Title: Impacts of metal mining on river systems: a global assessment

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Abstract: This paper quantitatively analyses the global dimensions and environmental impacts of metal mining activity on river systems. A novel geo-referenced global database is presented detailing all known metal mining sites, tailings storage facilities and failures. This is evaluated using process-based and empirically tested modelling to produce a global assessment of mining impacts on river systems and floodplains, human populations and livestock. Our results reveal the serious nature of long-term metal contamination of river environments. Worldwide, metal mines impact 479,200 km of river channels and 164,000 km^2 of floodplains We show that the number of people likely to be exposed to contamination by long term discharge of mining waste into rivers is almost 50 times greater than the number directly impacted by tailings dam failures.

One-Sentence Summary: High levels of river and floodplain metal contamination are revealed across the globe from historical and recent metal mining.

Main Text:

In 2018, mining had a market capital value of almost a trillion US dollars, and $600 billion in revenue *(1)*. It has been estimated that the annual production of solid mine wastes now makes up one third of the sediment budget for the Earth *(2)*, including metal mining *(3)*, and that ~1 million km^2 of the World is covered with mine waste *(4)*. Many of the richest geological deposits are being or have already been exploited, and companies are now turning to larger deposits with lower-grade ores. Such deposits generate more mine waste per unit extracted and the mine waste–related damage to the Earth's surface is likely to be exacerbated. Some of these wastes contain elements, such as arsenic, lead and mercury, in concentrations that may pose serious hazards to ecosystem and human health. Plants and crops grown on contaminated soils, or irrigated by water contaminated by mine waste, frequently contain high concentrations of metals and metalloids (hereafter referred to as 'metals') *(5)*. Animals grazing on floodplains often eat this plant material and sediment, especially after flooding when fresh metal-rich sediment is deposited *(6)*. This poses risks to their health and that of humans who consume their meat and milk.

Metal mining represents humankinds' earliest and most persistent form of environmental contamination. Waste from mining began to contaminate river systems as early as 7,000 years ago *(7)*. Water was usually involved in extraction and processing of metal ores, resulting in metals (dissolved and sediment-associated) being supplied to streams and rivers, dispersed downstream, and then deposited across floodplains often used for agricultural food production. Since the mid-nineteenth century, tailings dams have been used to store mine waste which has reduced direct supply into rivers, however, such structures are prone to failure with often severe consequences for ecosystems and human communities downstream *(8)*.

Here we bring together, for the first time, all spatial data that can at present be obtained globally on metal mines and tailings dams (historical and recent), including those that have failed; and we calculate the area of floodplains, and the number of humans and livestock affected. Path-making research undertaken by us (*9*, *10*) and others *(11)* over the last 40 years has demonstrated the role of dispersal *(12)*, storage *(13-15)* and remobilization *(16)* processes in the environmental fate of metals within rivers affected by metal mining, including those impacted by long term mining activities as well as those contaminated by sudden tailings dam failures. These studies have shown that more than 90% of metals are sediment associated, are typically transported 10-100 km downstream from the point where mining operations discharge into a watercourse, and are deposited and stored along river channels and especially on floodplains for extended (10^2-10^4 years) time periods *(10, 17)*. In the first industrial nations of Western Europe (notably the UK), and the USA, flood-related remobilization of contaminated floodplain sediment, resulting from historical mining during the 19th and early 20th century *(11, 13, 16)*, now constitutes the primary source of metal and metalloid contaminants in rivers. Small catchments (<500 km^2) can be extremely contaminated, but the larger rivers into which they feed tend to have significantly lower contamination levels because metal mine waste is diluted by uncontaminated sediment from non-mining sources *(18)*.

Methodology: Data on recent (defined in database sources at the time of publication as still in operation) and historical (defined in database sources as closed) metal mines worldwide, including their location, mineral commodities/mine type, and their operational status, were compiled into the Lincoln Centre for Water and Planetary Health (LCWPH) global metal mines database. Mine information was acquired from the United States Geological Survey Mineral Resources Data System (MRDS) (*19*) (73,917 mines worldwide), the BritPits database of the British Geological Survey (*20*) (8,459 mines in the United Kingdom), the S&P Global Market Intelligence database (*21*) (2,584 mines worldwide), and our own compilation of c. 100,000 additional mines from the worldwide academic and grey literature, including regional data published by government agencies and industry (tables S1-S2). Twenty-one types of recent and historical metal and metalloid mines were used in our modelling and analysis (tables S3a-S3b). We also compiled a georeferenced global database of metal mining tailings storage facilities and tailings dam failures based on the ICOLD/UNEP 2001 compilation (Bulletin 121) (*22*), the World Information Service on Energy (*23*), the World Mine Tailings Failures and Global Tailings Portal databases (*24*), in conjunction with our own compilation of source literature published by government and non-government organizations (tables S4-S5).

Together these spatial data represent, to our knowledge, the most comprehensive compilation of metal mine locations to date. We identified catchments affected by recent and historical metal mining by overlaying all mines, tailings storage facilities and tailings dam failures onto level 4 polygons of the HydroBASINS modelling framework (*25*). These depict watershed boundaries and sub-basin delineations at 15 arc second resolution across the globe. Within all sub-basins we estimated the length of river channel (km), the floodplain area (km^2) and the 100-year flood inundation area (km^2) downstream of each mine likely to be contaminated, by using a new process-based model of sediment-associated mining contaminant dispersal (figs S1-S12, table S6). This model calculates the extent downstream of a mine where concentrations of metal (Cu c.10.3 km; Pb c. 8.6 km; Zn c. 6.5 km) and As (c. 45.6 km) in river channel and floodplain sediments exceed guideline values for intervention and remediation (table S7). We ground-truthed our results in 15 catchments worldwide, ranging in size from 46 to 232,193 km^2 (tables S8-S11). Where tailings dams have failed and their height and volume of mine waste are known (165 from a total of 257), the length of river channel and area of floodplain affected was calculated (*26*). Using the Socioeconomic Data and Applications Center (NASA-SEDAC) population data of the year 2020 (*27*), and FAO Gridded Livestock of the World database (GLW v3.1) (*28*), the number of people and livestock (cattle, goat, and sheep) living on mining-affected floodplains was determined (tables S12-S13). The area of irrigated land based on FAO Global Map of Irrigation Areas (GMIA) in mining impacted floodplains was also calculated (table S14). Our geospatial integration of metal mine, tailings storage facilities, tailings dam failures, hydrographic, geomorphic, demographic and livestock databases enable us to evaluate globally the likely population exposure and uptake of contaminant metals into the human food chain (table S14).

Results: Worldwide there are 22,609 active and 159,735 abandoned mines, 11,587 tailings storage facilities and a further 257 reported tailings dam failures (Figs 1 and 2). Metal mining has affected some 164,400 km^2 of floodplains (112,400 km^2 from historical mines; 52,000 km^2 from recent mines) and 480,700 km of river channels (historical, 365,200 km; recent, 114,000 km) are affected by metal mining (Fig. 3; Table 1). We estimate that 23.48 M people live on mining-affected floodplains that also support 5.72 M livestock and include 65,600 km^2 of irrigated land (Table 1). Disaggregated on a continental scale, North America (recent 11,871; historical 80,995) and Oceania (recent 3,430; historical 53,233) have the largest number of known mines followed by South America (recent 3,240; historical 14,577), Europe (recent 1,024; historical 9,080), Asia (recent 1,817; historical 1,473), and Africa (recent 1,227; historical 377) (table S1). Oceania, Europe, North America and South America are mostly affected by historical mining, while recent mining activities are considerably more important in Africa and Asia (table S1).

North America stands out as the most impacted region in terms of river length (historical 174,500 km; recent 23,900 km) and surface area of floodplains (historical 36,700 km^2; recent 6,400 km^2) (Table 1). River channels and floodplains are also significantly impacted in Oceania (river length 106,100 km; floodplain 33,800 km^2), South America (81,700 km; 38,600 km^2) and Asia (60,900 km; 33,500 km^2), but to a lesser extend in Europe (14,800 km; 4,900 km^2) and Africa (17,300 km; 10,400 km^2) (Table 1). Asia with 14.53 M people living in affected floodplains is the most vulnerable region in terms of likely human exposure and uptake of contaminant metals into the human food chain, followed by North America (4.09 M), Europe (1.73 M), South America (1.53 M), Africa (1.19 M) and Oceana (0.42 M) (Table 1).

Undertaking the same audit for river catchments in which tailings dams have failed is less straightforward because data on dam height and volume of mine waste stored is only available for 165 out of the 257 recorded failures. Worldwide we calculate using this large but incomplete database that a minimum of 5,300 km of river channels and 4,950 km^2 of floodplains have been affected by TDFs (Table 2). The number of people living on floodplains that have been directly affected by TDFs is substantial (0.32 M) (Table 2), but our modelling indicates that the impact of these events on ecosystem and human health is two or three orders of magnitude smaller than in basins that have experienced historical and/or recent mining activity (Table 2).

Gauged by the number of people living on floodplains affected by upstream mining activity, China (9.74 M) and the USA (3.17 M) are the countries most at risk (tables S12 and S13) but surprisingly South Korea (0.79 M), Germany (0.35 M) and the UK (0.31 M) are ranked globally in the top 12 (supplementary information table S12), with the environmental legacy of historical mining being the most problematic in Western Europe. This significant finding is related to contaminated sediment dynamics and storage in these regions. Countries that by world standards have relatively short rivers (e.g., Chile, Japan, New Zealand, South Korea, UK), and particularly those with low sediment loads (e.g., Germany, UK) have higher levels of river channel and floodplain contamination as a consequence of limited dilution of sediment-associated mine waste *(29)*.

Implications: This global survey of the environmental and human health impacts of metal mining reveals that an estimated 23 M people live on floodplains affected by potentially dangerous concentrations of toxic waste derived from historical and/or recent upstream mining activity. However, because of incomplete reporting of mine locations and tailings dam failures, most notably within the BRICS countries, this is certainly a significant underestimation of the population at risk. In addition, the impacts of modern artisanal mining, in places such as Africa, are also still poorly documented. Human metal uptake can take place through polluted irrigation water *(5)* and through consumption of meat and secondary products from grazing animals *(6, 30)*. Contaminated fish is also known to be a source of metals for humans in mining-affected catchments *(31)*. But global data with sufficient granularity are not presently available to quantify these potential risks, export of food produced in these locations will undoubtedly enter a much wider human food-chain.

Ecological and societal impacts of recent tailings dam failures are locally catastrophic and have resulted in significant loss of life (*32*). However, our assessment indicates that the number of people likely to be exposed to unacceptably high concentrations of toxic metals by these accidents (estimated to be more than 0.32 M) people is almost 50 times smaller than in river floodplains affected by historical (11.39 M) and recent (12.08 M) metal mining. River contamination from metal mines is a significantly under-reported global problem that requires urgent mapping, remediation and management. Our new georeferenced database and process-based predictive modelling provide tools for locating areas of highest exposure where intervention should be prioritized, and further highlights catchments where new data are required. We conclude that metal mining contamination of rivers and floodplains poses a significant additional health risk to both urban and rural communities in Africa and Asia that are already burdened with water-related diseases. For the first industrial nations of Western Europe and the USA, this contamination constitutes a major and growing constraint to water and food security, compromises ecosystem services *(33)*, and increases antimicrobial resistance in the environment *(34)*. Increasing frequency of river flooding associated with anthropogenic global climate warming *(35)* will result in increased erosion and sediment-associated metal remobilization from recently and historically contaminated floodplains *(6)*, that now in many parts of the world constitute the principal source of metal contaminants in rivers. In addition, expansion of lower grade metal ore mining which generates more waste per unit extracted, coupled with the frequency of catastrophic tailings dam failures which appears to be on an upward trend (*36*), underlines the urgent need to routinely incorporate outputs from large-scale mining databases as reported here, to better manage metal contamination and risk of exposure downstream of historically and recently active metal mine sites.

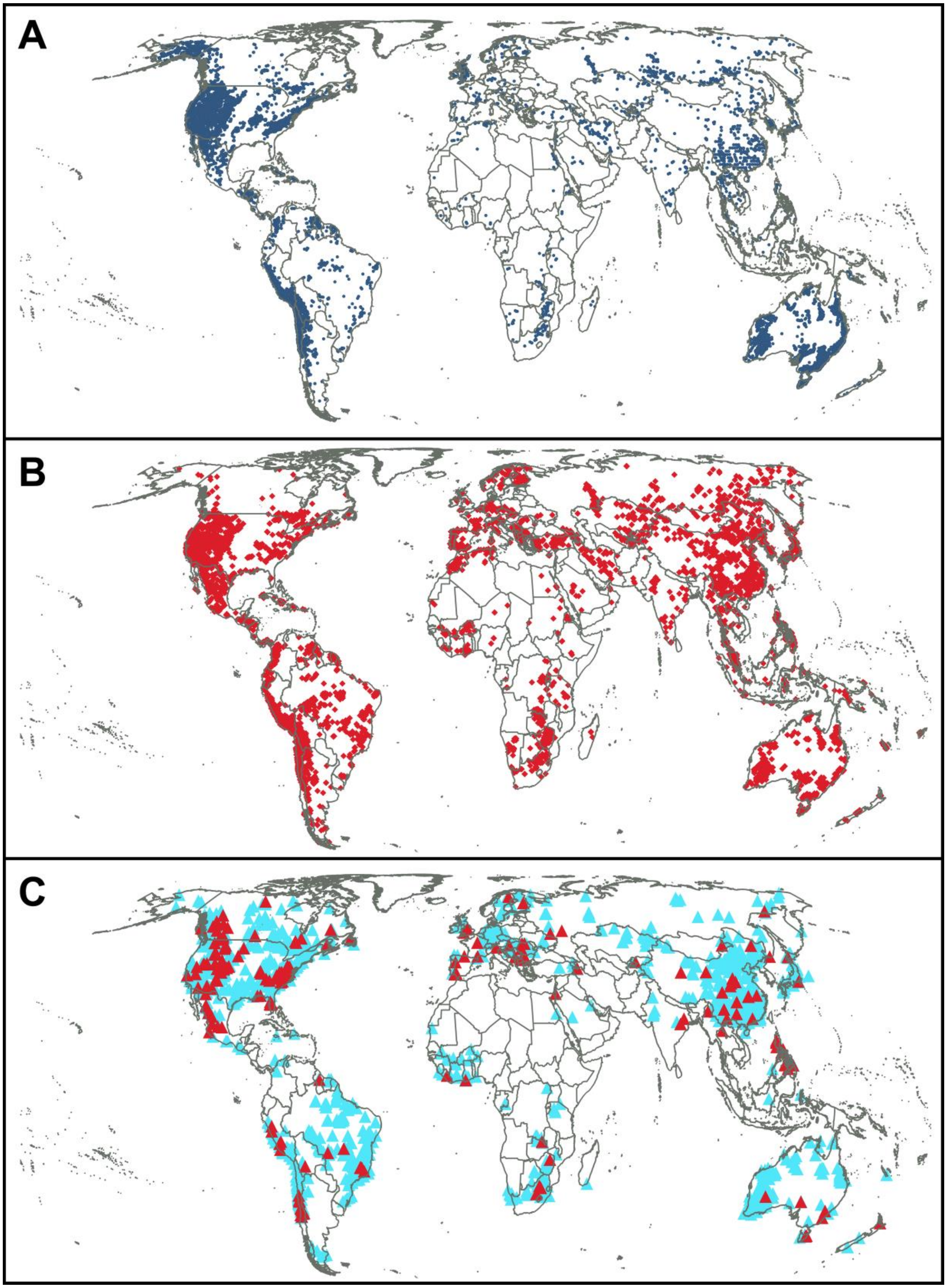

Fig 1. Global distribution of a) historical metal mines, b) recent metal mines and c) tailing storage facilities (blue triangles intact, red triangles failed). Mollweide global projection.

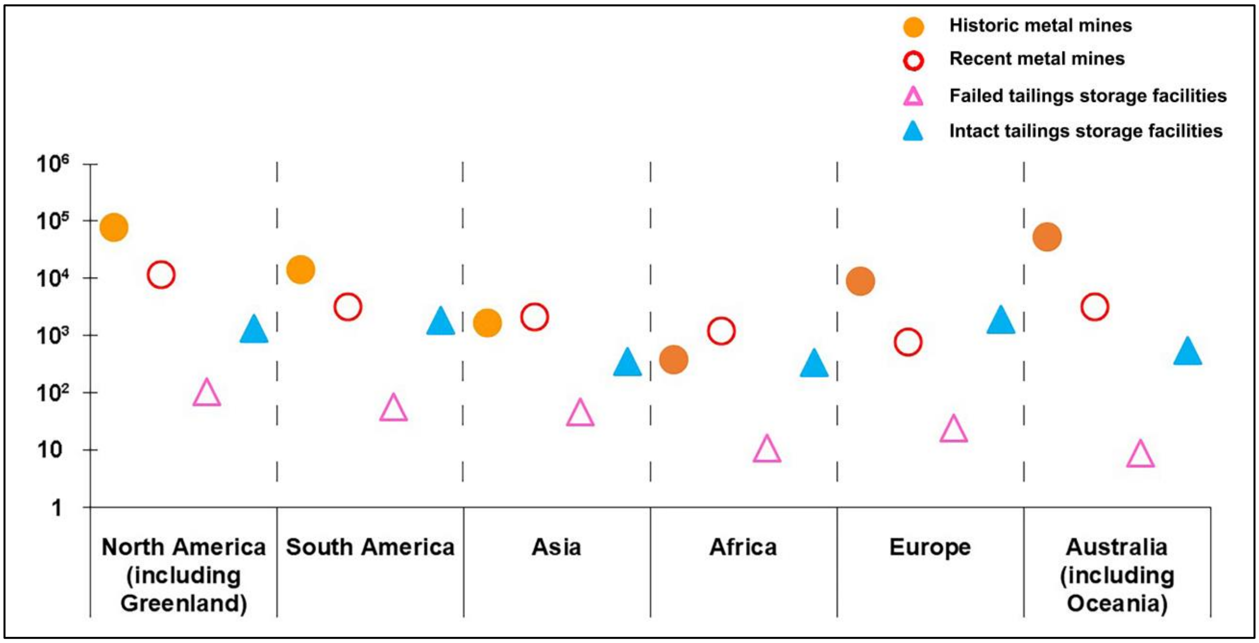

Fig 2. Metal mines (182,344) and tailings storage facilities (TSF) and failures worldwide (11,587 TSF and 257 failures). Y-axis units are Log_{10} number of mines and TSF.

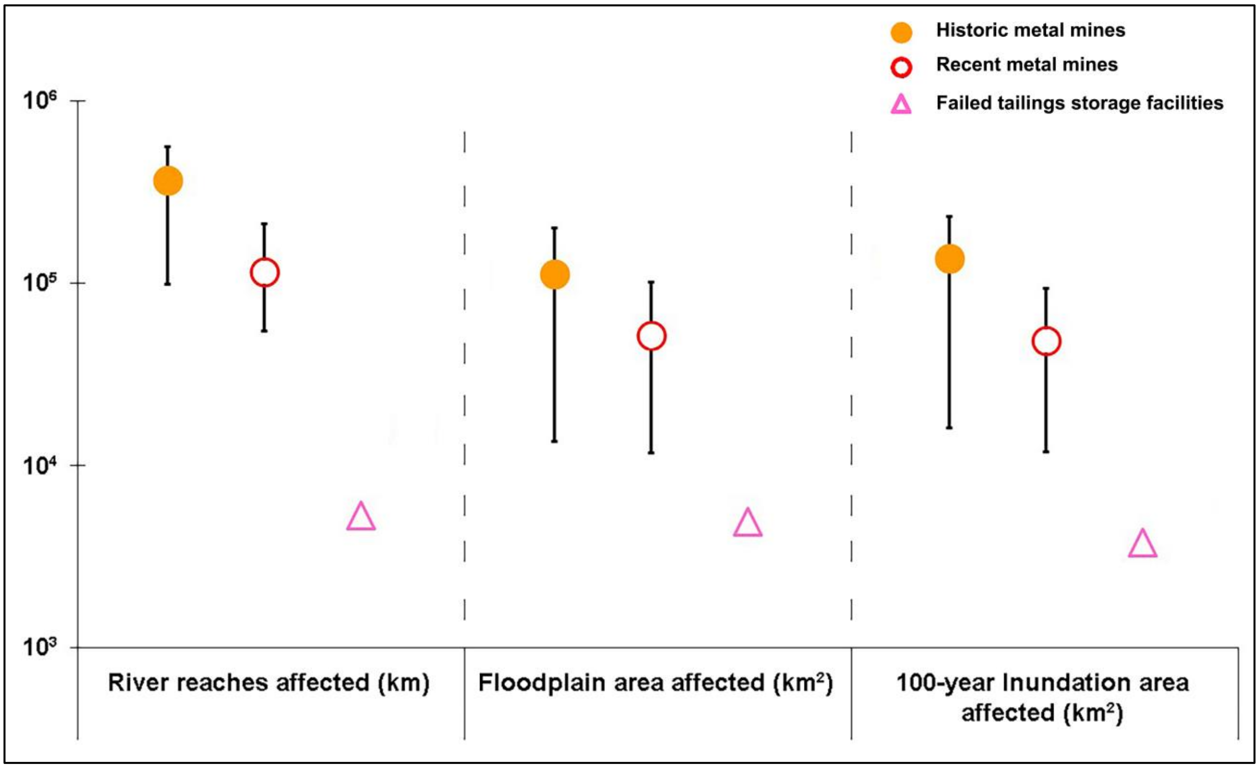

Fig 3. River length, floodplain and 100-year flood inundation area affected by metal mines and tailings storage facilities. Symbols indicate predicted values from the LCWPH model with 90% confidence intervals; symbols for failed tailing storage facilities are observed values. Y-axis units are Log_{10} number.

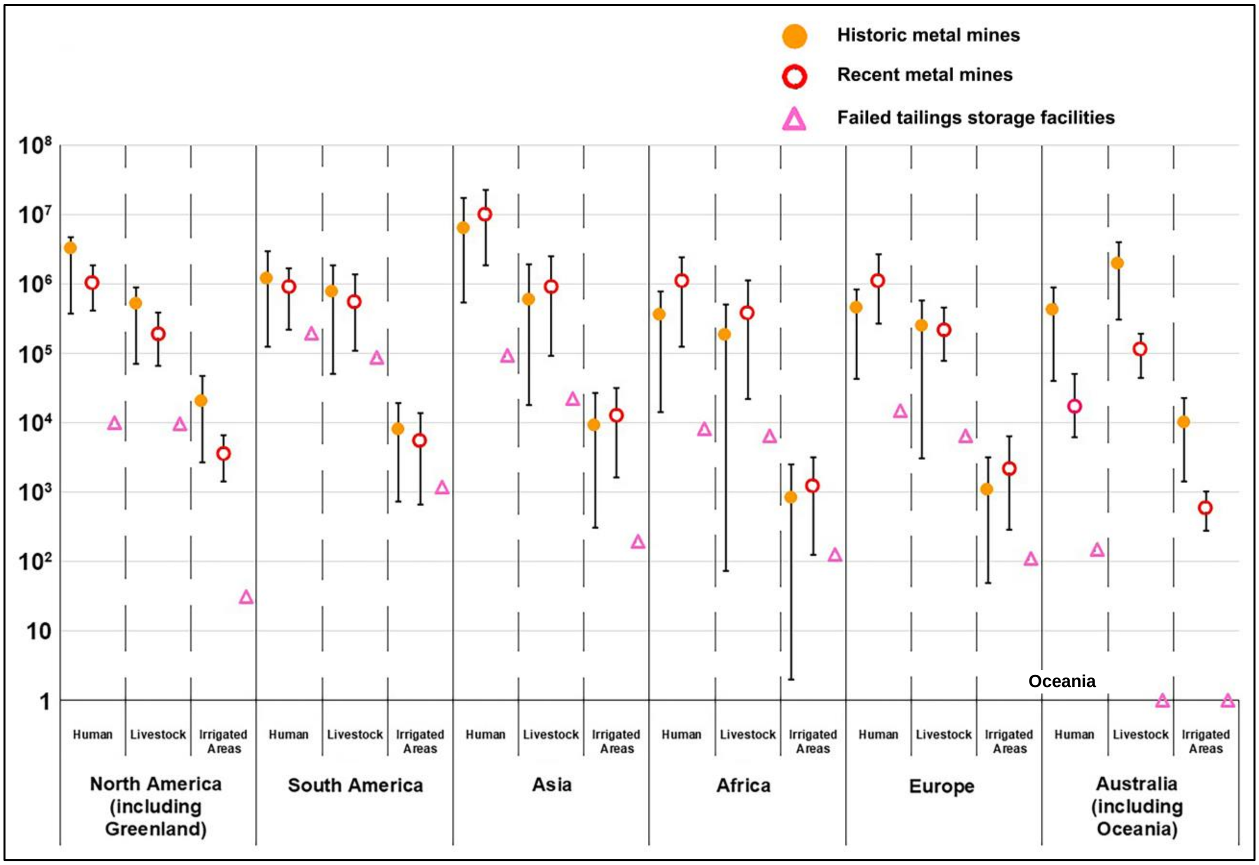

Fig 4. Human population, livestock (cattle, goat, sheep) and irrigated areas within metal mining affected floodplains and floodplains affected by tailings storage facilities failures. Symbols for mines indicate predicted values from the LCWPH model with 90% confidence intervals; symbols for failed tailing storage facilities are observed values. Y-axis units are Log_{10} number.

Table 1. Global assessment of hazard from metal mining contamination on river systems. Number of historical (H) and recent (R) metal mines; river length, floodplain, 100-year flood inundation and irrigated areas predicted to be affected by metal mining contamination (see table S13 for confidence intervals); with human population and number of livestock (cattle, goat and sheep) living on contaminated floodplains. Except for the number of mines, all figures are rounded to the nearest 10.

	Operating status	**N. America**	**S. America**	**Asia**	**Africa**	**Europe**	**Oceania**	**Total**
No. of mines	H	80,995	14,577	1,473	377	9,080	53,233	159,735
	R	11,871	3,240	1,817	1,227	1,024	3,430	22,609
River length affected (km)	H	174,510	52,660	25,120	5,400	5,550	101,960	365,210
	R	23,880	29,060	35,780	11,920	9,240	4,130	114,000
Floodplain area affected (km^2)	H	36,710	23,800	14,650	3,150	1,570	32,510	112,390
	R	6,420	14,830	18,800	7,290	3,370	1,290	51,990
100-year flood inundation area affected (km^2)	H	58,870	18,320	15,540	2,350	1,900	40,340	137,320
	R	6,860	10,670	20,290	5,740	3,590	1,520	48,650
Irrigated land in affected floodplain (km^2)	H	17,640	7,300	8,760	820	1,040	8,560	44,120
	R	2,120	4,900	11,090	1,130	1,920	310	21,450
Population in affected floodplains (1000s)	H	3,411	932	5,716	305	624	406	11,394
	R	677	595	8,811	883	1,103	15	12,084
Livestock in affected floodplains (1000s)	H	440	710	570	190	250	1,630	3,770
	R	120	440	810	360	140	70	1,950

Table 2. Global assessment of hazard from failed mine tailings storage facilities. Modelled contamination from 165 failed tailings storage facilities (TSF) for which runout distances were observed from the total of 257 failed TSF recorded in the LCWPH database. Predictions of contamination were derived from the LCWPH model using the observed runout distances. All figures are rounded to the nearest 10.

	N. America	**S. America**	**Asia**	**Africa**	**Europe**	**Oceania**	**Global**
River length affected (km)	1,790	2,120	390	120	850	70	5,340
Floodplain area affected (km^2)	1,390	2,090	380	170	890	30	4,950
100-year flood inundation area affected (km^2)	1,130	1,540	340	110	660	20	3,800
Floodplain irrigated land affected (km^2)	30	1,190	200	130	110	0	1,660
Population in affected floodplains	9,970	195,870	93,370	8,260	15,170	150	322,790
Livestock in affected floodplains	9,820	87,110	22,530	6,610	6,570	0	132,640

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