aznalcóllar, Spain, 1998, and Novaț-Roșu, Romania, 2000, represent end members of a continuum of the degree of transformation experienced by river catchments following TSF disasters. Aznalcóllar had a major physical remediation effort and transformation, whereas no physical remediation took place after Novaț-Roșu.

On 25 April 1998, TSF failure at Aznalcóllar released 5 million m³ of pH 2 water and 1.3 million m³ of As-bearing, Cu-bearing, Pb-bearing and Zn-bearing, pyrite-dominated tailings that formed a layer up to 4.0 m thick covering the riverbed and floodplain. Remediation operations were extensive, involving removal of 90–95% of tailings and approximately 4.7 million m³ of contaminated sediment, and riparian vegetation from the affected channel, floodplain and river terraces between April and December 1998. A second phase of remediation involving removal of an additional 1 million m³ of sediment took place in the summer of 1999 (ref. 127). This activity destabilized the channel and floodplain, resulting in erosion in the reaches nearest the failed dam wall and sedimentation in the downstream part of the catchment following 13 flood events between 1999 and 2002 (ref. 128). The Guadamar river basin was thus completely transformed by the TSF

Glossary

Ash The powdery inorganic waste material remaining after the combustion of mineral materials.	materials of the mined resource have been extracted; they can contain potentially toxic, corrosive and radioactive components.
Best available practice (BAP). Best available practices for tailings storage facilities, which include monitoring of physical mechanisms and human factors that could result in tailings storage facility failures.	Tailings dams TSF barriers constructed to hold back the tailings; it is the part of the TSF that has the highest tendency to fail.
Global Industry Standard on Tailings Management (GISTM). The global standard developed by the United Nations Environment Programme (UNEP), International Council on Mining and Metals (ICMM) and Principles for Responsible Investment (PRI) in 2020 that requires operators to be responsible for, and prioritize the safety of, TSF throughout its life cycle.	Tailings storage facility (TSF). Engineered facility designed to contain tailings; it can be an open pit, a dammed impoundment or an underground void.
Slags The glassy siliceous waste materials remaining after the smelting of metal ores.	TSF disasters TSF failures that cause severe impacts and result in serious disruption to social, environmental and economic systems.
Tailings Finely crushed rock and processing fluids left over after the economic	TSF failures Failures of the dam or other part of the storage facility designed to hold back the tailings in the TSF.
	Waste rock Mined rock that does not contain ore minerals at sufficient grades to be economic and does not undergo mineral processing.

disaster and related clean-up operations^{80,128,129}. Despite this, the area has naturally revegetated and is now designated as the Corredor Verde del Guadiamar (Guadiamar Green Corridor) (Fig. 5a), even though substantial amounts of historically contaminated sediments remain in the floodplain¹²⁸.

The failure of the Aurul tailings dam at Baia Mare in Romania on 30 January 2000 caused 100,000 m³ of cyanide and metal-contaminated water and sediment to be discharged into the Lapuș and Someș rivers. Only 6 weeks later, the failure of the Novaț-Roșu dam in the Baia Borșa area on 10 March 2000 caused 100,000 m³ of contaminated water and 40,000 tonnes of solid waste to be discharged into the Vaser and Vișeu rivers^{77,78}. Both failures occurred owing to high runoff caused by intense rainfall and snowmelt. Because mine waste from the TSF failures formed a small proportion of the total river sediment load during these flood events, they did not affect the river channel and floodplain morphology, except near the dams⁷⁷. However, the contaminated water passed through the catchments within a few weeks and was replaced with uncontaminated water whose concentrations fell below recommended guidelines for drinking water abstraction⁷⁷. No physical remediation was undertaken in the catchment, but some water management was conducted to reduce aqueous cyanide concentrations. The 2000 Novaț-Roșu, Romania, TSF failure led to the development of

the International Cyanide Management Code to improve management of cyanide at gold mines¹³⁰. Like the Guadiamar, however, the Romanian Lapuș-Someș and Vaser-Vișeu catchments have large amounts of legacy contamination in their floodplain sediments⁷⁸.

Ecosystem recovery

Often, efforts to quantify ecosystem recovery focus specifically on particular environments or types of organisms, such as bacteria, freshwater and estuarine fish, reptiles and trees. A whole ecosystem approach focusing on restoring habitats for all indigenous organisms has been adopted for some affected areas (for example, Mount Polley, Canada, 2014 (ref. 131)), but very few failure-affected catchments have background data on original ecosystems, making evaluation of the after-effects and the development of appropriate recovery schemes challenging.

Restoration schemes for ecosystems include engineering new habitats¹³¹, introducing animal refuges¹³², adding fertilizers and pH controls to soils¹³³, seeding with indigenous plants, and planting tree saplings^{131,133,134}. Revegetation is often the first activity to be attempted to stabilize deposited tailings and provide territory for fauna. Active reforestation following the 2014 Mount Polley, Canada¹³⁵, and 2015 Fundão, Brazil^{133,136}, TSF disasters promoted better seedling growth and floral and microbial diversity than natural regeneration. Moreover, the addition of small amounts of topsoil from unaffected native ecosystems can aid the recovery of soil microbes and improve seedling survival and growth¹³⁵.

Ecosystem recovery after TSF failures takes years to decades¹³⁴. Long-term monitoring of organism and vegetation health and change is required to quantify and promote recovery. TSF failures often occur in catchments affected by other anthropogenic disturbances, including sewage and other contaminant inputs, deforestation, and urbanization. It is important that efforts are made to understand the relative effects of all these human impacts on ecosystem recovery⁹⁶.

Socioeconomic recovery

Disasters are characterized by systems disruption and an inability of those systems to respond and recover^{28,29}. The first responders after a TSF failure are usually neighbours and local people^{137–139}. Where it is available, outside response can involve emergency rescue to save lives, protect key infrastructure and supply humanitarian aid. Disaster recovery can extend over years and decades whereas the rebuilding of homes and other infrastructure, securing replacement land, compensating for loss and damage, and reinstating critical services and infrastructure, such as water, health, and sanitation are resolved between disaster victims, mining companies and the state.

Following a TSF disaster, an important determinant of socioeconomic recovery is the impact on underlying institutional systems that individuals and organizations draw upon for provisioning and support¹⁴⁰, which serve as the necessary “scaffolding for economic growth and well-being”¹⁴⁰. Poor disaster recovery outcomes are often largely a result of the systems themselves failing to uphold standards that recognize the rights of displaced people¹⁴¹. Criticism extends to financiers, governments and project proponents, especially when sub-standard mitigations lead to impoverishment manifested by landlessness, joblessness, ill health, marginalization, social fragmentation, food insecurity, homelessness and reduced access to education¹⁴². Poor outcomes are attributed to both a lack of planning and an unwillingness to allocate sufficient capital to avoid disaster and remediate losses and their effect on social systems^{40,143}. Financial compensation, replacement land, and support services are the principal means advocated

to mitigate adverse impacts, despite recognition as being relatively ineffective¹⁴⁴ and the potential risk of leakage through corruption or mismanagement¹⁴⁵.

Before the 2015 Samarco and 2019 Brumadinho, Brazil, disasters, socioeconomic recovery in the aftermath of a TSF disaster had not been well documented. However, these two failures have illustrated how victims become deeply entangled in the politics of recovery and cumbersome bureaucratic arrangements that failed to deliver timely remedy¹¹⁷. Following these events, the impacts of local activism and its influence on recovery outcomes¹⁴⁶; the role of governance, law enforcement, and social context¹⁴⁷; access to information and community participation¹⁴⁸; and prospects for alternative livelihoods in the post-disaster landscape¹⁴⁷ have been explored in more detail. The main insights from this research indicate that disaster preparedness is weak across all actors, that disaster conditions emerge as a product of cumulative decisions made over decades that enables the final crisis, and that legal accountability is an extremely difficult objective to reach¹⁴⁹.

Overall, environmental, ecosystem and socioeconomy recovery after TSF failures and disasters depends on remediation and interventions that are sensitive to local environments and ecosystems, as well as appropriate and collaborative disaster preparedness.

Trends and mitigation of future disasters

This section outlines factors that can contribute to future TSF disasters and explores measures that can aid prevention or mitigation of consequences. The role of disaster management concepts, policies and circular economy strategies are also discussed.

Future trends in TSF failures

Climate change and its impact on extreme hydrological events tend to represent one of the principal controls on TSF stability worldwide in the future. Comparing the global distribution of intact and failed TSFs⁵ with maps of present Köppen–Geiger climate zones¹³⁶ (Fig. 6Aa) highlights that the majority of TSFs (54%) are in cold and arid regions (Fig. 6Aa) and 76% are located in areas with less than 100 mm precipitation per month. This climatic distribution raises two areas of concern. First, TSFs located in frozen or permafrost regions could become increasingly vulnerable to failure owing to permafrost thaw¹⁵⁰ and changes in the frequency of freeze-thaw cycles¹⁵¹. The increased likelihood of temperature-driven structural TSF failure should not be underestimated, especially because mine infrastructure was traditionally designed assuming climatic stability¹⁵⁰. Second, wind remobilization of tailings in TSFs might become an increasing human health problem owing to the increased risk of inhalation and bioaccumulation of contaminated dust in lung tissue¹⁰².

Under future climate change scenarios, the number of TSFs in arid and cold regions, or in areas with low to medium annual precipitation (<2,000 mm), is not predicted to increase (Fig. 6B). However, the number of TSFs located in many temperate (up to 124%) and tropical savannah (177%) zones will rise, and these tend to be exposed to higher rainfall (>2,000 mm yr⁻¹). Given that precipitation (both amount and intensity) is an important factor in many TSF failures (black dashed line, Fig. 6Ba), it is expected that changes in precipitation distribution by 2050 (Fig. 6Bb) will place a higher number of early twenty-first century intact TSFs at risk of failure, especially given that many are built on the sites of previously failed structures⁹.

Seismicity is another factor leading to many TSF failures. For economic and logistical reasons, TSFs are generally located at, or nearby, mine sites, as a result there is generally limited opportunity to deliberately locate TSFs in seismically stable zones. Globally, 63% of

TSFs are located in regions of low seismic hazard, but 13% are sited in areas classified as ‘high’ or ‘very high’ hazard (Fig. 6C); this raises serious management concerns given that TSF failure rates systematically rise as seismic hazard increases (Fig. 6Ca, black dashed line).

The cumulative effects of climate change, principally the predicted precipitation increases in some metal mining areas (for example, western parts of North and South America, China, India and sub-Saharan Africa), coupled with the likelihood that metal demand will drive expansion of mine processing and waste storage operations into more seismically unstable areas, will inevitably compromise the stability of many TSFs around the world.

Mitigating and preventing future disasters

Most TSF failures are owing to deviations from the BAP and not because understanding of these structures is insufficient to ensure their stability^{24,6}. Cost cutting measures and production pressures can prompt deviation from BAP^{33,50,152}. It is also possible that deviations from BAP occur because BAP is perceived to be overly restrictive. Deviation from BAP does not always result in catastrophic failure, and when it does, the failure might only occur many years after the deviation^{44,45,55}. This makes it more difficult to appreciate the deviation-consequence link. This process by which deviations from BAP come to be accepted has been termed normalization of deviance^{51,153}.

The elimination of catastrophic TSF failures requires not only adoption of BAP, but also a step-change in technology⁴⁵; that is, adoption of tailings disposal technologies whose safety is less vulnerable to deviations from BAP. This was stated in a report on the failure of the Mount Polley Tailings Dam in Canada: “Simply put, dam failures are reduced by reducing the number of dams that can fail”⁴⁵. A large number of technologies have been proposed to better manage tailings¹⁵⁴, but the most mature of these at the moment are the filtering of tailings to substantially reduce their water content (also known as dry-stacking) and underground storage⁴⁵. However, adoption of both technologies remains limited². Despite the mechanical advantages of filtered tailings it must be recognized that there are important reasons why they might not be the best tailings storage solution under certain scenarios. In particular, the mineralogy of the tailings can be such that the filtration process yields inconsistent results¹⁵⁵ and the potential for acid and metalliferous drainage generation could be increased¹⁵⁶. Furthermore, because of the reduced water content of the filtered tailings, dust suppression measures in these facilities are important considerations¹⁵⁷.

A further innovation is to extend the BAP frame of reference by incorporating disaster management concepts and frameworks, as discussed in this Review. This would result in the engineered structure being analysed in a broader political, institutional, geographical, and social context, including locations where human exposure and vulnerability are most severe. TSF disasters, although important, are only one of several ways that mining can impact on river catchments. To better understand the potential detrimental effects of TSF failures, two approaches could be embedded within BAP protocols. First, ground-based and satellite-based observation systems can be used to monitor TSF stability and identify precursors (for example, construction practices¹⁵⁸, land deformation¹⁵⁹, seismic noise¹⁶⁰) that could substantially increase the likelihood of failure. These dataset types, and others, have already been integrated into DAMSAT¹⁶¹, a web-based system that merges Earth observation and other data to help governments and mining companies monitor TSFs, and estimate the downstream risks they pose. Second, process-based modelling and mapping tools

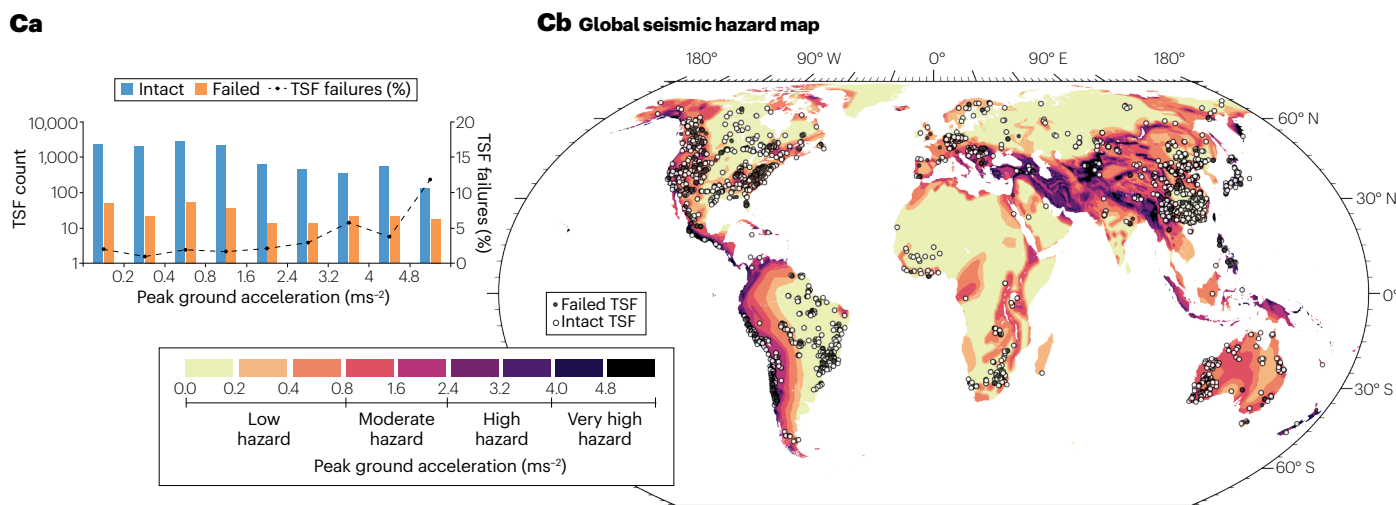
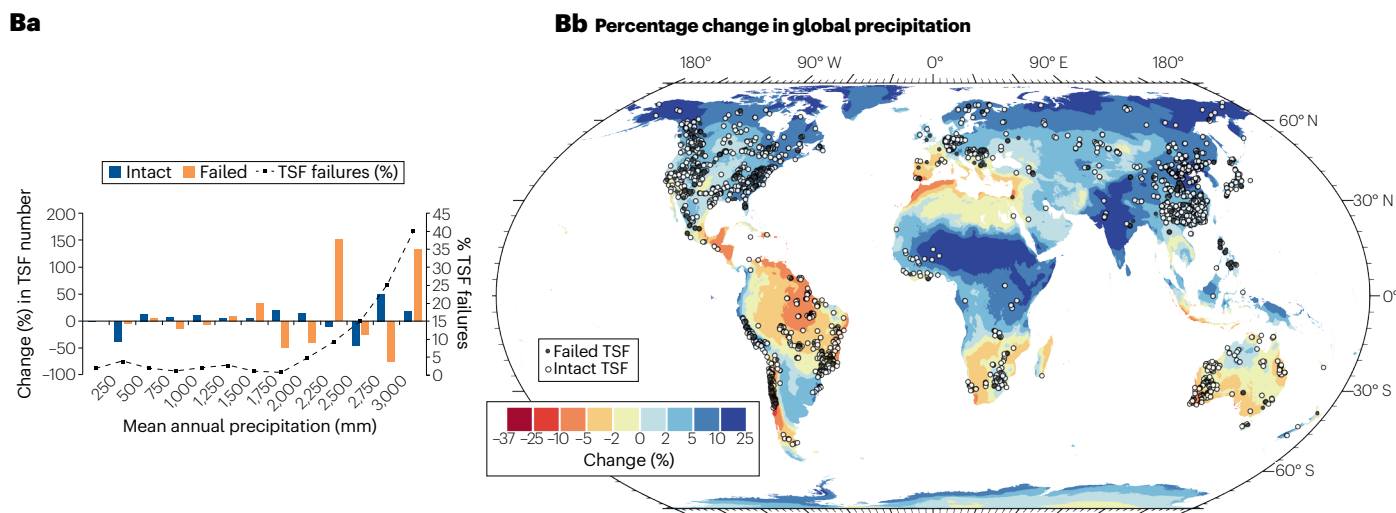
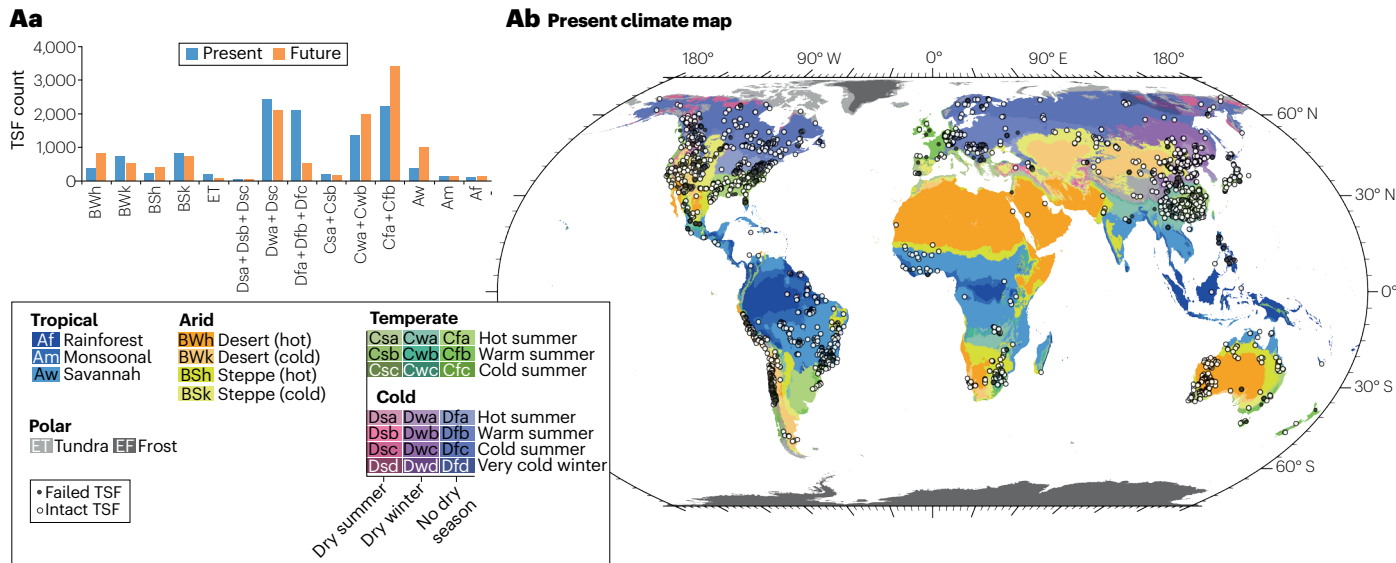


Fig. 6 | Distribution and frequency of TSFs and TSF failures. **Aa**, The number of early twenty-first century intact TSFs in various Köppen–Geiger climate zones compared with the predicted number in the future (2071–2100)⁵. **Ab**, The distribution of TSF failures and intact TSFs in Köppen–Geiger climate classification climate zones¹³⁶. **Ba**, The number of early twenty-first century intact and failed TSFs plotted against mean annual precipitation⁵. **Bb**, The distribution of TSF failures and intact TSFs superimposed on the predicted

percentage change in global precipitation (by 2050)¹⁸⁴. **Ca**, The number of early twenty-first century intact and failed TSFs plotted against peak ground acceleration. **Cb**, The distribution of TSF failures and intact TSFs compared with global seismic activity¹⁸⁵. The stability of many TSFs around the world will be compromised by climate change-related increases in precipitation in some areas and expansion of mining into seismically unstable areas.

can be used to assess the distance downriver that particulate waste tends to be dispersed from a disused, active or planned mine^{9,162}, and the risk that released contaminants might pose to ecosystem and human health⁵. Mapping and modelling assessments can be undertaken anywhere in the world from local to national scales, and ground-truth data can be provided on population and livestock at risk, the impact on biodiversity and habitats, and how changing hydroclimates tend to affect the environmental footprints of future mining. This will inform decision-makers and managers in the mining industry, environmental regulatory authorities, local and national governments and project affected people.

Future policy and standards

Efforts to formulate policy and standards have progressed, for example, through the GISTM. At the time of writing this Review, this instrument was without an implementing body or enforcement regime; however, the multi-stakeholder process through which it was forged has opened a space for debating what ‘should’ be done to avoid disastrous TSF failures. This exercise has elevated the topic in industry circles through a deliberate focus on facility-level activities and interactions¹⁶³ between tailings specialists and other scientific domains. These interactions have continued post-publication of the GISTM, with innovations in waste reduction moving to the forefront of research and debate¹. Another important outcome is the explicit emphasis placed on the actual TSF rather than the corporation that reports on its status. A running critique of global policy initiatives relates to their reliance on self-reporting by corporate entities without third-party verification.

The GISTM is a voluntary initiative. Embedding norms into a voluntary standard means that the ability of government and community actors to prevent or respond to disaster will be limited if companies do not participate. Although members of the International Council on Mining and Metals (ICMM) have publicly indicated their intent to align their reporting practices with GISTM, this does not provide a legislative basis for compliance or for victims seeking to secure reparations for loss and damage in the aftermath of a disaster¹⁴⁷. Codifying global policy norms in national legislation provides greater scope for justice in both the general accountability for facility design, and management in the case of failure. In the current system, affected people and victims are forced into the accountability sphere through the non-action or weakness of other agents. The part played by other influential actors in setting design criteria, regulatory provisions, or as beneficial owners, should be reflected in future governance regimes.

Prioritizing evidence in the development of social and environmental protections and safeguards would be beneficial in tailings design, operational management, closure, community consultation, early warning systems, emergency response, and public disclosure. Such evidence-based approaches would require a far higher level of investment in research and human rights due diligence than can be seen in the present day.

Circular economy could reduce TSF impacts

Circular Economy describes the technical, environmental and economic systems aimed at eliminating waste and pollution through maximization of resource use and reuse, remanufacturing and recycling. There has been an increasing body of work on circular economy strategies for mining, with an emphasis that a combination of circular economy processes is necessary to systemically manage waste streams via reduction, reprocessing, upcycling, downcycling, and stockpiling and disposal^{164,165}. In the context of avoiding TSF failures, reducing waste volume is paramount, especially when located near human settlement areas and ecologically sensitive regions.

There has been a wide variety of attempts to repurpose mine tailings with mixed success^{164,165}. Given the properties of the tailings and economic barriers, tailings repurposing has included use as supplementary cementitious materials¹⁶⁶, geopolymers¹⁶⁷, ceramics^{168,169}, aggregate¹⁷⁰ and carbon capture and storage^{164,171}. Tailings, however, are rarely fit for other purposes and the public is understandably cautious about using the discards of the mining industry as products. An alternative approach is the production of by-products through the addition of mineral processing to generate clean and purposeful products and reduce the volume of tailings production in the first instance. Examples of this approach include ore-sand^{120,172,173} and high-purity silica¹⁷⁴.

In all cases, the feasibility of implementing circular practices to reduce impacts posed by tailings is context specific¹⁷⁵. For the bulk usage of materials in construction applications, these materials need to be close to the market in which they will be used. Such cases also represent locations where TSFs can present elevated risks owing to their closer proximity to local communities and infrastructure. For settings that are distal to markets, the value (social, environmental and economic) gained from using bulk materials can be markedly reduced as a result of the cost and risks associated with bulk material transport. For best waste reduction, minimization of waste at the point of production is key: either through additional mineral processing stages to capture products from what otherwise would report to tailings or through more targeted metal–material extraction such as through the application of ‘keyhole’ techniques¹⁷⁶.

Preventing and mitigating the consequences of future TSF disasters is an interdisciplinary task. The range of activities include gathering more information on the location, characteristics and surroundings of TSFs, the adoption of construction methods that are more robust in geotechnical terms and the development of circular economy and waste reduction strategies.

Summary and future perspectives

All TSF failures are serious events. These events can become disasters when they cause severe disruption to the functioning of ecological and social systems²⁹. The mining industry has been hesitant to use the term ‘disaster’, presumably to avoid the associated liability²⁸. This Review has used the term ‘disaster’ as a conceptual lever for understanding human exposure and vulnerability to tailings failures, including risks

to health, housing, and livelihoods. There is potential to augment the analytical scope of tailings management by drawing on, and aligning with, disciplines that help to provoke questions about how and why disaster risk forms, and TSF fail. The challenge for researchers is to support the analysis of the underlying structural and systemic aspects of disaster risk, without threatening corporate sensibilities or their support to study these events and facilities.

At the mine site scale, the major issues surrounding TSF safety relate to the volumes of tailings that need management and the structure, engineering and monitoring of the TSF. Collaborative, industry-engaged research could explore new economic and financial models to drive circular economy principles into tailings management. Life cycle assessment should be linked with tailings engineering to support integrated research that considers climate change-related changes in intense rainfall or snowmelt, flooding and contaminated dust dispersal by stronger winds. Finding alternative ways to produce and store tailings with less water also has potential for reducing, or even eliminating, the risk of TSF failure at the mine site level.

At the catchment and landscape scale, TSF disasters have had devastating consequences for people, ecosystems and place. Entire river systems have experienced major disruption from both chronic and acute tailings-related incidents, and many ecosystems worldwide are consequently in need of remediation and new management practices. Moving forward, research on a far broader spectrum of impact mitigation strategies should be undertaken to inform practice and develop more holistic guidelines for recovery at the landscape level. Future guidance would need to be underpinned by principles of transparency and broad-based public participation, recognizing that harm from poor tailings management can show up in both catastrophic and chronic ways. The GISTM aims to prevent sudden TSF failure, whereas attention should also be paid to ‘slow motion’ disasters, including the chronic impacts of mine contamination on the world’s river systems⁵.

Multi-scalar, inter-disciplinary systems of governance are required to mitigate the effects of TSF failures, learn lessons, and use that knowledge to prevent future occurrences. To date, little research has been conducted on post-disaster response and recovery. Future research should build on attempts to link tailings facility locations to situated risk factors, including political stability, levels of corruption, freedom of the press and climate change. Improving spatial and time series analysis could reduce reliance on corporate disclosures and improve visibility of priority locations and patterns of concern⁴¹. Ethnographic case studies and qualitative research remain important for understanding the lived experience and local understandings of mining impacts and the imposition of tailings-related risk.

Prevention of TSF failures is an interdisciplinary field of policy and practice. Specialists in engineering, business, economics, politics and the physical, social and health sciences are needed to tackle mining and waste-related issues in new and creative ways. The value and necessity of interdisciplinary approaches becomes evident when TSF fail and whole-of-system responses are required to begin the slow process of recovery. This Review highlights that necessary improvements in TSF safety can be made by identifying problems and possibilities across the disciplinary spectrum in the design, consultation, permitting and operational phases of these facilities. Such an interdisciplinary, multi-stakeholder, approach will help both those involved in TSF safety and people who face tailings-related risk, to adapt to the material demands of the energy transition, shifting geopolitics and climate change.

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