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Sustainable mining in tropical, biodiverse landscapes: environmental challenges and opportunities in the archipelagic Philippines

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Review

Sustainable mining in tropical, biodiverse landscapes: Environmental challenges and opportunities in the archipelagic Philippines

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A R T I C L E I N F O

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A B S T R A C T

The rising demand for critical metals presents a major economic opportunity for mineral-rich countries. For a sustainable transition to a low-carbon future, it is essential to minimise impacts of mineral resource development to the environment, ecosystems, and societies of these nations. Although there has been considerable progress in the social aspects of the mining sector, environmental metrics are not showing comparable improvement. The Philippines exemplifies this challenge as a country that aims to conserve its exceptional biodiversity to maximise ecosystem services while expanding mining activities for economic growth, in a geographical setting with high mineral potential and vulnerability to natural hazards and climate change. Similar to many mining areas, environmental baselines are mostly non-existent, compounded by a legacy of mining impacts despite an established policy framework. We review issues associated with large- and small-scale mining and identify underlying research challenges and opportunities in the Philippines. Potential environmental research pathways include (i) innovative approaches for catchment scale characterisation and identification of contaminant sources; (ii) quantifying and predicting contaminant transport; (iii) deployment of flexible monitoring devices for larger-scale water quality monitoring programmes; (iv) tailings dam monitoring and management; and (v) resource assessment and metal recovery in ores and tailings. By integrating geomorphological tools with geochemical data, as well as 2D/3D numerical modelling techniques, it becomes possible to predict and understand the behaviour and fate of contaminants across different spatial and temporal scales. The development of cost-effective water quality assessment devices and protocols can help overcome logistical challenges in monitoring a wider range of hydrological conditions. Advanced applications of remote sensing, combined with machine learning, and

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geophysical monitoring systems provide new opportunities to detect mining footprints and observe change in tailings dams more effectively. Potential impacts of mine wastes can be further minimised by exploring innovative technologies such as the use of metal-accumulating native plant species and environmentally safe solvents to reprocess modern and legacy tailings. Insights from these pathways will enable the realisation of a more sustainable mining future, through the incorporation of findings into existing and future governmental and small- and large-scale mining policy and practice. This will lead to sustainable development for society, particularly in nations that are well positioned to benefit from sustainable mineral resource development.

1. Introduction

The global transition to a low-carbon future is driving unprecedented growth in the minerals sector, including metals such as Cu, Cr, and Ni which are widely used for a range of clean energy systems and technologies (International Energy Agency, 2021, 2023). This requires more mining and processing of mineral resources because it is impossible to maintain supply through a circular economy alone (Hagelüken and Goldmann, 2022; Smith and Wentworth, 2022). Resource-rich countries stand to benefit from the increased mineral production if economic growth is balanced with environmental and social issues (Hund et al., 2020). In this regard, the extractives sector has increasingly shifted to sustainable mining practices which aim to maximise benefits from all mined/moved materials throughout the mining life cycle while minimising impacts to the environment, ecosystems, and people (Aznar-Sánchez et al., 2019; Gorman and Dzombak, 2018; Herrington and Tibbett, 2022). Mining projects can contribute to economic growth and poverty reduction through taxes and royalties, and by providing public services, infrastructure, facilities, and employment opportunities (Alves et al., 2021; Smith and Wentworth, 2022). Before mining permits are issued, projects are also typically required to have environmental management plans in place to minimise damage and potential contamination around and downstream of the mining areas and to rehabilitate impacted areas, both during operations and after mine closure.

Although there has been significant progress in community investment and mine safety, environmental indicators (e.g. water, air, and soil quality; biodiversity impacts) are not improving at the same rate (Aska et al., 2023; International Energy Agency, 2023; Macklin et al., 2023). The environmental legacy of mining remains a major, if not the biggest hindrance, to the sustainable development of the minerals sector worldwide. As an extractive industry, metal mining is often associated with drastic landscape changes and environmental degradation (Dethier et al., 2023; Hudson-Edwards et al., 2011; Macklin et al., 2006, 2023). The activities involved in mining operations, such as removal of vegetation, excavation, and displacement of solid materials on the Earth's surface, may affect all ecosystem components including substrata, topography, hydrology, soil, vegetation, fauna, and atmosphere (Martín-Moreno et al., 2016; Tarolli and Sofia, 2016; Tibbett, 2024). In addition, metal mining produces huge volumes of waste because the grade of the extracted ores is typically only a few percent or less. The largest mining-related waste stream is tailings; a mixture of predominantly fine (<2 mm) sediment particles, processing water and chemicals remaining after the valuable commodity is removed from the mined product (Kossoff et al., 2014). It is estimated that globally, between 5 and 7 billion tonnes of tailings are produced annually (Edraki et al., 2014). In large-scale operations, tailings are usually stored in tailings dams, whilst mining waste from artisanal and small-scale mining (hereafter collectively referred to as small-scale) is often left untreated and transferred directly to river systems. Tailings may still contain metals and sulfur that may cause acid mine drainage, as well as toxic chemicals used for metal extraction (e.g. cyanide, Hg), which can have long-lasting impacts on water resources and ecosystem functionality (Byrne et al., 2012; Jarvis et al., 2019). It is therefore imperative to develop strategies to address these fundamental issues to help achieve a net positive impact for the environment and society (Herrington and Tibbett, 2022).

As one of the most mineralised countries in the world, the Philippines is a key player in the global minerals sector, with over USD 1 trillion worth of untapped metal reserves (Australian Trade and Investment Commission, 2023; Philippine Statistics Authority, 2017). The Philippines was the second largest producer of Ni from 2011 to 2022 (Brown et al., 2017; Idoine et al., 2022; U.S. Geological Survey, 2023) and an important producer of Au, Cu, and Cr during different periods in the last century (Bryner, 1969; Cutshall, 1942; Rossman, 1970). One approach to comparing mineralised countries is through the calculation of mineral rents, which are the difference between the value of production for a stock of minerals at world prices and their total costs of production. Minerals included in the calculation are Sn, Au, Pb, Zn, Fe, Cu, Ni, Ag, bauxite and phosphate (World Bank Group, 2023). Among leading mineral producing countries, the Philippines has one of the highest mineral rents relative to land area (approximately USD 20,000 per km^2), which is comparable to countries such as Australia and Peru (Supplementary Table 1). Yet, the Philippines is much less developed compared to these countries based on the United Nations' Human Development Index (United Nations Development Programme, 2023); there is thus considerable potential for mining to contribute further to socio-economic development. With the current mining laws in place and the recent lifting of a 9-year moratorium in new mineral agreements (Executive Order No. 130, 2021), it is expected that mining will expand in the country.

Tropical ecosystems and biodiversity hotspots face increasing risks due to mining expansion (Aska et al., 2023; Luckeneder et al., 2021). In common with other tropical, mineral-rich, emerging economies such as India and Indonesia (Organisation for Economic Co-operation and Development, 2022), the Philippines is a global conservation priority (Posa et al., 2008) – a "highly vulnerable region of high irreplaceability" (Brooks et al., 2006, p.59). In addition, these areas are also vulnerable to geologic and hydrometeorological hazards, which can aggravate environmental pressures (Holden, 2015). Hence, these nations are beset by a paradox of conserving biodiversity to maximise ecosystem services while expanding mining activities for economic growth and to enable a global-scale sustainable transition to low carbon technologies, in geographical settings that are rich in minerals but susceptible to natural hazards.

Achieving sustainability in mining hinges on the adoption of innovative approaches and technological advancement focussed on the better use of minerals and minimising waste and contamination (e.g. Endl et al., 2021; Liang et al., 2024; Sánchez and Hartlieb, 2020; Yu et al., 2024), which can help fulfil key social and economic indicators such as value adding and health and safety (Alves et al., 2021; Aznar-Sánchez et al., 2019). From this perspective, there is a need to analyse the challenges and opportunities towards achieving environmentally sustainable development of mineral resources in nations such as the Philippines. Here, we identify key research gaps that underpin these issues, explain why they are particularly relevant in such settings, and explore potential pathways to address these research challenges to deliver wider beneficial societal impacts. As an exemplar of a tropical nation with rich biodiversity, underdeveloped mineral resources, and considerable climate change impacts, opportunities and challenges for sustainable mining in the Philippines will have global relevance for achieving comparable outcomes elsewhere, especially in regions at a similar level of development.

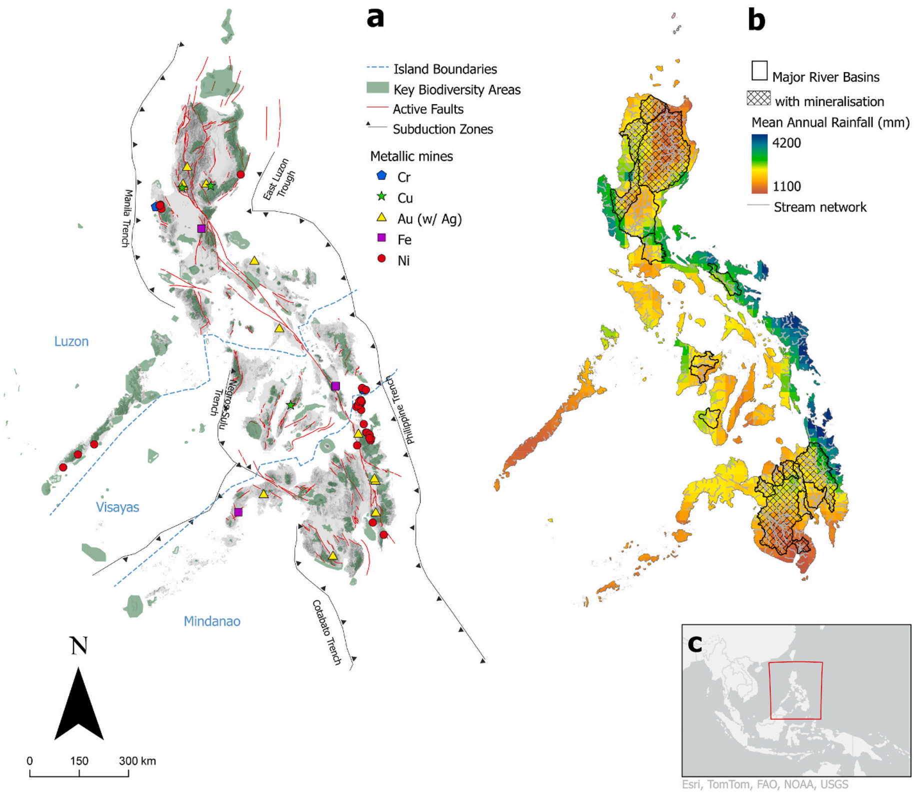

Fig. 1. Regional setting and thematic maps of the Philippines, including: **a** tectonic system with active faults (Aurelio and Pena, 2010; DOST-PHIVOLCS, 2015), major island boundaries, key biodiversity areas, and operating metal mines (DENR-BMB, 2021b; DENR-MGB, 2023a); **b** major river basins, including mineralised basins, and mean annual rainfall derived from the APHRODITE dataset from 1998 to 2015 (DENR-RBCO, 2022; Yatagai et al., 2023); **c** inset map showing the location of the Philippines with respect to other countries in SE Asia.

2. Geographic setting, mining history, and policy settings

The first part of this literature review provides the regional and geographic setting, mining history, and policy settings for contextual understanding of the main environmental challenges related to the mining sector and why these are particularly relevant in the Philippines. The historical trends of Au, Cr, Cu, and Ni mining in the 20th and early 21st centuries were primarily compiled using publicly available data from the Philippines' Mines and Geosciences Bureau and from the World Mineral Statistics Archive of the British Geological Survey. A qualitative approach (Harwell, 2011) was used to analyse consistency in policy discourse for initiatives that have promoted the mining sector on the one hand and tried to address related social and environmental concerns on the other hand. In the case of small-scale mining activities, effectiveness and impacts of the People's Small-scale Mining Act (Republic Act No. 7076, 1991) are discussed considering the situation on the ground.

2.1. Regional, geological, and geomorphological setting of the Philippines

The Philippine archipelago is a collection of over 7500 islands in Southeast Asia that is broadly categorised in three main geographical regions: Luzon, Visayas, and Mindanao (Fig. 1a). The Philippines is located within the convergence zone of the Philippine Sea Plate, Sundaland-Eurasian Plate, and the South China Sea basin (Aurelio and Pena, 2010; Wu et al., 2016). It is characterised by several volcanic arc chains that developed from the subduction along the Philippine Trench on the east, and the Manila, Sulu-Negros and Cotabato Trenches on the west (Fig. 1a). The archipelago is composed of accreted and amalgamated terranes of continental, island arc, and oceanic-ophiolitic affinities (Hall, 2002). The consolidation of these terranes has resulted in high uplift rates, active volcanism, and the formation of metallogenic districts across the entire archipelago (Aurelio and Pena, 2010; Sajona and Domingo, 2011; Yumul et al., 2003). Consequently, the occurrence of mineral deposits and mining activities in the country is directly connected to its geologic setting and tectonic evolution (Yumul et al., 2021).

The Philippines has a tropical climate characterised by high temperatures, humidity, and precipitation levels (DOST-PAGASA, 2021). There are two distinct seasons (dry and wet), but the occurrence and timing of these vary depending on the region. The mean annual rainfall ranges between 965 and 4064 mm, with rainfall distribution varying throughout the country (Fig. 1b). The country is also subjected to an average of 20 tropical cyclones per year (1991–2020), which mostly occur in the wet season (DOST-PAGASA, 2023). Tropical cyclones usually bring torrential rainfall that can reach catastrophic levels: for instance, 1089 mm of rain was recorded on a single day (July 4, 2001) in Baguio City (DOST-PAGASA, 2022). These weather events often cause widespread damage through flooding and rain-induced landslides (DOST-PAGASA, 2023). In addition, an average of 20 earthquakes are recorded daily in the country, mostly as a result of the movement of the 1300 km long Philippine Fault (DOST-PHIVOLCS, 2017). Due to high level of exposure and vulnerability to geological and hydrometeorological hazards, combined with a lack of coping and adaptive mechanisms in place, the country has been identified to have the highest disaster risk in the world in 2022 (Bündnis Entwicklung Hilft, 2022). Accordingly, such hazards can severely affect mining operations and infrastructure, as evidenced by numerous incidents of flooding, landslides, and tailings spills associated with weather-related incidents reported since the 1960s (Holden, 2015).

The river basins in the Philippines are highly diverse in terms of morphometric and topographic characteristics (Boothroyd et al., 2023). There are 18 major river basins (i.e. with drainage areas >1400 km^2) that serve essential freshwater supply to sustain agricultural, domestic, and commercial demand (Tolentino et al., 2016). At least 10 out of the 18 major river basins have known mineralisation and/or large-scale

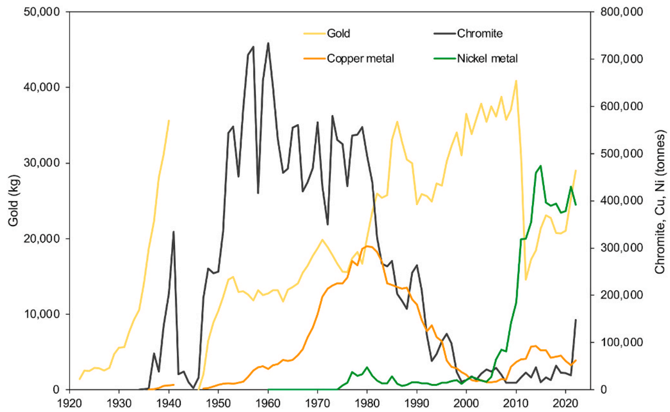

Fig. 2. Historical trends of metal production (Au, Cr, Cu, and Ni) in the Philippines in the 20th and early 21st centuries, compiled and converted into metric units using publicly available data from the DENR-MGB (2023b) for the years 1998–2022 and from the World Mineral Statistics Archive of the British Geological Survey (2023) for the pre-1998 period.

mining activities: Abra, Agno, Agusan, Apayao-Abulug, Buayan-Malungon, Cagayan, Cagayan de Oro, Rio Grande de Mindanao, Ranao (Agus), and Tagoloan (Fig. 1b). These catchments encompass a range of climatic regimes, ecosystems, mineralisation types, and various durations of mining activity.

The Philippines is also recognised as one of the 18 megadiverse countries and a global biodiversity hotspot (Scarano et al., 2024). It is home to numerous endangered and critically endangered species, with exceptionally high levels of endemism: about 50% endemism of terrestrial vertebrates and 45–60% for vascular plant species (Posa et al., 2008). The country is also reported to have the highest concentration of marine species per unit area in the world (Carpenter and Springer, 2005), with an estimated 30,000 km^2 of coral reef ecosystem hosting roughly two-thirds of all hard coral species in the world (DENR-BMB, 2021a). There are designated protected areas in the country, defined by law as “outstandingly remarkable areas and biologically important public lands that are habitats of rare and endangered species of plants and animals, biogeographic zones and related ecosystems, whether terrestrial, wetland or marine” (Republic Act No. 11038, 2018; Republic Act No. 7586, 1992). Protecting Key Biodiversity Areas (Fig. 1a), including terrestrial, coastal and marine protected areas is essential to support fisheries, forestry, and agriculture, which collectively provide a variety of ecosystem services, as well as tourism. Between 2000 and 2022, these industries contributed an average of 12.7% and 7.4% to the country’s gross domestic product (GDP), respectively (Philippine Statistics Authority, 2023a, 2023b).

2.2. Mineral resources in the Philippines

The Philippines is rich in precious and base metal deposits, such as: Au (e.g. vein-type epithermal with Ag, volcanogenic massive sulfide deposits), porphyry Cu (with Au), podiform Cr deposits (e.g. metallurgical and refractory types), Ni (Co–Sc) laterite, and polymetallic, i.e. containing Cu, Au, Ag, and Zn (Bryner, 1969; Cooke et al., 2011; Rossman, 1964; Yumul et al., 2003). These mineral deposits are distributed throughout the archipelago (Fig. 1b), influenced by the type of magmatism, structural controls, and lithology, among others (Sajona and Domingo, 2011; Yumul et al., 2003).

Mining activity in the Philippines commenced before official records began in the mid-16th century when Spanish colonisers started placer (alluvial) Au mining in various places, followed by Cu mining in Panay Island and in Benguet Province during the 18th century (Domingo, 1993). In 1903, shortly after the arrival of the Americans, the Benguet Corporation began operating the Antamok Mine as the first modern mine in the country wherein they utilised both surface and underground mining for Au, with new tunnelling methods, and ore flotation and cyanidation techniques (Chaloping-March 2017; Domingo, 1993). Based on historical metal production data (Fig. 2), Au production boomed in the 1930s, with the Baguio Mining District in Benguet becoming the most important Au mining region in the country (Cutshall, 1942). After World War 2, the introduction of new technologies such as open-pit mining spurred the growth of Cu mining, peaking in the 1970s and, at the time, enabling the country to become one of the top Cu producers in the world (Domingo, 1993). Some of the oldest Cu and Au large-scale mines are still in operation at present, including the Lepanto Consolidated Mining (ca. 1936), Atlas (ca. 1955), and Philex Mining (ca. 1958). Meanwhile, Cr mining started in 1933 at the Acoje Mine in Zambales (Rossman, 1970). After World War 2, the Philippines became one of the largest Cr producers, particularly of refractory type Cr (Melcher and Forbes, 1953); from the 1950s until the mid-1960s it supplied 20% of the total ‘free world’ production (Rossman, 1970). Like Cu, the production of Cr steadily declined from the 1980s, in contrast with Au, which continued its gradual increase (Fig. 2). Large-scale Ni mining was officially documented in the 1960s, but massively expanded in the mid-2000s, producing about 10–20% of the global Ni supply between 2011 and 2022 (Brown et al., 2017; Idoine et al., 2022; U.S. Geological Survey, 2023).

With the expansion of large-scale mines, small-scale mining activities also thrived, operating along the borders or within the large-scale mining claims (Chaloping-March 2017). In some instances, small-scale miners have discovered minerals in previously unexplored deposits, such as Au in Central Palawan in Luzon, Samar in Visayas, and in the Dinagat Islands in Mindanao (Domingo, 1993). Small-scale mining activities particularly expanded in the 1990s, coinciding with the decline in the large-scale sector due to low metal prices, opposition to large-scale mining, and permitting issues (Sajona and Domingo, 2011). In contrast with large-scale Au/Cu mines, which are either surface/open pit or underground with greater areal extent with well-controlled ore processing procedures, small-scale miners mainly operate underground at much smaller extents and have limited safety controls. Small-scale activities include ‘pocket mining’ (i.e. tracing Au veins through makeshift tunnels), panning, milling, and ‘joining’ (i.e. women reworking tailings to recover residual Au) (Chaloping-March 2017). These small-scale enterprises have continued to operate in mining districts across the archipelago.

At present, there are 56 large-scale metal mines operating in the country: 33 Ni mines, 12 Au mines, 4 Cr mines, 4 Fe mines, and 3 Cu mines (DENR-MGB, 2023a). There is no official number of small-scale mining operations in the country. The total production value of metallic minerals was USD 4.3 billion in 2022, with Ni, Au, and Cu accounting for 49%, 38%, and 11%, respectively (DENR-MGB, 2023a).

2.3. Policy framework and implementation

For decades, the Philippine government has tried to make the mining industry a major contributor to the economic development of the country. In the 1970s, the mining and quarrying sector contributed 1.4% of the GDP (National Economic and Development Authority, 2022). However, from 2000 to 2020 the average contribution of the sector decreased to 1.0% of GDP, providing 0.5% of total employment in 2022 (Philippine Statistics Authority, 2023a, 2023c). In mining-intensive areas in the Philippines, the sector contributes up to 25% of the regional GDP (Arcilla, 2017). While laws and regulations have been in place since the 1980s for the development of large- and small-scale mining, only 8.5% of 9 million hectares of land with high mineral potential in the country is covered by mining tenements (DENR-MGB, 2023a). As such, there will be more areas impacted by mining activities as the sector expands in the future; thus, an appropriate policy and practice landscape is important if sustainable mining is to be achieved.

The central contemporary laws that govern the mining industry are

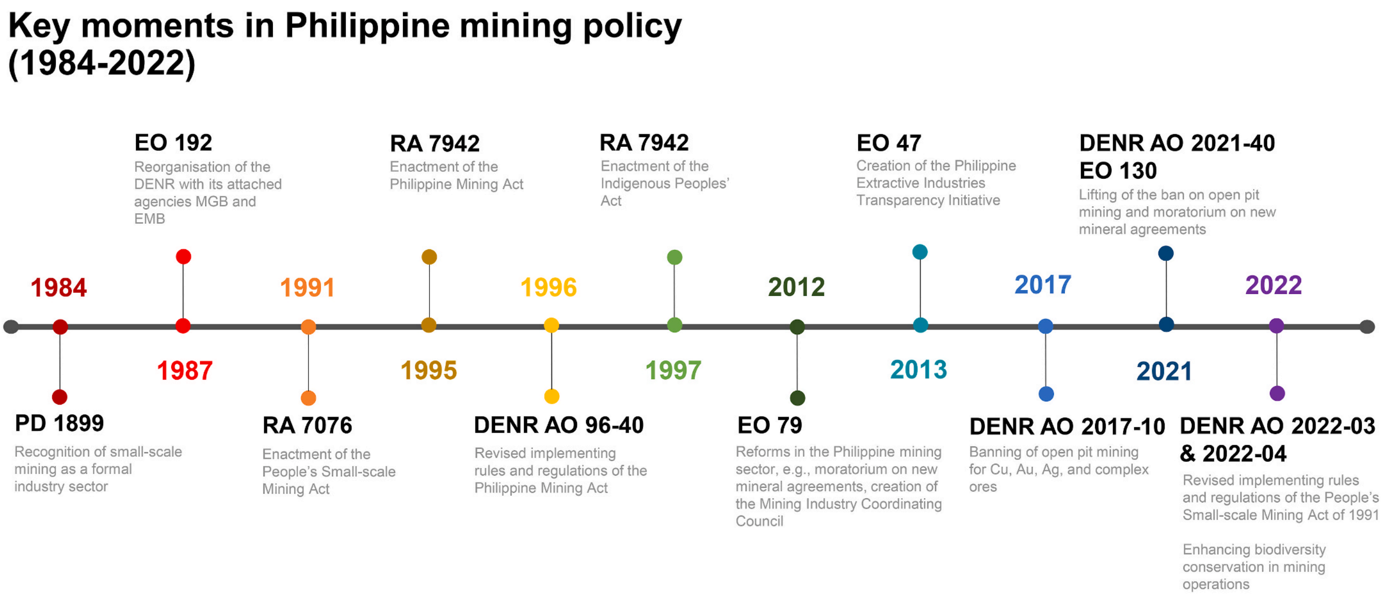

Fig. 3. Timeline showing key moments/changes in policy relevant to the Philippine mining and minerals sector in the last 40 years (i.e. 1984-2023). These laws include Republic Acts (RA), Presidential Decree (PD), Executive Orders (EO), and Department of Environment and Natural Resources - Administrative Orders (DENR AO).

the Philippine Mining Act (Republic Act No. 7942, 1995) and the People's Small-scale Mining Act (Republic Act No. 7076, 1991) for large-scale and small-scale mining, respectively (Fig. 3). The Philippine Mining Act requires all mining operations to use appropriate technology and facilities that minimise contamination, and to prepare and implement environmental management and social development programs. Meanwhile, the People's Small-scale Mining Act establishes areas suitable for small-scale mining and includes provisions for environmental protection, community development and enforcement of safety and health programmes. Another important law concerning the mining industry is the Indigenous People's Rights Act (Republic Act No. 8371, 1997), which promotes and protects the rights of indigenous communities, especially in consenting to activities that may affect their domain.

Between 2010 and 2020, major changes in policy concerning the Philippine minerals sector were made (Fig. 3). Reforms in the mining sector were legislated in 2012, which directed strict compliance with environmental standards and imposed a moratorium on new mineral agreements until a new law on revenue-sharing schemes and mechanisms was passed (Executive Order No. 79, 2012). A policy-governing body, the Mining Industry Coordinating Council, was also formed, which created a map to identify specific areas closed to mining and that included not only the protected areas but also areas geographically close to mining. In 2013, the Philippine Extractive Industries Transparency Initiative (EITI) was created to promote sustainable practices and green technologies for the mining sector, administered by a multistakeholder group composed of government, industry, and civil society representatives (Aguilar and Chan, 2022). In 2017, the government imposed a ban on open-pit mines for the extraction of Cu, Au, Ag and complex ores. It was argued that open pits cause adverse impacts to the environment mainly due to acidic and metal-laden water, erosion of mine waste dumps and vulnerability of tailings dams to geological hazards. After a multi-stakeholder review on the performance of large-scale metal mining operations from 2018 to 2020 (National Economic and Development Authority, 2022), the moratorium on new mineral agreements and open-pit mining ban was lifted in 2021 – nine years and four years after these were imposed, respectively (Executive Order No. 130, 2021; DENR Administrative Order No. 2021-40, 2021). In 2022, the Department of Environment and Natural Resources (DENR) established additional guidelines on small-scale mineral processing and tailings storage facilities (DENR Administrative Order No. 2022-03, 2022) and required mining operators to integrate biodiversity measures into environmental management programmes, such as conducting economic valuation of ecosystem services and using native species for ecological restoration (DENR Administrative Order No. 2022-04, 2022).

The 2023–2028 Philippine Development Plan (National Economic and Development Authority, 2023) proposes a roadmap to revitalise the mining industry that was negatively affected by the 2020–2021 COVID-19 pandemic. The Plan proposes to develop value-adding activities and downstream industries for the mining sector. It mentions that a special fiscal regime will be designed to ensure that the state receives an appropriate share of the economic rent enjoyed by extractive industries, particularly mining.

The existing laws have provided a degree of accountability and transparency in mining operations, particularly for large-scale mines, overseen by the DENR. However, some of the most serious mining-related disasters in the Philippines have occurred after the enactment of these laws (discussed in Section 3). In contrast, small-scale mining remains largely informal despite the implementation of regulatory laws. It has been impossible to constrain all small-scale mining activities within declared people's small-scale mining areas (Pascual et al., 2020). Small-scale gold mining is estimated to account for over 70% of the total production in the country, yet the economic contribution of the small-scale sector is unclear (Domingo and Manejar, 2020; Pascual et al., 2020). The weak enforcement and monitoring of small-scale activities have led to an increase in illegal mining operations, abuse of mining permits, non-compliance with regulations and taxes, and unsafe mining practices such as using Hg and makeshift tunnels, among others (Arcilla, 2017; Mones, 2018; Yumul et al., 2021). These issues have compounded the negative public perception of mining in the country.

3. Environmental impacts of mining in the Philippines

The Philippines has a complex and long-standing history regarding mining waste (Habana, 2001). Until the late 1980s it was common practice to directly dispose tailings to rivers, lakes, or the sea through pipelines and box conduits (Briones, 1987). Prior to the Philippine Mining Act of 1995, the environmental impacts of large-scale mining had been poorly documented despite over a century of mining operations. Upon its promulgation, the law enabled mining accidents to be properly investigated. Examples of these are the mine tailings dam failures from Marcopper Mine in Marinduque (1996), Rapu Rapu Mine in Albay (2005), and Philex Mine in Benguet (2012) (David, 2002; Mineral Policy Institute, 2006; Monjardin et al., 2022; Senoro et al., 2019). In the Marcopper and Philex accidents, approximately 1.60 Mm^3 and 20.7 Mt of metal-laden tailings flowed into and contaminated the nearby river systems, respectively (David, 2002; DENR-PAB, 2013). In the case of Marcopper, roughly 180,000 m^3 to 260,000 m^3 of tailings material was released into the marine environment, with elevated concentrations of Cu, Fe, Mn, and Zn detected from marine sediments and corals (David, 2002)' which persisted in the sediments more than 20 years after the disaster (Monjardin et al., 2022; Senoro et al., 2019). In the case of Rapu Rapu, multiple cyanide spills and extensive acid mine drainage originating from the mine resulted in massive fish kills and significant loss of livelihood (Holden, 2015; Martin and Newman, 2008).

Aside from tailings dam failures, the erosion and deposition of sediment from metalliferous areas presents another important issue, especially in opencast Ni mining areas (Bird et al., 1984; Mudd, 2010). Large-scale Ni mining typically uses strip mining methods, which requires the removal of the overlying topsoil and vegetation to access the Ni laterite ores. To control the transport of metal-laden sediment originating from ore stockpiles, excavation areas, and dirt roads to areas downstream of the mines, mining companies construct a series of settling ponds that can accommodate thousands of cubic meters of runoff. In theory, these structures are designed in a series to decant the sediment-laden runoff and allow suspended particles to settle in one pond while the upper portion of the water will spill over to the next pond and so on until the runoff discharged from the last settling pond into the river has become significantly less turbid. However, despite mitigation measures, Ni mining sites have been shown to contribute to the disproportionate sediment loads of rivers during the rainy season (Apodaca et al., 2018). Sediment yields can reach up to eight times higher than adjacent non-mining catchments and may contribute more than 70% to overbank deposits following floods (Domingo et al., 2021, 2023). These flood sediments typically drape downstream areas thereby causing siltation which can severely impact rice production and render fishing sites unproductive (Migo et al., 2018).

The environmental impacts from the release of large volumes of metal-contaminated sediment into river systems is not limited to large-scale mining operations. The safe disposal of tailings and waste material from small-scale mining activities remains unresolved and will require considerable financial and logistical investment considering the sheer number of small-scale miners in the Philippines. Small-scale miners typically use cyanide to separate Au and Ag from the ore, and Hg to create an amalgam for precious metal extraction (Appleton et al., 1999; Drasch et al., 2001; Velásquez-López et al., 2010). These toxic substances are pervasive in small-scale mining practices because of their simplicity in application and relatively low cost (Israel and Asirot, 2002). In 2000, the estimated consumption of Hg used in various small-scale gold mining sites in the country was 10,000–30,000 kg/yr (Veiga et al., 2006). However, due to the lack of proper disposal facilities, most miners dispose of untreated wastewater containing Hg and/or other potentially toxic elements directly into the surrounding rivers and creeks (Cortes-Maramba et al., 2006; Gibaga et al., 2023), which eventually flow into coastal areas and open seas. For instance, the Hg concentrations measured in the untreated tailings material and wastewater disposed into water bodies in the towns of Paracale and Jose Panganiban in Luzon were 11.5 mg/kg and 0.18 mg/L, respectively (Samaniego and Tanchuling, 2018). Aside from fluvial impacts, roasting of the amalgamated metals exposes communities to Hg vapor by inhalation, eventually mixing with rainwater and ending up in water bodies where it can be converted to methylmercury (Maglambayan et al., 2005; Samaniego and Tanchuling, 2018). These contaminants can persist well beyond the lifetime of the mine operations, and their potential remobilisation, transformation, and bioaccumulation pose serious risks to water quality, aquatic ecosystems, and human health (Lecce and Pavlowsky, 2014; Macklin et al., 2006; Singer et al., 2016). It is clear lessons need to be learned about the longevity and safety of post-mining landscapes, which must be based on understanding how post-mining systems evolve with natural processes (DeJong et al., 2015).

4. Research gaps and opportunities

In this section, we discuss the main challenges for achieving environmentally sustainable mining and the key research gaps that underpin these issues. We then highlight research opportunities to address such challenges, with broader implications to the mining sector and society.

4.1. Challenge: the complexity of separating the impacts of mining from different anthropogenic pressures

In many nations, the longevity and scale of legacy mining have made it difficult to disentangle the impact of mining from other anthropogenic pressures such as agriculture, industry and urbanisation. This is because many river catchment indicators of mine pollution (i.e. metal(oid)s in water, sediment, and biota) can also be sourced from sediment draining from urban areas, pesticides, and metal-enriched sewage sludge applied to agricultural land (Buta et al., 2021; Defarge et al., 2018). In addition to this, contaminated sediment in catchments can also be stored in fluvial deposits (i.e. sand/gravel bars, floodplains, and terraces) for 10^2–10^4 years, and become secondary sources of pollution when remobilised during high river flows or when disturbed by anthropogenic activities (Dennis et al., 2009; Lecce and Pavlowsky, 2014).

In recent years, the relative importance and sources of mining-derived contaminants in river catchments have been established by monitoring changes in the mass loading of pollutants along a river course (Byrne et al., 2020). Under this approach, synchronous measures of contaminant concentrations and river flow are made at strategic locations across a river catchment, for example upstream and downstream of major potential source areas such as urban areas and mining districts. Changes in contaminant load can be used to identify source areas and quantify the pollutant load attributable to different source areas (Kimball et al., 2002). However, while pollutant mass loading data can be invaluable in isolating the impacts of mining in river catchments, in practice the acquisition of river flow data, synchronised with water quality data, at multiple sites in river catchments is costly and logistically challenging in larger catchments due to (a) natural diffusion of impacts, (b) increasing number of factors as scale increases, and (c) technical difficulties of monitoring in these areas, which typically have turbulent streams without permanent gauging mechanisms in place (Jarvis et al., 2019; McIntyre et al., 2016). Understanding the contemporary and potential functionality of a river, the location and concentration of primary and secondary contamination sources, and how they are connected to the river system is fundamental to understanding how contamination will be distributed and stored within catchments over the next 10^{3}-10^4 years. This is especially important with predicted climate change impacts on typhoon frequency and magnitude, and urban expansion in SE Asia.

4.1.1. Opportunity: application of a combined geomorphological and geochemical approach for catchment scale characterisation and identification of contaminant sources

How mine waste is locally stored and dispersed through catchments can be elucidated through the analysis of the river geomorphology, hydraulic regime, and risk of engineered structures (e.g. tailings dams) to failure. Various river classification techniques have been developed to map the diversity and distribution of channels and floodplains within a catchment (Belletti et al., 2015; Kasprak et al., 2016). These can be used to infer the channel and floodplain geomorphic units where waste may be dispersed to and stored. The River Styles Framework (Brierley and Fryirs, 2005) is a process-based classification system where river reaches are classified based on their valley confinement, presence or absence of floodplains, channel planform, distribution of channel and floodplain

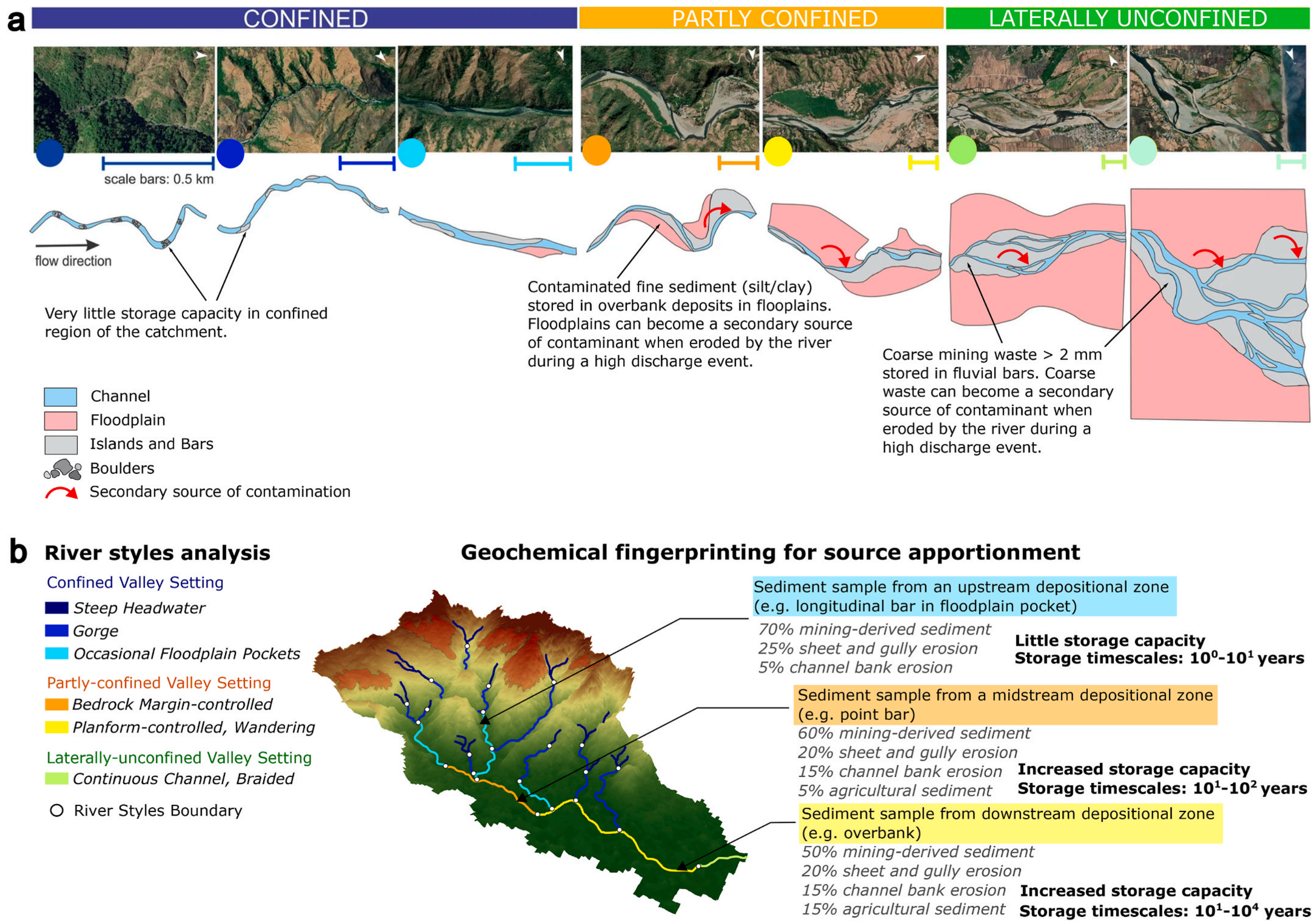

Fig. 4. **a** Conceptual illustration of how geomorphological characterisation can show patterns of sediment storage and dispersal. This example is based on using a river styles analysis of the Bislak Catchment, Luzon (adapted from Tolentino et al. (2022)). The Bislak Catchment is not impacted by mining but the different valley settings and geomorphic unit distributions are used to illustrate how contaminated sediment could be stored, eroded and transported. **b** Conceptual illustration of a catchment-scale characterisation and identification of contaminant sources using a combination of geomorphological characterisation from river styles analysis and sediment source apportionment data from geochemical fingerprinting, using the mining-impacted Santa Cruz Catchment in Luzon as example (modified from Domingo et al. (2023)).

geomorphic units and channel substrate. Fig. 4a illustrates a conceptual, catchment-scale application of this Framework and how it can be used to interpret sediment (including mine waste) dispersal and storage. This approach can be used both to predict the location of historic or 'legacy' mining waste sediment stores or where future waste could potentially accumulate along the fluvial network, which can assist river management by enabling appropriate contamination mitigation strategies. In more detail, Fig. 4a shows that sediment entering the confined river style has a higher likelihood of being reworked, remobilised, and flushed downstream due to steep channel gradients and a lack of storage capacity. In contrast, sediment added to an unconfined style with shallow aggrading channels is more likely to be locally stored within lateral bars and floodplains, and remobilised during flood events that cause channel migration (Dennis et al., 2009; Lewin and Macklin, 1987; Macklin et al., 2006; Miller, 1997; Walling et al., 2003). Such deposits become secondary sources of contamination, reintroducing mine waste into the fluvial environment for decades to centuries after mining activity has stopped (Dennis et al., 2009; Lecce and Pavlowsky, 2014; Macklin et al., 2003, 2023; Miller et al., 2004; Walling et al., 2003). The hydraulic regime, linked to both local climate and river style, also influences the calibre of sediment transported through a reach (Bird et al., 2021; Domingo et al., 2021). Fine waste, which often contains higher concentrations of contaminants, can be transported under a range of different flow conditions including extended periods of low/base-flow. The bedload transport of coarse mine waste (>2 mm) is often limited to higher discharge events or in regions of the channel which experience confined flows in narrow valley settings (Macklin and Lewin, 1989).

River classification can be complemented by other catchment-scale approaches to better understand and manage sediment/contaminant routing and storage within a catchment, especially considering that tropical catchments have highly diverse hydromorphologic attributes (Kuo and Brierley, 2013; Tolentino et al., 2022). For this purpose, integrating geochemical techniques such as sediment fingerprinting with geomorphological analyses could provide a powerful link between river style, river behaviour, and subsequent contamination storage/release (Fig. 4). Fingerprinting techniques fundamentally assume that sediment sources possess one or more conservative properties that can be measured and used to distinguish one source from another (Collins et al., 2017). Using a geochemical fingerprint, the spatial and temporal changes in sediment mobilisation and relative contribution of different sources can be identified and quantified in other samples collected within the catchment (Palazón and Navas, 2017). In the mining setting, sediment geochemistry has been used to establish provenance and apportionment from key sources within the catchment. Recent applications, which demonstrate the wider potential of this approach, include elemental concentrations and radionuclides analyses (e.g. K, Th, U,

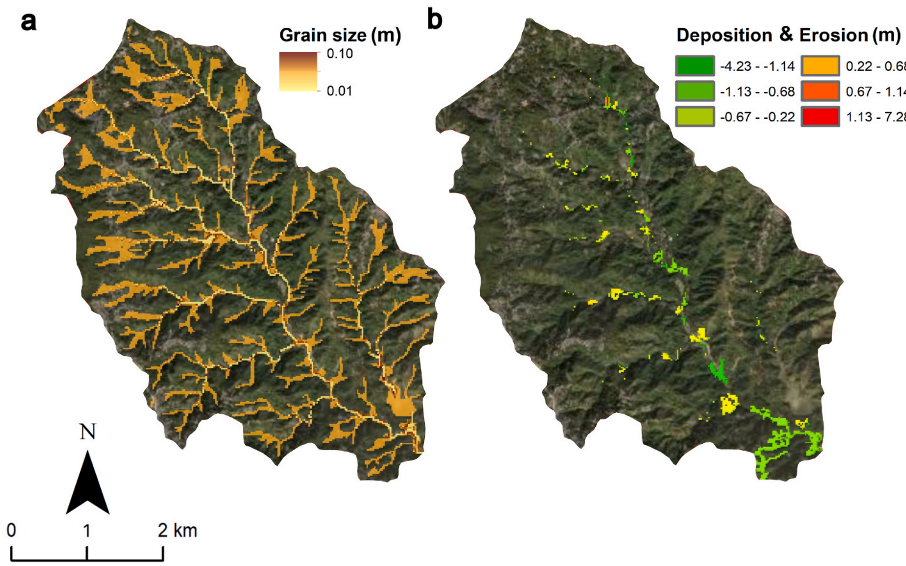

Fig. 5. Application of the CAESAR-Lisflood model to predict (**a**) grain size distribution of transported sediments and (**b**) deposition and erosion patterns in the Ucab sub-catchment in Luzon, which is part of the larger Itogon catchment that is impacted by large- and small-scale mining activities.

^{137}Cs, ^{210}Pb) in Ni mining-impacted Thio River in New Caledonia (Sellier et al., 2020) and the Santa Cruz River in the Philippines (Domingo et al., 2023); and bulk isotopic ratios (e.g. ^{206}Pb/^{207}Pb, ^{208}Pb/^{206}Pb) in the Hazeltine Creek, Canada several years after the Mount Polley mine tailings spill (Bird et al., 2021). Compound-specific stable isotopes (e.g. δ^{13}C of various fatty acids) can potentially be used to further differentiate other sediment sources based on land cover (Lizaga et al., 2021, 2022).

4.2. Challenge: quantifying and predicting the environmental impacts of contaminated sediment from legacy, future, and contemporary mining

Once contaminated sediment enters a fluvial system, the fate of the contaminant is contingent on the fluvial geomorphology and associated sediment transport processes (Macklin et al., 2006). Whilst field sampling of sediments from geomorphic units (e.g. sand/gravel bars, terraces, floodplains) can generate point data on contamination type and concentration, the contamination type and concentration between sample points is often unknown. It is difficult to predict where contaminated sediment will be transported or stored over longer timescales (10^{3}-10^{4} years) as river morphology and functionality can change in response to climate and/or anthropogenic induced disturbances, which result in changes to both sediment (both contaminated and non-contaminated) and water discharges (Hilmes and Wohl, 1995; James, 1989; Lewin and Macklin, 1987). Furthermore, this geomorphic response to changes in drivers (sediment supply, climate, flow) can exhibit a complex and non-linear response (Schumm, 1979) with one part of a catchment giving a different response to identical events at different times (Coulthard et al., 2005). Understanding the legacy of previous mining practices (prior to tailings construction), contemporary waste disposal and storage from small- and large-scale mining, and future waste inputs and redistribution are fundamental. This is particularly true in the Philippines where the storage and disposal of mining waste from both large-scale and small-scale mines was not regulated until the late 1980s (see Section 3).

4.2.1. Opportunity: numerical morphodynamic modelling for rehabilitation and prediction of contaminated sediments in mined areas

Understanding the movement and location of contaminated sediment from the past through the future can be explored using numerical models that focus on the morphodynamics of river sediment transport and deposition (Macklin et al., 2006). This has previously been carried out with 1D models incorporating the US EPA's WASP model (Macasieb et al., 2014) and with more theoretical approaches (Pizzuto, 2020). However, these methods are limited dimensionally (1D) and by the shorter timescales (series of events) that they operate over. There is also the unexplored potential for numerical models to predict how future contamination patterns may change – especially important in the context of a changing climate. Additionally, a few studies have modelled contaminated sediment transport over entire river catchments – at the decadal to centennial scales over which sediment (including contaminated sediment) is reworked (Coulthard and Macklin, 2003; Hancock et al., 2010). Approaches at catchment and decadal scales are important, as the movement of contaminated sediment depends on the size of hydrological events as well as both point sources, such as mine or processing sites, and diffuse sources such as floodplain or channel bed deposits being remobilised. Further, the addition of large volumes of uncontaminated sediment from other erosional processes (including bank erosion and landslides) can result in contaminated sediment dilution during very large flood events (Dennis et al., 2003).

One numerical approach is CAESAR-Lisflood (CL) (Coulthard et al., 2013), an open source catchment-scale hydrodynamic and morphodynamic model. Taking inputs of a catchment digital elevation model (DEM), rainfall and sediment properties, CL can predict erosion and deposition patterns in three dimensions (Fig. 5) as well as suspended and bedload fluxes at sub-event time scales for simulations spanning days to 1000s of years. Early versions of the CAESAR model were used to successfully predict channel and floodplain Pb and Zn contamination over three dimensions (concentrations over spatial extent and depth) in the River Swale catchment, UK (Coulthard and Macklin, 2003) by tracing sediment input from historic mine sites. Since then, CL has been greatly enhanced by the addition of a full 2D hydrodynamic model and has now been used to study and predict catchment morphodynamics in over 100 separate studies around the world. Most recently to trace the fate of sediment from a series of landslides in Wenchuan, China (Xie et al., 2022).

Models such as CL could be transformational to the understanding of contamination issues in the Philippines and associated impacts of climate change on landform stability. For instance, such models can help determine how important the physical connectivity between mine site and nearby rivers is, as well as investigate the relative roles played by large mine sites compared to many smaller artisanal operations in adding mine affected sediment into local river systems. However, there are some challenges to be addressed, as models such as CL can require significant quantities of data including rainfall, sediment grain sizes and a representative DEM of the catchment surface, with sufficient detail of the channel. This can limit their application to areas of good data availability and due to the model complexity, there can be a trade-off between the size of the area covered and the level of detail (size of grid cells) representing the land surface. At present, 2D models such as CL only simulate the physical movement of contaminated sediment and do not consider the chemical transfer of metals between solution and sediment particle (Hudson-Edwards et al., 1998) that can be modelled in 1D (e.g. WASP; Macasieb et al., 2014). Nevertheless, these limitations need to be considered in the context of how useful partial or low-resolution forecasts may be in comparison to none.

4.3. Challenge: A lack of water quality evidence to inform policy

To detect and attribute water quality changes due to mining, it is essential to have baseline and routine monitoring datasets covering a wide range of hydrological conditions (Zapico et al., 2017). In the UK and USA, national water quality programmes and datasets have provided clear evidence of the impact of legacy and contemporary mining activities in river catchments and facilitated the rehabilitation of mines (Byrne et al., 2017; Gozzard et al., 2011; Mayes et al., 2010; Runkel et al., 2013). In the Philippines, however, water quality data are scarcely available, and datasets that do exist typically do not include the full spectrum of analytes required to monitor and evaluate the potential impacts of mining on water quality. This is due to the limited geographic coverage, insufficient frequency of monitoring, lack of advanced monitoring technologies, inadequate human and financial resources, and poor data management, among others. Mining operations are typically located in headwater catchments with poor road connections except to the mine site, high susceptibility to geohazards and, in the case of Mindanao, political instability and security issues. The limited geographic coverage of monitoring stations and resources allocated in rural areas has resulted in a lack of regular and systematic water quality monitoring (DENR-EMB, 2020; National Water Resources Board, 2011), which makes it difficult to assess and address water pollution issues comprehensively. Infrequent monitoring cannot capture the real-time changes in pollution events, missing out on the short-term pollution spikes following heavy rains or tailing dam failures, resulting in unreported and unaddressed contamination (Asian Development Bank, 2019; Bautista and Mendoza, 2018). In addition, the lack of advanced monitoring technologies may fail to identify all the pollutants, potentially overlooking harmful substances that can affect ecosystems and human health (Asian Development Bank, 2019). Furthermore, many local government units and environmental agencies lack the necessary staff, equipment, and technical expertise to conduct comprehensive water quality monitoring (DILG, 2017), which leads to gaps in data coverage and quality. Finally, there is no national water quality monitoring programme due in part to the financial constraints of water quality analyses, but also due to the variable accessibility of rivers and the logistical costs associated with sampling programmes. If data are collected from various agencies and institutions, they may not be centralised or made accessible to other stakeholders, which further hinders the ability to conduct thorough analyses, develop informed policies, and engage communities in water quality management.

4.3.1. Opportunity: establishing a flexible and bioavailability-based water quality monitoring approach

Historically, water quality has been monitored globally, and in the Philippines, using a technique known as grab sampling (Vrana et al., 2005; Zhang et al., 2016); where a volume of water is retrieved from a specific location along a river and at a specific moment in time, and then analysed in a laboratory for constituent concentrations. This method is well established, relatively simple to implement, and inexpensive, assuming a low spatial and temporal sampling frequency (Audet et al., 2014). However, the costs of sampling can soon become prohibitive if large numbers of samples are required to understand how contaminant concentrations fluctuate over time (Hawker et al., 2022).

High temporal resolution data can be acquired using high-frequency grab sampling systems (Byrne et al., 2013), but high-frequency sampling can reduce the spatial resolution of a monitoring programme due to high start-up and running costs and infrastructural challenges (Fones et al., 2020). An opportunity therefore arises to move away from grab sampling methods and explore the use of less traditional monitoring techniques such as diffusive gradients in thin-films (DGT). Diffusive gradients in thin-films are small, relatively cheap, devices that can be used to monitor labile (bioavailable) inorganic and organic contaminant concentrations in rivers (Sherwood et al., 2009). They are deployed *in situ* in rivers, and continuously accumulate target solutes (e.g. trace and toxic metals) onto a binding layer throughout their deployment period. The rate of metal diffusion into the DGT is proportional to the metal concentration within the water column and as such when the DGT is removed, a singular time-averaged concentration for the whole deployment period can be calculated (Davison and Zhang, 1994). This offers a temporal resolution that cannot be gained through infrequent grab sampling. The DGT result is however an average concentration wherein any peaks in pollution will have been integrated (Zhang et al., 2016), making the extent of specific pollution instances hard to assess. Nevertheless, DGT has been used successfully alongside gammarid and grab sampling methods to monitor metal concentrations in a national scale study, where it was demonstrated that the tool appropriate for monitoring was dependent upon which metal and fraction was being analysed – with the three methods complementing each other (Uher et al., 2018).

Application of DGT in Philippine rivers could help address two critical knowledge gaps that currently limit the effectiveness of catchment management. First, it is widely understood that high river flows associated with rainfall events can drive increases in the flux of soluble metal species (Byrne et al., 2013; Gozzard et al., 2011). However, it is not simply the magnitude of the rainfall-runoff event that controls metal flux. Catchment wetness and metal mine waste geochemical and mineralogical properties also strongly influence the flux of metals through catchments (Byrne et al., 2020; Hudson-Edwards et al., 2003), and so there are considerable unknowns about when metals enter rivers in the Philippines and what the processes driving catchment mobilisation are – both of these knowledge gaps mean targeted management interventions are difficult. The time-integrated sampling capability of DGT offers the opportunity to establish robust estimates of metal concentrations and flux across different seasons and, assuming the DGT deployment method is resilient, DGTs can be deployed during very high river flow periods associated with typhoons where data on soluble metal concentrations and flux does not exists. The DGT methods' resilience to wet and dry season conditions in the Philippines has previously been demonstrated (Villanueva et al., 2013) wherein DGTs were housed in bamboo cages with holes drilled in the sides to protect them during adverse weather conditions. Second, the Philippines is one of the most biodiverse nations in the world, and it is also geologically diverse, suggesting that natural river water chemistry could vary widely across the archipelago. The implications for metal pollutants from mining activities is that the bioavailability and potential toxicity of metals could vary between river catchments as a function of water chemistry (de Paiva Magalhães et al., 2015; Miranda et al., 2022), as could the concentration of natural background levels of metals. The opportunity presented by DGT in this instance is that bioavailability of metals could be mapped at the national scale, allowing different environmental quality standards for metals to be developed that are ecologically relevant and specific to different river catchments and/or geological regions.

4.4. Challenge: tailings dam safety

Tailings dams are amongst the largest engineered structures in the world and the number of catastrophic dam failures are increasing globally (Owen et al., 2020). Approximately 1.2% of known tailings dams worldwide failed during the past century (Azam and Li, 2010; Islam and Murakami, 2021), a substantially higher proportion than the failure rate of water retention dams (Davies, 2002). Such failures can cause severe impacts on downstream catchments including destruction of vegetation and infrastructure, and loss of ecosystems and human lives (Guimarães et al., 2023; Kossoff et al., 2014; Rico et al., 2008). Recent examples of disasters associated with tailings dams failures and their immediate impacts include the 2019 collapse of the Brumadinho tailings dam in Brazil with at least 259 deaths (Silva Rotta et al., 2020); the 2015 Mariana tailings dams failure that killed 19 people and spread pollutants along 665 km of watercourses reaching the Atlantic Ocean (Carmo et al., 2017); and the 2009 failure of the Karamken tailings dam in Russia that killed two people and released 1.1 Mm^3 of tailings pond water containing cyanide and thiocyanate (rhodanide) (Glotov et al., 2018). Medium-to long-term impacts of tailings dam failures include persisting hot spots of increased contaminant concentrations in surface waters (Olías et al., 2012), remobilisation of contaminants deposited in fluvial sediments due to channel instability and erosion caused either by human action or by flood events (Dennis et al., 2003; Lecce and Pavlowsky, 2014; Macklin et al., 2006) and floodplain contamination caused by the spill of metal and metalloid elements which, when mobilised, can be potentially toxic to biota and particularly humans (Hudson-Edwards, 2003; Liu et al., 2005; Rico et al., 2008).

Tailings dam failures can be the result of inferior methods of construction, lax quality control measures incorrect assumptions in design or maintenance failures (Bowker and Chambers, 2016; Chambers and Higman, 2011; Vanden-Berghe et al., 2011). Failures are often triggered by overtopping, slope instability, earthquakes, or water seepage (Clarkson and Williams, 2020; Islam and Murakami, 2021). In the Philippines, there have been seven recorded incidents of tailings spills since 1993, which were all preceded by a heavy rainfall event (Holden, 2015). In other countries, landscape evolution models have been used to simulate the long-term geomorphic stability of post-mining landforms and structures to inform rehabilitation design (e.g. Hancock, 2021; Lowry et al., 2019). However, tailings dam monitoring and management practices need to be enhanced to help prevent these man-made disasters from occurring, especially in areas more vulnerable to natural hazards such as the Philippines.

4.4.1. *Opportunity: improving the monitoring and management of tailings dams and storage facilities through remote sensing and geophysical methods*

The use of remote sensing to identify and monitor tailings dams, including the impacts of their failures, substantially increased in recent years. This is partly due to an increasing availability of remotely sensed data, combined with improved methods capable of processing large datasets (e.g. cloud computing and machine learning). Remote sensing sensors that employ Interferometric Synthetic Aperture Radar (InSAR) technologies can be used to detect early warning signals of tailings dam failure. These include land deformation (Carlà et al., 2019; Du et al., 2020; Grebby et al., 2021; Mura et al., 2018), strata compaction and settlement (Hu et al., 2017), ground displacement and subsidence (Carlà et al., 2019; Mura et al., 2018; Thomas et al., 2019) and deformation of the dam itself (Grebby et al., 2021; Mazzanti et al., 2021). Surface displacement can be also monitored via repeated surveys using Uncrewed Aerial Vehicles (UAVs) employing optical cameras (Rauhala et al., 2017) in conjunction with Structure for Motion (SfM) photogrammetry, or Light Detection and Ranging (LiDAR). Optical satellite sensors can be used to monitor land cover characteristics such as vegetation which, in combination with slope values derived from DEMs and rainfall data, can be used to classify tailings ponds into different risk groups (Che et al., 2018). Satellite remote sensing can be also used to quantify the impacts in the aftermath of dam failures including monitoring water turbidity and tracking sediment movement and resuspension through rivers (Rudorff et al., 2018) and the coastal ocean (Coimbra et al., 2020).

More recently, the combination of remote sensing with machine learning has opened new ways that allow the identification and monitoring of ‘unknown’ mines and tailings dams, as a means of tracking increasing small-scale mining activities. Compiled databases of remotely sensed imagery of known tailings dams (Ferreira et al., 2020) can be used as training data inputs into machine learning algorithms. Such algorithms have been successful at identifying unlicensed mines in Brazil (Balaniuk et al., 2020) and China (Li et al., 2020; Yan et al., 2021). Global-scale mining land use datasets for large- and small-scale mines have been derived using these approaches (Tang and Werner, 2023). A vast dataset of expert-labelled training images will be required to further expand and automate such applications (Maus and Werner, 2024).

Similarly, geophysical technologies for monitoring natural and engineered slopes have advanced rapidly due to the need for improved landslide early warning systems (e.g. Whiteley et al., 2019). Many of these emerging applications are highly applicable to tailings dams, such as geoelectrical approaches to detect moisture driven changes in the subsurface (e.g. Dimech et al., 2022; Martínez et al., 2021; Oliveira et al., 2023) and seismic methods to examine ground motion and the geomechanical properties of slopes (e.g. Mollehuara-Canales et al., 2021; Ouellet et al., 2022).

Key trends and advances in geophysical observations of tailings dams include integrated observations and the shift from characterisation to long-term monitoring. The use of multimethod approaches (e.g. Mollehuara-Canales et al., 2021; Rey et al., 2022; Tavakoli and Rasmussen, 2022) enable a broader range of deterioration mechanisms to be detected; in particular the joint monitoring of moisture driven (from geoelectrical methods) and geomechanical (from seismic monitoring) changes in the structure are facilitating improved slope stability assessment. Likewise, a shift from characterisation (i.e. 2D/3D) to monitoring (4D) is being enabled by advances in monitoring instrumentation including bespoke geoelectrical monitoring systems (e.g. Chambers et al., 2022) and the development of nodal seismic systems and Digital Acoustic Sensing (DAS) (e.g. Miah and Potter, 2017; Tsuji et al., 2023). Recent studies show that the new opportunities for geophysical monitoring are beginning to be utilised for the monitoring of tailings storage facilities (Dimech et al., 2023, 2024; Olenchenko et al., 2020; Ouellet et al., 2022; Yurkevich et al., 2021). The wider developments in geophysical monitoring technology have clearly opened an opportunity for further monitoring of tailings facilities in future work. Remote sensing methods such as UAV photogrammetry are increasingly used in combination with geophysical reconnaissance and monitoring work, to provide surface observations and enable the derivation of DEMs to complement geophysical datasets and to aid geophysical processing and interpretation (Guireli Netto et al., 2023; Hussain et al., 2022; Whiteley et al., 2021). Recent developments in machine learning have allowed the use of algorithms to rapidly produce ground models from geophysical datasets (Whiteley et al., 2021). Remote sensing and geophysical methods may be complemented by community-based monitoring (Ruppen et al., 2021), an approach particularly pertinent when regulators are hindered by financial, technical or personnel constraints or state capture (Ruppen and Brugger, 2022).

4.5. *Challenge: resource assessment and metal recovery in ores and tailings*

Accurate characterisation of ore deposits and waste materials throughout the mining life cycle is important for environmental and economic purposes. In terms of environmental management, geochemistry and mineralogy influence the stability of the minerals/elements and their potential to cause environmental hazards (Jamieson et al., 2015). For instance, mineralogical data of ores and tailings could indicate if substantial amounts of potentially toxic elements (e.g. As, Pb) and iron sulfide minerals (e.g. pyrite and pyrrhotite) that could cause future instances of acid mine drainage are present (Hudson-Edwards et al., 2011; Wang et al., 2014). Accounting for a significant amount of non-economic sulfides in an ore deposit could allow proactive adjustments to isolate, contain, and reduce the sulfide content in the waste products (e.g. tailings), rather than reactive mitigation measures later on, when the costs will be more prohibitive (Arcilla, 2017). A more efficient removal of target metals, and of a wider suite of metals during initial processing of ores and concentrates could reduce future environmental impacts and produce tailings more amenable to remediation.

Additionally, tailings may contain economic metals or other materials that were not recovered due to less efficient processing methods, or those that were not considered valuable at the time of processing (Falagán et al., 2017). The inadequate liberation of minerals can be attributed to various factors, including the geological characteristics of the ore, mineral associations within the deposit, and the complex mineralogy of the deposit itself (Alcalde et al., 2018; Babel et al., 2018). In the case of Cu deposits in the Philippines, which are predominantly associated with refractory sulphides like pyrite, the strong association between chalcopyrite and pyrite can lead to poor copper recovery when employing conventional extraction methods (Aikawa et al., 2022; Owusu et al., 2014). Ultimately, this could be driven by a low cost-benefit ratio – if the expenses associated with separation and liberation outweigh the potential economic gain (Alcalde et al., 2018).

To enhance the economic viability of reprocessing tailings, it becomes crucial to evaluate the current level of mineral liberation and optimise the liberation process (Babel et al., 2018; Jena et al., 2022). Depending on the chosen metallurgical method, this optimisation may involve employing various techniques such as further crushing, grinding, and comminution to reduce the material into smaller particles. If tailings are already in a fine state upon disposal, advanced mineral processing methods must be utilised to effectively optimise the mineral liberation process (Jena et al., 2022). A key consideration for processing tailings, however, is that the tailings material should not be destabilised by excavation for reprocessing to avoid dam stability issues. Amongst the technology in development, hydrometallurgy has emerged as a highly promising approach for metal recovery from *in situ* complex ores and mine tailings. Hydrometallurgy applied *in situ* circumvents the energy cost, technical challenges, and environmental impacts associated with physically re-excavating and mineral processing the tailings material. Potential solutions currently being explored to optimise solvent flow within mine tailings include: electrokinetics (e.g. Torabi et al., 2021), bioleaching (e.g. Ye et al., 2017) and low viscosity solvents (e.g. Schueler et al., 2021).

There are other important factors to consider in the recovery of metals from tailings. Due to length of time associated with the dumping of tailings, they are commonly heterogenous in nature in both physical and chemical characteristics (Nyenda et al., 2021). For example, tailings are invariably fine grained, with modern tailings often finer (e.g. <75 μm diameter) than older (e.g. <250 μm diameter) deposits. This could be considered beneficial for *in situ* leaching because the fine-grained nature of the deposits enables high exposure of a percolating solvent with the target metal bearing mineral(s). However, the fine-grained nature of tailings can also present complexities associated with hydraulic conductivity, with hard rock tailings exhibiting typical conductivity values between 10^{-6} to 10^{-7} m/s (Aubertin et al., 1996). Given the nature of their deposition, mine tailings can also often exhibit a stratified structure which can result in differential vertical and horizontal hydraulic conductivity, with initial measurements suggesting that older, coarser tailings have greater hydraulic conductivities. Preferential flow is another common phenomenon, which is due to a range of processes such as: spatial inhomogeneity in tailings particle size distribution or physicochemical changes to the tailings, such as wetting and drying cycles. Such inherent elements present a range of technical challenges associated with any potential *in situ* leaching operation.

4.5.1. *Opportunity: using native plants for stabilisation and metal extraction*

Vegetation development on tailings is challenging due to the lack of plant nutrients and the presence of toxic metals (Domingo and David, 2014; Wang et al., 2017). For instance, a recent study at Philex Padcal Mine in Luzon found N concentrations in tailings to be seven times lower than the surrounding forest, while Cu concentration was at least an order of magnitude higher (Lazaro et al., 2024). However, there are plant species that can tolerate and 'hyperaccumulate' specific metal(s) in their systems up to hundreds- or thousands-fold greater than other plants without symptoms of toxicity (Baker and Whiting, 2008; Garbisu and Alkorta, 2001). Such plants can be used to stabilise metals in the soil through establishment of surface cover to reduce exposure to erosion agents, and root accumulation to reduce metal mobility, helping prevent off-site contamination (Bolan et al., 2011). Due to their unique characteristics and potential environmental benefits, there is significant interest in using metal hyperaccumulators to exploit ore deposits that are otherwise uneconomic to mine using conventional methods (Brooks et al., 1998). For such purposes, identifying the species and number of hyperaccumulator plants that can possibly be used for a target element serves as the priority (Corzo Remigio et al., 2020).

In the Philippines, there are at least 28 identified hyperaccumulators, of which 11 species are endemic (Duddigan et al., 2023).The country has been identified as one of those with the greatest potential for phytomining – the harvesting and processing of metal-concentrated plant material – particularly for Ni, due to the presence of woody hyperaccumulator species such as *Phyllanthus* spp. that is reported to accumulate up to 16.9% Ni (van der Ent et al., 2017). First reported in the country by Baker et al. (1992), there are currently at least 19 identified Ni hyperaccumulator species that can accumulate more than 1% Ni in their aboveground tissues (Duddigan et al., 2023; Fernando et al., 2013, 2014; Gotera et al., 2020; Quimado et al., 2015).

In addition to Ni, there are also Cu and As hyperaccumulator species that have been discovered in the country such as *Pityrogramma calomelanos* and *Pteris melanocaulon* for Cu (Ancheta et al., 2020; Claveria et al., 2019; Dahilan and Dalagan, 2017; De la Torre et al., 2016); *Pteris melanocaulon, Nephrolepis biserrata, Pityrogramma calomelanos,* and *Cynodon dactylon* for As (Ancheta et al., 2020; Claveria et al., 2019). The use of such plants for tailings remediation can potentially reduce contamination of tailings and recover residual metals for processing at the same time. While native plants have been previously used for tailings revegetation and stabilisation (Aggangan and Aggangan, 2012; Domingo and David, 2014), further studies are warranted on the propagation protocols, nursery management, and field growth and health of established and potential hyperaccumulators on mine tailings such as *Pinus kesiya,* a native pine species that grows on Cu–Au mine tailings at the Philex Padcal Mine. More research on the physiology and nutrient requirements of hyperaccumulators (Duddigan et al., 2023), and identifying and isolating microorganisms and mycorrhiza from tailings will be necessary to develop a wider-scale application of these plants to assist ecological restoration. Further opportunities lie in coupling hyperaccumulator, or metal tolerant plants (where tailings characteristics do not support hyperaccumulators), with novel organic solvents that may synergistically enhance metal extraction.

4.5.2. *Opportunity: using organic and environment-friendly solvents for metal extraction*

In recent years, mining companies have been exploring tailings as primary and secondary sources of metals. In the Philippines, the depletion of primary easily mined high-grade deposits necessitated the development of the capability to process lower grade resources, which makes reprocessing of historical tailings possible. For instance, tailings facility 1 (TSF1) at the Philex Padcal Mine contains 85 Mt of tailings deposited from 1971 to 1981, grading 0.24% Cu and 0.46% Au, which is higher than the current ore grades fed to the processing plant (Philex Mining Corporation, 2022). The combined value of Cu and Au in TSF1 is estimated to be approximately $4500 M USD. There is a strong consequent driver to develop new, environment-friendly approaches to economically recover such valuable metals from complex ores and mine tailings.

Target metals within mine tailings have been recorded as both present in their original mineral phase (e.g. Cu in chalcopyrite) but also as secondary precipitates and/or sorbed onto mineral surfaces (Juneidi et al., 2015; Lindsay et al., 2015). Given this often-complex distribution, coupled with the urgent need to implement more environmentally sustainable mineral processing and metallurgical techniques, much interest has been applied in recent years in the development of *in situ* hydrometallurgical approaches towards such metal recovery. Within this the selection of a suitable solvent is a fundamentally important consideration. Traditional solvents, such as strong mineral acids (e.g. H_2SO_4) for Cu, or cyanide for Au, are well demonstrated as effective for metal leaching (Abbott et al., 2011; Johnson, 2014); however, they have the potential to cause significant environmental damage should leakage occur. There is currently considerable interest in the development of new solvent formulations and applications which can exhibit comparable leaching efficacy, but at lower environmental toxicity and using those which can undergo more rapid biodegradation (Jenkin et al., 2016). Alternative solvents currently being explored, including a select number of organic acids such as citric acid and methanesulfonic acid, have been proven as highly promising (Crane and Sapsford, 2018). Such acids demonstrate comparable efficacy for target metal dissolution (Crane and Sapsford, 2018) and can also undergo more rapid biodegradation than conventional mineral acids, such as H_2SO_4 (Habbache et al., 2009).

Another alternative approach is to employ non-aqueous solvents such as Deep Eutectic Solvents (DES), in particular Type 3 DES which are mixtures of choline chloride (vitamin B4) and a hydrogen bond donor such as an amide, carboxylic acid, or alcohol. These are highly suited to leaching of tailings through a range of benefits including low volatility, high target metal selectivity, relatively low cost and low ecotoxicity. As mixtures of Lewis and Brønsted acids and bases they are infinitely tuneable (Abbott et al., 2011) and ternary and quaternary systems are possible as well as hybrid systems that are transitional to organic acids or aqueous salt systems. DES have been demonstrated to leach sulfides, oxides, arsenides, and even gold, in a range of geological matrices (Anggara et al., 2019; Jenkin et al., 2016; Pateli et al., 2020). Furthermore, these organic, ammonium rich, solvents will biodegrade after use to simple compounds (Juneidi et al., 2015) that can provide nutrients to microbes and plants, hence accelerating the development of ecosystems on the tailings.

Implementation of a successful *in situ* leaching system for tailings requires not only an effective solvent, but also: a) the ability to track and potentially control solvent movement, b) an understanding and management of the effects of solvent dilution by groundwater or rainwater, c) the capture of metals and, ideally, solvents after leaching for reuse to improve process economics, d) established evidence of the solvent and degradation products being environmentally safe *and* publicly acceptable, e) the promotion of ecosystem development by the residual solvent ideally achieved by adding organic matter on degradation and/or liberating nutrients from the tailings to promote plant growth, and f) the feasibility of accomplishing these steps economically. Solvent tracking may be possible with geoelectric techniques such as electrical resistivity tomography (ERT) and induced polarisation (IP) to identify the solvent and the increase in conductivity due to leaching of metal ions, as well as detecting dilution with water. Geoelectrical techniques have previously been employed in examining heap leaching and contaminant transport (Kuras et al., 2016; Rucker et al., 2009). Electrokinetics, which uses an electrical field to influence movement of ions on the electrical double layer of mineral surfaces, may be a viable technique to control solvent movement to promote leaching and capture the target metals (Martens et al., 2021; Torabi et al., 2021). Solvent selection will require careful screening of potential solvents for not just efficiency and cost, but also

Table 1
Research challenges and key recommendations for environmental sustainability.

Research challenges	Key recommendations
1. The complexity of separating the impacts of mining from different anthropogenic pressures	Adopt process-based river classification techniques (e.g. river styles analysis; Brierley and Fryirs, 2005) to interpret dispersal, storage, and remobilisation potential of contaminated sediment at the catchment scale, especially for tropical catchments, which have highly diverse hydromorphologic attributes (e.g. Tolentino et al., 2022). Geomorphological characterisation should be coupled with geochemical analysis (e.g. sediment fingerprinting techniques; Collins et al., 2017) to establish provenance and quantify the relative contribution of different sediment sources in the catchment, particularly those that are mining derived (e.g. Domingo et al., 2023).
2. Quantifying and predicting the environmental impacts of contaminated sediment from legacy, future, and contemporary mining	Use open-source, catchment-scale numerical models (e.g. CL model; Coulthard et al., 2013) that can predict erosion and deposition patterns in 3D (e.g. Coulthard and Macklin, 2003), as well as suspended and bedload fluxes at different spatial and temporal scales. Such models can help elucidate sediment connectivity (e.g. Xie et al., 2022) and landform stability under the influence of various natural and anthropogenic factors, including climate change.
3. A lack of water quality evidence to inform policy	Deploy flexible, inexpensive water quality monitoring devices (e.g. DGT) that can collect time-integrated measurements of bioavailable concentrations of contaminants (e.g. Sherwood et al., 2009; Zhang et al., 2016). National scale application of DGT devices may be possible due to their resilience to adverse weather conditions in the Philippines (e.g. Villanueva et al., 2013), which will allow for robust estimates of metal concentrations and fluxes across different seasons and catchments.
4. Tailings dam safety	Explore emerging geophysical monitoring techniques for mine waste and tailings storage facilities, including multimethod approaches and bespoke four-dimensional geoelectrical monitoring systems (e.g. Chambers et al., 2022; Rey et al., 2022). Remote sensing combined with machine learning can be used to detect early warning signals of tailings dam failure (e.g. Grebby et al., 2021) and the presence of unlicensed mining activities and infrastructure (e.g. Balaniuk et al., 2020).
5. Resource assessment and metal recovery in ores and tailings	Develop protocols for the wider-scale application of native hyperaccumulator species (e.g. Quimado et al., 2015) to assist in stabilising and extracting metals from tailings and low-grade ore deposits. This will require further examination of the native plants' physiology and nutrient requirements, as well as the identification and isolation of microorganisms and mycorrhiza from tailings material. Develop *in situ* metal leaching approaches for tailings and ore deposits using environment-friendly organic acids and non-aqueous solvents that have been shown to effectively recover metals from a range of geological matrices (e.g. Jenkin et al., 2016; Crane and Sapsford, 2018). Scaling up novel solvent application will require careful screening for

(*continued on next page*)

Table 1 (*continued*)

Research challenges	Key recommendations
	cost-efficiency and environmental impacts at different experimental stages, together with the development of solvent control and monitoring techniques. These leaching approaches may be progressed in partnership with phytomining techniques offering potential synergisms.

degradation, ecotoxicology, nutrient availability, environmental impact and public acceptability. This will require a staged approach from initial desk and laboratory studies to field mesocosm experiments, in tandem with stakeholder engagement at all stages. A particular challenge in the Philippines, which also applies to other tropical climates, is the heavy seasonal rainfall which would tend to dilute solvent and wash it out. However, it may be possible to turn this into an opportunity to make use of the seasonal cycle to leach metals in the dry season and then washing out solvent in the rainy season. If successful, *in situ* leaching will potentially result in a step change in the minerals industry, as mining operators will be able to produce valuable metals from tailings whilst remediating them of toxic metals and accelerating ecosystem development.

5. Key recommendations

Table 1 provides a summary of actionable insights derived from the main environmental challenges that hinder sustainable mining and the emerging research opportunities to address the gaps discussed in Section 4. These recommendations are intended to enable the advancement of more sustainable mining practices not only in the Philippines but also in other regions at a comparable stage of development.

6. Conclusions

In the Philippines, a range of tools and technologies that encompass a number of integrated recovery actions at different stages of the mining life cycle (Fig. 6) would allow for quantifiable assessments of environmental impacts (Gorman and Dzombak, 2018) and create a framework for sustainable mining. The impacts of legacy and contemporary mining can be better understood through integrative approaches despite the lack of existing baselines. Combining geomorphological tools with geochemical data (e.g. river styles analysis and sediment fingerprinting), and 2D/3D numerical modelling-based methodologies (e.g. CL model) would allow quantification and prediction of contaminant behaviour and fate at varying spatial and temporal scales. Flexible and inexpensive environmental monitoring devices can also be developed for water quality monitoring programmes (e.g. DGT), which can provide opportunities to create baseline datasets in a wider range of hydrological conditions that are otherwise difficult to obtain. State-of-the-art techniques in remote sensing with machine learning and geophysical monitoring systems have opened new possibilities for monitoring tailings dams to help manage and minimise impacts of mine waste both within mining sites and beyond. Innovative technologies can also be developed to enable efficient and economically viable processing of modern and legacy tailings using hyperaccumulator plant species and novel environmentally benign solvents to recover more metals whilst decontaminating tailings, promoting a circular economy of metals and enhanced ecosystem services.

In a global perspective, ensuring a reliable supply of minerals requires policy interventions that incorporate sustainability standards and innovations (International Energy Agency, 2023). The adoption of science-based approaches to support stricter environmental regulations on mineral/metal production can also contribute towards socio-economic development while preserving the environment. It is equally important that policies, underpinned by research, are effectively implemented to address social and legal issues (e.g. Arcilla, 2017; Domingo and Manejar, 2020; Pascual et al., 2020; Yumul et al., 2021). Enabling sustainable mining policy and practice, underpinned by research advances, will lead to an equal and inclusive framework for regulating large- and small-scale mining, and ultimately, to a sustainable mineral resource development in the mineral-rich developing countries like the Philippines.

CRediT authorship contribution statement

Justine Perry T. Domingo: Writing – review & editing, Writing – original draft, Visualization, Project administration, Formal analysis, Data curation, Conceptualization. **Gawen R.T. Jenkin:** Writing – review & editing, Writing – original draft, Visualization, Formal analysis, Data curation. **Laura Quick:** Writing – review & editing, Writing – original draft, Visualization, Project administration, Conceptualization. **Richard D. Williams:** Writing – review & editing, Project administration, Conceptualization, Writing – original draft. **Karen A. Hudson-Edwards:** Writing – review & editing, Writing – original draft. **Cecilia Tortajada:** Writing – review & editing, Writing – original draft. **Patrick Byrne:** Writing – review & editing, Writing – original draft. **Tom J. Coulthard:** Writing – review & editing, Writing – original draft. **Jenielyn T. Padrones:** Writing – review & editing, Writing – original draft. **Rich Crane:** Writing – review & editing, Writing – original draft. **Cris Reven L. Gibaga:** Writing – review & editing, Writing – original draft. **Grigorios Vasilopoulos:** Writing – review & editing, Writing – original draft. **Kate Tungpalan:** Writing – original draft. **Jessie O. Samaniego:** Writing – original draft. **Emma Biles:** Writing – original draft, Writing – review & editing. **Alexandria M. Tanciongco:** Writing – original draft. **Jonathan E. Chambers:** Writing – original draft. **Marilyn O. Quimado:** Writing – original draft. **Angel T. Bautista:** Writing – original draft. **Francis Ian P. Gonzalvo:** Visualization. **Karmina A.**

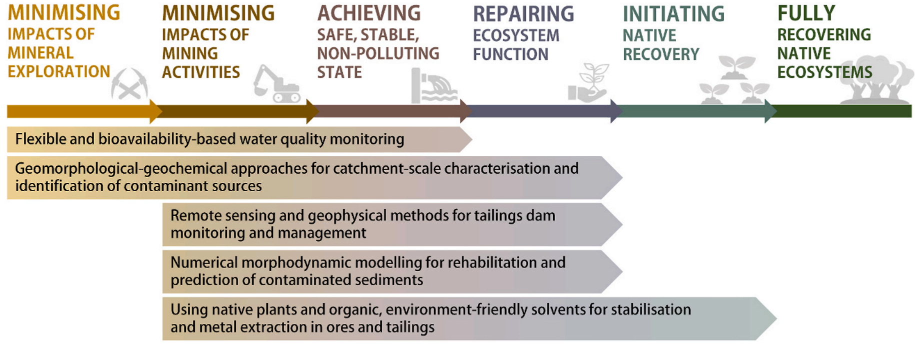

Fig. 6. The adoption of technologies and tools mapped onto recovery actions throughout the mining life cycle (modified from Gann et al. (2019) and Young et al. (2022)).

Aquino: Writing – review & editing. **Russell T. Swift:** Writing – review & editing. **Loucel E. Cui:** Writing – original draft. **Richard Chalkley:** Writing – original draft. **Mark Tibbett:** Writing – review & editing. **Decibel V. Faustino-Eslava:** Writing – review & editing. **Carlo A. Arcilla:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Supplementary material has been provided in this submission.

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Appendix A. Supplementary data

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