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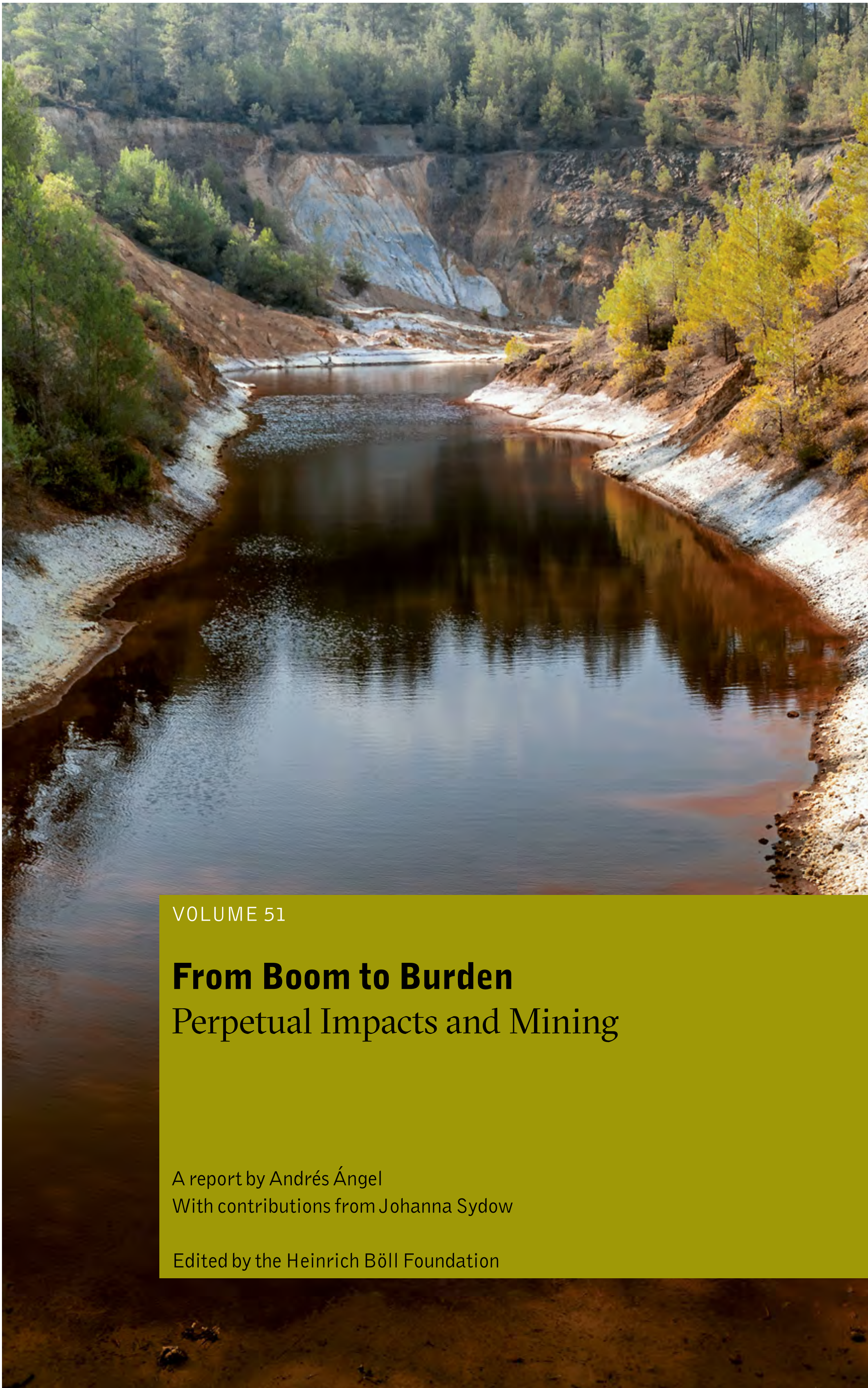

VOLUME 51

From Boom to Burden
Perpetual Impacts and Mining

A report by Andrés Ángel
With contributions from Johanna Sydow

Edited by the Heinrich Böll Foundation

FROM BOOM TO BURDEN: PERPETUAL IMPACTS AND MINING

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Edited by the Heinrich Böll Foundation

Author and contributor

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PREFACE

Massive infrastructure projects, the building and mobility sectors, digitalisation, the armaments industry and the drive to decarbonise the global economy are rapidly increasing the demand for minerals globally. Although some policies are focusing more on recycling and how to extract raw materials from urban mines, many others are aiming to open new mining projects.

Since the start of Russia's war of aggression against Ukraine, the race for raw materials has intensified. Regions and countries all over the world have been setting up their raw materials strategies and policies in an attempt to secure access to raw materials without relying upon China, which currently controls immense shares of the raw materials market. In this race, environmental and social standards also seem to be losing ground, with enormous potential consequences for local communities and the environment, now and in the future. In this rush for coveted minerals and metals such as copper, gold, bauxite, lithium and others – many of which are classified as «critical» – the long-term consequences of this extreme intervention in landscapes and ecosystems are often lost from focus.

Yet, in this context, it is extremely relevant to look at the legacy of this sector, analyse the long-term as well as future impacts and burdens, be aware of them and understand how to prevent them in the future. This report specifically looks at the long-term impacts that often seem invisible when a new mine is being set up.

The perpetual impacts, costs and burdens caused by mining can only be addressed when they are named in their different dimensions. Environmental damage is only one of them. There are also impacts due to changes in the social fabric as soon as mining activities begin, and culturally important or spiritual places or practices can be significantly disturbed by the large-scale interventions that mining entails.

This report strives to shed light on the various biophysical as well as sociocultural long-term impacts of mining, with a special focus on the biophysical impacts, which, in addition to the others, can mean massive long-term monetary costs for states. It analyses different national and regional approaches to perpetual impacts, and it offers recommendations on what to consider in current raw materials policies. With this report, we aim to contribute towards a debate and the creation of policies that consider not only the immediate consequences of these impacts, but also those that will affect the future generations of this planet.

Berlin, December 2024

Johanna Sydow and Annette Kraus
International Environmental Policy Division, Heinrich Böll Foundation

EXECUTIVE SUMMARY

Understanding the real cost of perpetual impacts – those environmental impacts that are expected to persist for centuries, millennia or longer, and whose end date cannot be determined with reasonable and substantial evidence – is a long overdue issue that society must confront. As a result of their properties, they entail insoluble institutional challenges. We simply cannot guarantee that our institutions will last long or function properly enough to manage them. This phenomenon is known as the «atrophy of vigilance».

They may also present other challenges such as valuation difficulties, delayed impacts, the transfer of impacts between projects and perpetual treatment requirements, all of which are explained in detail in this report.

These impacts have been systematically unaddressed and misrepresented, especially in the context of mining projects, and hardly discussed or not addressed at all in certain jurisdictions. They can be classified in two main dimensions: biophysical and sociocultural. The first dimension includes categories such as water quality decrease, landscape modification and destruction of natural components, among others, while the second dimension encompasses phenomena such as loss of livelihoods, traditional practices and knowledge destruction of sacred sites, to name a few. These are irreparable losses, and some of them require active perpetual management, and therefore perpetual financial costs.

Although this report is focused on the biophysical impacts of mining, these specific types of impacts are not restricted to this sector, but can arise from many other activities, and even from the cumulative consequences of human activities on the planet. Thus, the anthropogenic global warming and the crossing of tipping points are some examples. To illustrate this, the complexity of these systems and the tipping persistence are presented as evidence.

Concrete case studies from the nuclear waste management and mining sectors are described in further detail to illustrate the difficulties of their mitigation and the urgency of addressing this issue.

Whereas nuclear waste can be stored and locked in geological repositories designed to isolate it for up to one million years, mining infrastructure and mining waste usually remain on the surface – or close to it – indefinitely. Mining pits, tailings dams and waste rock piles are therefore exposed to atmospheric, hydrological and geological processes that compromise their chemical, physical and ecologic stability. They require perpetual monitoring, and in many cases active treatment/management measures without a foreseeable end. This is the case of the Berkeley Pit – included in this report – one of the many mines in the United States expected to require water management in perpetuity, and whose impacts compromise the surrounding wildlife

and communities to this day. Mitigation and remediation measures are severely limited by considerations of technical feasibility and the financial availability of resources.

Experiences and positions of some jurisdictions in North America, Latin America and of the European Union (EU) regarding perpetual mining impacts are explored in this report. From open-pit mining bans in Costa Rica and El Salvador; Colorado's 2019 explicit prohibition of projects predicted to require perpetual water treatment; Colombia's unpreparedness, documented through official replies to information requests from 2017 to 2022; Peru's promising regulatory and institutional framework; to the general guidelines provided by the main EU Directives, this section provides an overview of some actions being taken on the matter.

Finally, recommendations and conclusions that are specific to the European context and consider supply chain responsibilities in third countries are presented, such as ensuring that baseline studies are devoid of economic pressures, using methodologies that are verifiable for all stakeholders and the general public; assessing and fostering the creation of financial mechanisms to manage environmental liabilities in the long-term or in perpetuity; performing independent financial assessments of environmental impact statements to check their feasibility; promoting circularity, especially in instances that involve critical and strategic materials; and finally, when needed, taking bold steps to ban projects that predict having certain impacts in perpetuity. This last recommendation is presented as a reasonable alternative to the unreasonable burden of perpetual costs.

ABBREVIATIONS

AMD	Acid Mine Drainage
ARD	Acid Rock Drainage
ANLA	Environmental Licenses Agency (Agencia Nacional de Licencias Ambientales) [Colombia]
BGR	Federal Agency for Geosciences and Raw Materials (Bundesanstalt für Geowissenschaften und Rohstoffe) [Germany]
CO_2	Carbon Dioxide
CRMA	Critical Raw Materials Act
EEA	European Environmental Agency
EIA	Environmental Impact Assessment
EIS	Environmental Impact Statement
EPA	Environmental Protection Agency [US]
EU	European Union
FPIC	Free, Prior and Informed Consent
GHG	Greenhouse Gas
GT	Gigaton
LSOP	Large-scale Open-pit (mining/mine/s)
MADS	Ministry of Environment and Sustainable Development (Ministerio de Ambiente y Desarrollo Sostenible) [Colombia]
MBMG	Montana Bureau of Mines and Geology [US]
MDEQ	Montana Department of Environmental Quality [US]
PB	Planetary Boundary
PH	Potential of Hydrogen
PKKP	Puutu Kunti Kurrama and Pinikura people
POC	Point of Compliance
PPM	Parts Per Million
PWL	Protective Water Level
REE	Rare Earth Element
TSF	Tailings Storage Facility
UBA	Environmental Agency (Umweltbundesamt) [Germany]
UN	United Nations
UNEP	United Nations Environment Programme
UNFC	United Nations Framework Classification for Resources
US	United States
WIPP	Waste Isolation Pilot Plant

GLOSSARY

ACID MINE DRAINAGE: Type of mine drainage that exhibits lower-than-natural pH values. It is typically produced when water reacts with sulphide minerals contained in the mined rocks (pyrite and others) generating sulphates – commonly sulphuric acid – which in turn lowers the pH. Under acidic conditions, elements such as arsenic (As), cadmium (Cd), copper (Cu) and iron (Fe) may leach and become available.

ACID ROCK DRAINAGE: Naturally occurring acid drainage due to the interaction between water and sulphide-rich rocks.

ACTIVE SAFETY MEASURES/TREATMENT: Measures that require continuous or periodical human inputs such as monitoring, maintenance and human-made power sources to adequately fulfil their purpose.

ALKALINE MINE DRAINAGE: Type of mine drainage that exhibits higher-than-natural pH values. It is typically produced when water reacts with calcite or dolomite exposed from mining activities. These minerals can dissolve and capture hydrogen ions, thus increasing pH (reducing acidity). Under alkaline conditions, elements such as arsenic (As), selenium (Se), molybdenum (Mo) and antimony (Sb) may leach and become available.

ANTHROPOCENE: A «term widely used since its coining by Paul Crutzen and Eugene Stoermer in 2000 to denote the present geological time interval, in which many conditions and processes on Earth are profoundly altered by human impact.» (Subcommission on Quaternary Stratigraphy, 2024)

BACKFILLING: In the context of mine reclamation, it refers to the practice of filling the pit, tunnels or other voids generated by the activity with waste material.

CARBON TUNNEL VISION: A view on global environmental issues that is exclusively or disproportionately centred on GHG emissions, in particular CO_2, without considering or marginally considering others.

CONTACT WATER: Water that comes into contact with potential pollutants (WSP Canada Inc., 2016).

CRITICAL RAW MATERIAL: Non-energy, non-agricultural raw material with high economic importance and supply risks related to a high concentration of supply in very few third countries (Directive 2024/1252, 2024).

DELAYED IMPACT: Impact that only becomes significant after a lag time or latency period.

ENVIRONMENTAL IMPACT STATEMENT: «A detailed written statement [...] analyzing the environmental impacts of a proposed action, adverse effects of the project that cannot be avoided, alternative courses of action, short-term uses of the environment versus the maintenance and enhancement of long-term productivity, and any irreversible and irretrievable commitment of resources.» (USDA, n.d.)

ENVIRONMENTAL IMPACT: Difference in the magnitude of a measurable variable of interest, attributable to a specific project and/or activity.

EUROPEAN CRITICAL RAW MATERIALS ACT (CRMA): Piece of legislation from the European Union passed in April 2024 with the stated objective of ensuring access to a «secure, resilient and sustainable» supply of non-agricultural, non-energy raw materials considered critical due to their economic importance and high supply risks (Directive 2024/1252, 2024).

INERT WASTE (OR «STERILE»): «Waste that does not undergo any significant physical, chemical or biological transformations. Inert waste will not dissolve, burn or otherwise physically or chemically react, biodegrade or adversely affect other matter with which it comes into contact in a way likely to give rise to environmental pollution or harm human health. The total leachability and pollutant content of the waste and the ecotoxicity of the leachate must be insignificant, and in particular not endanger the quality of surface water and/or groundwater.» (Directive 2006/21/EC, 2006)

LAG TIME OR LATENCY PERIOD: Interval between two related phenomena. In environmental science, it may be the time that passes between an activity that generates a disturbance and a subsequent impact (Puettmann & Bauhus, 2023). Usually, the lag time is counted up until a certain threshold of significance for an indicator has been reached or exceeded (concentration, critical mass, reaction rate, volume, etc.).

LEACHATE: «Any liquid percolating through the deposited waste and emitted from or contained within a waste facility, including polluted drainage, which may adversely affect the environment if not appropriately treated.» (Directive 2006/21/EC, 2006)

MINE DRAINAGE: Effluent that has been polluted due to the contact with mined materials or any potential pollutants from mining activities. Acid mine drainage is the most prevalent type, but alkaline mine drainage may also occur. Both can leach potentially harmful elements for human health and for ecosystems (US EPA, 2023).

MINING (MINERALS): Economic activity consisting of the extraction, concentration and simple transformation of minerals, metals and rocks.

MITIGATION: Control or reduction of the negative impacts on a system.

MONITORING: Longitudinal and systematic observation of the changes in the environmental conditions of a specific element or area.

ORE: Naturally occurring material (rock, mineral) from which a mineral, a metal or an element of interest can be extracted or is preferentially extracted due to economic, technical or other types of feasibilities.

PASSIVE SAFETY MEASURES/MITIGATION: Measures that rely on inherent design characteristics and/or on the natural conditions or dynamics of the system to fulfil their purpose.

PERPETUAL IMPACT: Environmental impact estimated to persist for centuries, millennia or longer, whose end date cannot be determined with reasonable and substantial evidence, and which entails wicked institutional challenges (atrophy of vigilance).

PIT: Excavation made using mechanical and/or chemical means (explosives) to get to the material of interest. Along with rock piles and tailings impoundments, it is usually the main landscape feature left by open-pit mining.

POST-CLOSURE STAGE: Phase of a project that follows the closure stage. Typically consisting of management and monitoring activities, including mitigation/remediation. In the context of perpetual impacts and depending on the project, this stage can last several times the duration of the project itself from exploration to closure.

PSYCHOLOGICAL DISTANCE: Subjective experience of feeling that something is close or far away from the self, the here and the now (V. Boivin & Boiral, 2022).

REHABILITATION: The «treatment of the land affected by a waste facility in such a way as to restore the land to a satisfactory state, with particular regard to soil quality, wild life, natural habitats, freshwater systems, landscape and appropriate beneficial uses.» (Directive 2006/21/EC, 2006)

REMEDIATION: Structural correction of a negative impact on a system.

ROCK PILES OR HEAPS, MINING DUMPS, STERILE DUMPS: Accumulation of mining wastes without a significant enough concentration of materials of economic interest to be previously separated by chemical or other means. Due to these low or negligible concentrations, these materials are termed «sterile» (see «inert waste»).

SCALE OF INTEREST: Resolution or level at which a phenomenon is considered to be worth examining and/or significant.

SOCIAL DISCOUNT RATE: Factor used to represent the perceived value of consuming a certain resource in different points in time. Using a very high discount rate assumes little importance to future benefits and costs of consumption in the present and vice versa (Freeman et al., 2018; The White House, 2024).

SOLASTALGIA: Pain associated with the recognition of an immediate threat or harm to a place where one resides and/or that one loves and a desire for the place to continue existing as it is to provide comfort or solace (Albrecht et al., 2007).

STRATEGIC RAW MATERIAL: Non-energy, non-agricultural raw material essential to national defence and whose supply depends wholly or in part on foreign countries (American Geological Institute, 1997).

SUBSIDENCE: Sinking of a terrain's surface with neglectable horizontal motion. It may be driven by natural processes (solution, compaction, thawing, etc.) or by human activities (groundwater or oil extraction, underground mining infrastructure collapse, etc.) (American Geological Institute, 1997).

TAILINGS STORAGE FACILITY: Infrastructure of any type that is designed for containing tailings (impoundment, dam, drystacking disposal site, etc.).

TAILINGS: Mining waste that has been physically and chemically transformed and from which most materials of economic interest have been extracted. There are mainly two types: humid and filtered. Alternatively: «waste solids or slurries that remain after the treatment of minerals by separation processes (e.g. crushing, grinding, size-sorting, flotation and other physico-chemical techniques) to remove the valuable minerals from the less valuable rock» (Directive 2006/21/EC, 2006).

TIPPING ELEMENT: The «subsystems of the Earth system that are at least subcontinental in scale and can be switched -under certain circumstances- into a qualitatively different state by small perturbations.» (Lenton et al., 2008)

TIPPING POINT: The «critical point – in forcing and a feature of the system – at which the future state of the system is qualitatively altered.» (Lenton et al., 2008)

Introduction

Mining is everywhere. Every building, tool, appliance, gadget, means of transport and even commodity has mined materials included in their production processes at some point. It is therefore an extremely important activity for our species and an integral part of our development as a civilisation. Its positive impacts are, therefore, numerous, and the comforts we enjoy in modern society would be unthinkable without it.

As we confront the impacts and looming threats of climate change, the promise of transforming and growing energy systems through the extraction of energy transition minerals is appealing. However, there is no such thing as a free meal. Although mining has undeniable benefits, its negative impacts can outlast the activity itself by hundreds or thousands of years, or even longer. It is up to us to decide which impacts we accept, yet sound decision-making requires sufficient information – particularly about perpetual impacts – which remains limited.

This report aims to address an information gap that obscures the full costs of mining, especially regarding impacts that persist beyond extraction. This gap often leads to asymmetry between project proponents and other stakeholders, such as local communities, which ultimately may lead to environmental conflicts (Ángel, 2019). Bridging this gap and developing solutions is particularly urgent, as many coal mines globally are closing or nearing closure, while new mines are opening to meet the rising demand for energy transition materials.

Aware of the potential risks that a global-scale energy transition may bring, the Office of the Secretary-General of the United Nations (UN) has created the Panel on Critical Energy Transition Minerals – composed of 25 UN Member States and 14 non-state actors – which produced seven principles to build trust among stakeholders of the critical materials supply chains. These principles were published in the 2024 report «Resourcing the Energy Transition Principles to Guide Critical Energy Transition Minerals towards Equity and Justice» (UN Secretary-General's Panel on Critical Energy Transition Minerals, 2024).

The principles include an actionable recommendation to set a Global Mining Legacy Fund to manage abandoned mining liabilities. Although this is a much needed and valuable achievement, with regard to perpetual impacts, more specific efforts from a precautionary approach are needed to avoid those deemed unacceptable rather than focusing on mitigating them after their onset.

Based on this background, the present report aims to provide a basic conceptual framework on perpetual impacts, discuss their profound implications, explore some case studies and provide remarks on management alternatives from around the world to inform communities, civil society organisations, academia, and the public and private sectors to foster better governance of the issue.

An urgent matter: Why now?

A frequent argument used by stakeholders to downplay the environmental impacts of extractive projects is that «all human activities have an impact». Although true, this narrative often sidesteps discussions on the case-specific magnitude, rate and scale of impacts. Such avoidance hinders public understanding of the projects' true costs and limits informed discussions on consequences and alternatives. In countries with weak environmental institutions, this approach can lead to environmental assessments that overlook potentially decisive factors.

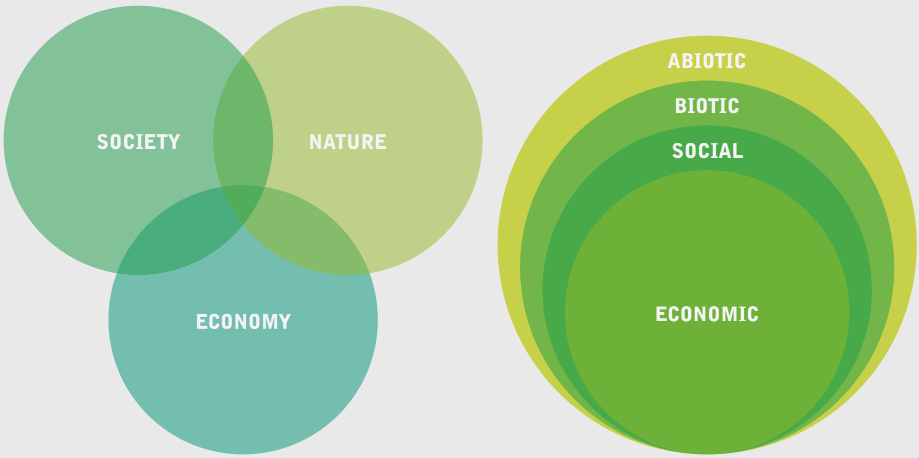
This strategy usually works and has been used in many sectors whose projects may entail significant environmental impacts. Stakeholders with vested interests in one sector frequently argue in favour of theirs and against others in the hope that the public identifies them, at least temporarily, as the least costly choice. In the context of mineral extraction, public conversations tend to focus on narratives around green and sustainable mining, development, economic growth through foreign investment and others, rather than on concrete biophysical and sociocultural impacts. The discourse sometimes even permeates environmental impact assessment processes, and institutions are pressured to approve projects without fully pondering the full extent of their positive and negative impacts.

Certain questions are frequently left unanswered, and in the worst cases, even go unaddressed, for example: Who pays for pit lake water quality treatment after the project ends? Who monitors the remaining rock piles/tunnels to guarantee their physical stability once the company is gone? Who will prevent/manage contact water seepage from the tailings dam or impoundment in five decades? Can the potential loss of cultural practices/livelihoods/sacred sites be compensated? If so, how? These are examples of questions that the public and incumbent officials should always ask when discussing and assessing a mining project proposal. If these questions are left unanswered, the whole process of impact assessment is structurally flawed.

An open social dialogue on the magnitude and persistence of environmental impacts would help correct this misrepresentation. The perpetual impacts framework aims to characterise and communicate more accurately the attributes of impacts whose persistence is undefined, that exhibit irresoluble uncertainty and lead to insoluble institutional challenges, with the ultimate goal of avoiding long-term negative externalities. It opens up a door for discussing approaches based on both weak and strong sustainability applied to impacts management. The former refers to a framework that assumes strong value comparability and perfect compensation, whereas the latter refers to the opposite (Martínez Alier, 2011). Concretely, this means that weak sustainability posits that common value ground can always be found and that any losses (biological, cultural, health, etc.) are susceptible of being adequately compensated (financially), whereas strong sustainability considers value diversity and the possibility of instances in which complete compensation is not possible.

Therefore, a vision of the management requirements of mining which accepts that not all impacts can be internalised or compensated would include an upfront and thorough discussion of post-closure costs, responsibility frameworks and, nowadays, even discussions about the trade-offs between the local or regional level and the global level – a topic that is explored further in other sections of this report.

Figure 1: Weak vs. strong sustainability
Diagram representing the weak (left) and strong (right) sustainability frameworks. Among other key differences, in a weak sustainability framework, nature is seen as an input of the economic system, there is strong comparability of values and full compensability. In a strong sustainability framework, the economy is subordinated to, and limited by, nature, value comparability is weak and compensability is only partial.



Source: Own graphic; Giddings, 2002.

In the context of mining, this framework highlights the frequently occurring but rarely-discussed costs that persist indefinitely after a project itself has finished and that occur due to both the design of the activity itself and the dynamics of the impacted systems. These are the so-called perpetual impacts, which have profound unaddressed social and environmental implications. It is indispensable to spread awareness of their existence and to conduct serious societal debates on them. This is relevant not only for preventing them in future projects, but also for managing already existing ones.

Current discussions in Europe

Last year, the EU introduced the Critical Raw Materials Act to secure its raw materials supply by reducing dependency on China. The Act promotes increased mining, processing and recycling efforts, with a focus on strategic projects and partnerships. Companies can submit requests to the European Commission to have their projects designated as «strategic».

In its first call for applications, the EU received more than 170 project proposals, which it is evaluating using the United Nations Framework Classification for Resources (UNFC) to determine eligibility as strategic projects. These projects may receive special support. They are assessed along three dimensions: Project feasibility, geological knowledge, and social-ecological viability. The latter is mainly assessed by analysing how the project can contribute to the fullfillment of the Sustainable Development Goals. By this, the UNFC criteria emphasise the potential benefits of mining operations while focusing less on associated risks, though they do account for the full life cycle of a mining project, including remediation.

In our interpretation, this approach would require assessing perpetual costs; however, given the vague guidelines within the framework and the current rush to launch new projects, there is a significant risk that such considerations may be overlooked. Furthermore, the EU ties its definition of «strategic projects» to a commitment to certify each project. Certification schemes will need to be accredited by the EU. From our view to qualify as strategic, any project should consider perpetual impacts from the planning stage, necessitating high standards for environmental impact assessments and monitoring. Yet, within the EU, demands for deregulation and efforts to expedite environmental impact assessments could further undermine the essential need to address perpetual impacts.

Interpreting environmental due diligence from a strong sustainability perspective, the EU Batteries Regulation also requires addressing perpetual impacts throughout the entire supply chain.

Perpetual Impacts: A Conceptual Approach

Environmental impacts

Although definitions vary from jurisdiction to jurisdiction, in the context of this report, an environmental impact is defined as the change in magnitude of a variable of interest that is attributable to a project and/or activity. It is also important to highlight that impacts are neither intrinsically beneficial nor detrimental, but can be – or even have – mixed effects, depending on their interaction with the matrices affected. In simpler terms, it can be imagined as the change in the magnitude of a selected indicator such as potential of hydrogen (pH) value, water flow change (cubic metres per second), royalties paid (€), number of relocated persons, cultural sites affected or job positions created, income loss due to a health condition (€), concentration of a certain pollutant (mg/L), etc.

Depending on the matrix or dimension they affect, impacts are classified by type. Rathi (2021) mentions the following: physical, chemical, biological, health, social and economic. However, some of these categories may be closely related and even causally linked, so it may not be practical or meaningful to separate them. For simplification, only two will be distinguished in this report: biophysical and sociocultural, which encompass the first and last three aforementioned types, respectively. It is important to remark that both health and economics are included as part of the second category.

Finally, it is important to recognise that not all the consequences of a project can be objectively evaluated or directly quantified due to knowledge constraints, lack of capacity, their intrinsic incommensurability, valuation preferences and other circumstances. However, when possible, it is desirable to have as many quantifiable and meaningful variables associated to facilitate the representation and understanding of the magnitude of the changes introduced by a project in the local, regional and global socioecological scales.

Why perpetual?

Environmental impact assessments (EIAs) have traditionally used methods that assess factors such as intensity, extent, duration, reversibility, synergy and accumulation to gauge the magnitude and importance of impacts. For instance, impacts are often categorised by persistence: short-term (days to weeks), medium-term (weeks to months), and long-term (months to years). However, some impacts are so prolonged – or even indefinite – that they must be considered permanent on a human timescale.

Moreover, not only can they persist for extremely long periods of time (centuries, millennia or longer), but might also require management via, for example, monitoring and mitigation activities without a foreseeable end. These impacts are often referred to in literature as «residual», «legacy», «permanent», etc. (USGS, 2024). Although no single word captures the complexity of these impacts, the present report proposes the term «perpetual» due to its antecedents and the etymologies of both this and other similar terms, which are explained next.

Among other meanings, «residual» is described as «resulting or left from something that was previously present» but also as «remaining after most of something has gone» («Residual», 2024). This second definition may erroneously convey that the repercussions of an activity after it has ceased are less consequential than those coetaneous to it. On the other hand, although «legacy» alludes to an aftermath – in the sense of being «something that is a result of events in the past» («Legacy», 2024) – it leaves out the time aspect, which is essential in the discussion.

Lastly, «permanent» and «perpetual» share the prefix *per*, which can be interpreted as «thoroughly» («Permanent», 2024); however, they differ in their second roots, *manere* and *petere*, which respectively mean «to stay» and «to go towards». Although it is true that it is the nature of perpetual impacts to remain, it is important to acknowledge the dynamic aspect of this category of impacts, and this is better captured by the second term.

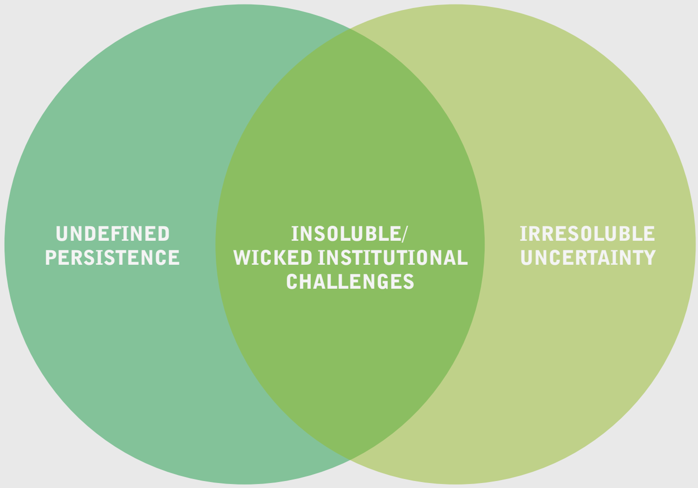
Regardless of the preferred term, the main message of this report is that, as a society, we need to be aware of their existence and consequences, that appropriate instruments to manage them must be in place and that lack of awareness in the context of a green extractivism boom may lead us to unintended permanent costs, so there is a pressing need for action.

Essential characteristics

In the context of a project, an environmental impact should be considered perpetual if it exhibits two essential characteristics: **undefined persistence** and **irresoluble uncertainty**. The first refers to its indeterminate or extremely long, estimated duration, which may even exceed by orders of magnitude that of the project itself, while the second refers to the lack of sufficient scientific evidence that reasonably indicates an end to it.

Some direct or indirect impacts leading to, for example, the biological extinction of an endemic species, permanent loss of ecological niches, community livelihoods, knowledge, cultural practices and/or social or economic structures, etc., could reasonably be deemed as irreversible if enough evidence exists to demonstrate that exceptionally serious damage has occurred or – from a precautionary approach – if it has a very high probability to occur should there be a particular disturbance.

Figure 2: Essential characteristics
The two essential characteristics of perpetual impacts and the resulting insoluble or, respectively, wicked institutional challenges.



Source: Own graphic.

Regarding the definition, it is important to highlight two aspects:

a. «Perpetual impact» as a category is independent from a perceived or estimated severity or magnitude, as it only refers to the duration. Generally speaking, however, and considering that all human activities entail impacts, discussions around them start occurring if stakeholders deem them to be relevant enough.
b. Considering the magnitude of the risk involved, a precautionary approach should be used, meaning that if there is uncertainty about the duration of a certain impact, the highest classification should be assumed.

It is important to remark that the extractives sector has been observed to be prone to illegal conduct carried out by some of its agents, and there are several verified instances of corruption, state capture and human rights violations, among other things. Gudynas (2019) offers an overview of the close relation between the extractive sector, corruption and violence in countries of the Global South.

Moreover, although they cannot and should not be characterised as mere and conventional «impacts» due to their criminal nature, instances of human rights violations and corruption taking place in the context of extractive projects are to be assessed and prevented via individual risk assessments and can constitute perpetual impacts. This is the case where, due to the dynamics introduced by a project – be they internal or external – an entire human group is exterminated or their practices are permanently modified due to the loss of knowledge transmission or even abandoned. This aspect is expanded upon below in the discussion around the sociocultural dimension of perpetual impacts.

Secondary characteristics

Besides the two aforementioned characteristics, perpetual impacts, especially the biophysical impacts that are related to mining, may exhibit others that are worth mentioning. It is important to remark that not all of these are necessarily essential to them, and may therefore also be associated with short-, medium- and long-term impacts. Some examples are provided below.

Integral valuation difficulties

Fully accounting for the costs of long-term impacts is complicated by many factors, and it is likely even more challenging in the case of perpetual impacts. Not only do they compromise direct use values, but they also affect non-use values such as option, bequest and existence. It is important to stress that when valuing perpetual impacts; non-use values gain more relevance relative to short- or medium-term impacts due to their intrinsic intergenerational nature. Present bias and the resulting social discount rates are aspects to consider and may hide the real costs.

To better explain each type of value, let us consider a flooded mining pit and its potential associated types:

- *Direct:* The materials removed to get to the ore – called «overburden» – plus soils and vegetation may not be used, constituting a loss.
- *Option:* Some of the potential future uses of the site are lost. The area cannot be used for forestry purposes and cannot provide the same ecosystem functions as before, while other uses may be gained, for example as recreational areas.
- *Bequest:* Future generations may never have access to the resources (mineral, biological, cultural) present before extraction because they have been deeply altered or already used and exhausted.
- *Existence:* Any natural systems present before the pit construction (woods, rivers, mountains) – independent of our capacity of or interest in using them – would be gone.

Such differences in use preferences – and therefore, in valuation frameworks – may be irreconcilable and evolve into full-fledged environmental conflicts, especially when uses are linked to cultural practices. One such example comes from the Muğla Province, in Turkey, where expanding coal mines to feed the Yatagăn power plant and others in the country have already affected the nearby traditional economy based on olives by destroying groves and threatening the villages of Yeşilbağcılar and Turgut (350, 2024; Gümüşel & Gündüzyeli, 2019).

Another factor that makes integral valuation extremely difficult are the inherent limitations associated with impact prediction, as these limitations are exacerbated in the context of highly complex projects spanning very long periods. One of the most comprehensive and robust pieces of evidence of such limitations was produced for the field of water quality impacts by Kuipers et al. (2006).

They provide extensive research comprising an initial review of 104 environmental impact statements (EISs) for 71 major hardrock mines in the United States, and an evaluation of the accuracy of water quality prediction in a representative selection of 25 among them before comparing them with the actual water quality data at the mine sites. The study found that all EISs predicted acceptable water quality levels after mitigation, but predictions that considered these mitigation activities were based on inadequate information.

It also found that 76 % of the mines (19 out of 25) polluted the groundwater or surface water enough to exceed water quality standards. Moreover, the predictions regarding the efficacy of mitigation efforts were not any better. In fact, 73 % and 77 % of the mines exceeded surface water and groundwater standards, respectively, in spite of predicting the opposite if mitigation activities had been in place. Finally, of the 19 mines that exceeded standards, 63 % had higher than acceptable levels of lead, mercury, cadmium, copper, nickel or zinc, while 58 % experienced issues with arsenic and sulphates, and 53 % showed exceedances in cyanide (Earthworks, 2006).

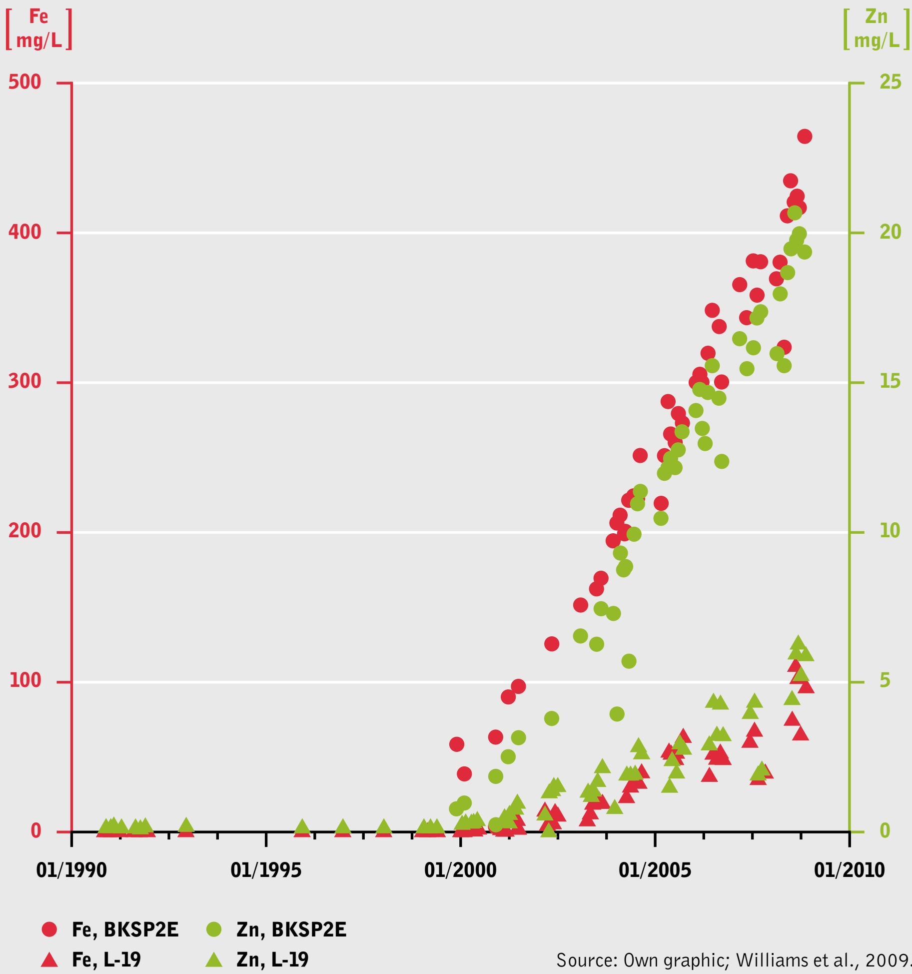
Delayed impacts and latency times

Environmental impacts may not manifest themselves during the extraction stage or immediately after it. They may exhibit latency times that mask their real magnitude or persistence, thus eliciting a false sense of security in decision-makers. Considering that some jurisdictions lack appropriate post-closure regulations and/or ignore long-term environmental monitoring and perpetual impacts altogether, it is indispensable to have appropriate risk assessment methodologies, meaningful stakeholder participation and sound prediction methodologies.

For example, water quality parameters in a mining site may stay within acceptable and stable values for months, years or even decades after extraction has ended. However, they may vary dramatically afterwards. In other cases, the conditions are such that water quality issues arise soon after the operation begins, and therefore responsibility allocation is more straightforward, such as in the case of the Buckhorn mine in the state of Washington, US (Okanogan Highlands Alliance, 2024b).

Figure 3: Delayed Impacts

Iron and zinc concentrations at the Landusky mine between 1990 and 2000. The mine was abandoned in 1998 by Pegasus Gold Corporation due to bankruptcy. The site was taken over by the US Bureau of Land Management and the Montana Department of Environmental Quality (MDEQ). Up until 2009, the closure costs amounted to USD 57 million. Due to the high concentration of sulphides and the potential for leaching acid and heavy metals, the mine is expected to require water treatment in perpetuity.



Source: Own graphic; Williams et al., 2009.

Impacts transfer

Both passive and active mitigation measures require materials and energy, although the former likely require arguably much less than the latter (see glossary). This is because passive systems such as artificial wetlands, geomembrane linings and permeable reactive barriers are expected to fulfil their purpose in the medium and long terms without human intervention once installed. Conversely, active systems, such as managing pH values by adding crushed limestone to pit lakes, require the periodical input of reactives. Of course, passive systems cannot last indefinitely, but the assumption is that their lifetime before any intervention is required is significantly longer.

If the materials used to build these systems or the reactives to put these measures in place must be sourced from outside the original mining area, then it can be argued that, at least partially, the demand from an extraction project is driving further extraction and capture of energy outside their area of influence and are therefore responsible for them as well.

An example of this is the periodic limestone addition to control pH in pit lakes that is mentioned above. Limestone is a geological material, and therefore it has to be extracted, processed and transported to the treatment area, thus generating impacts outside of the project's obvious area of influence.

This treatment is used in some European regions, where lignite mining has transformed the landscape forever. In East Germany (Lusatia), West Poland (Silesia) and Northern Czechia (Bohemia), artificial pit lakes and waste rock piles have extensively replaced meadows, hills and plains, and although there are opportunities to use some of this leftover infrastructure for recreation or provision of certain ecosystem services (Lund & Blanchette, 2023), caution must be exercised to carefully assess whether the net balance is positive. This is because some pit lakes require periodic neutralisation treatments (LMBV, 2021), which demand financial, human, technical and other types of resources.

Neuwieser See (Elsterheide, Saxony, Germany): Some pit lakes, like this one in Lusatia, require periodic neutralization to prevent pH decrease, in this case conducted by limestone ships.

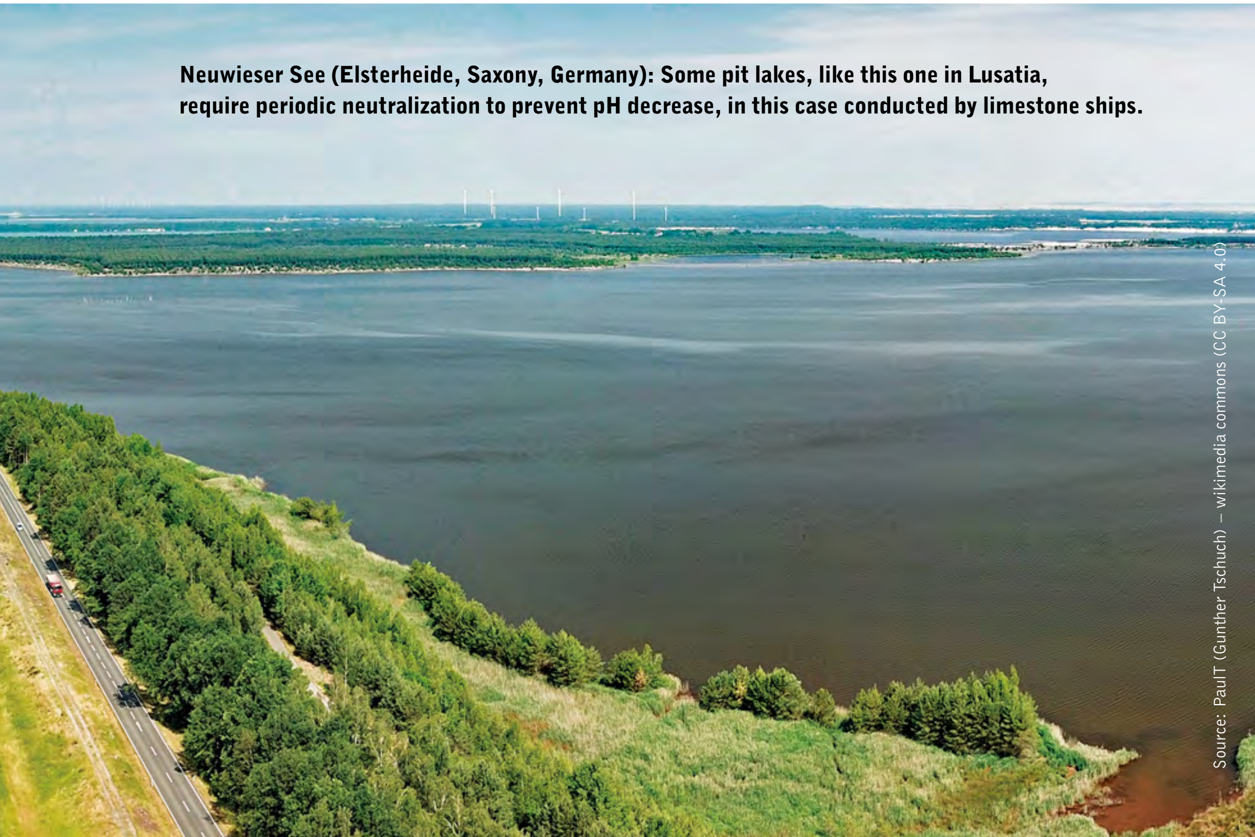
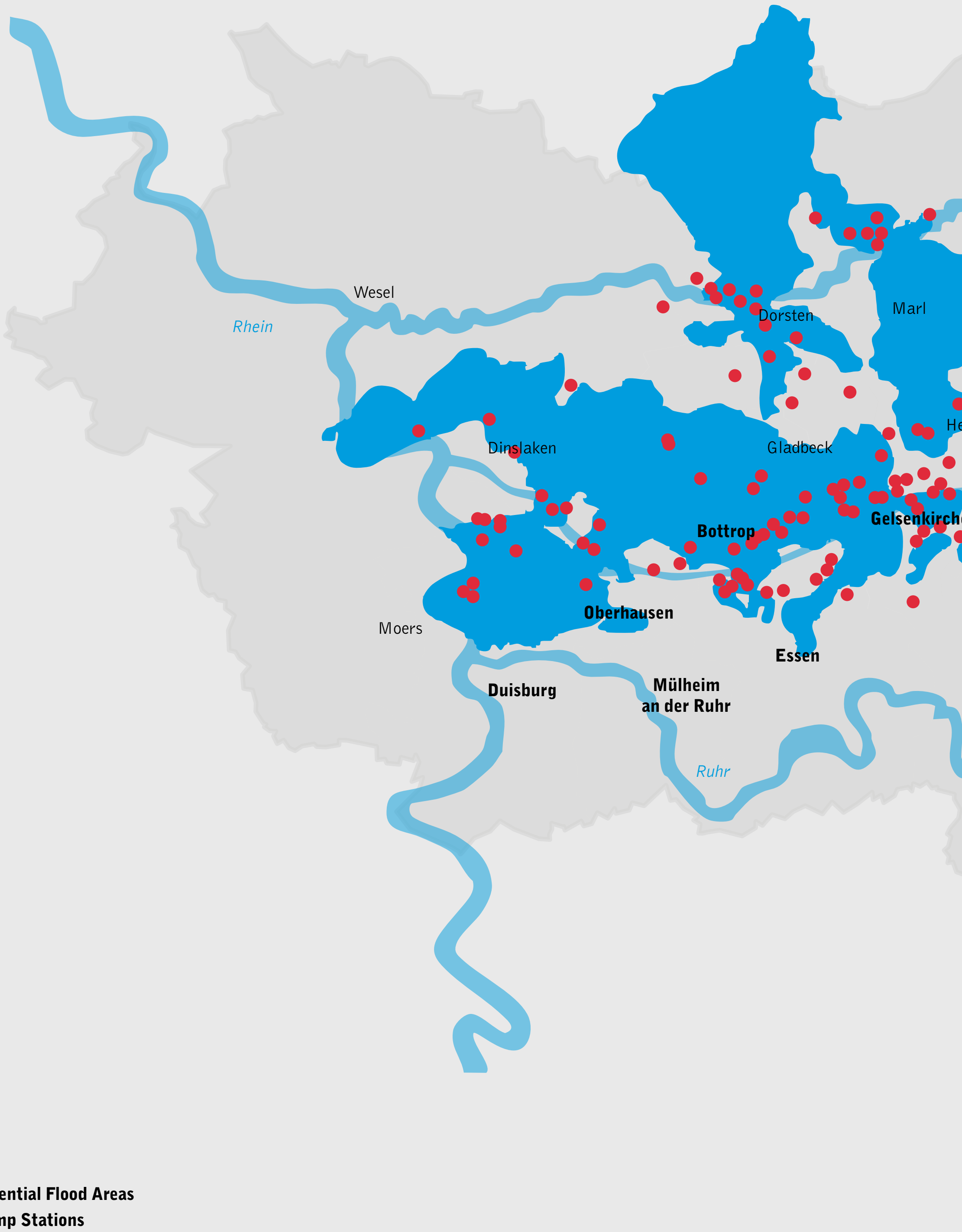
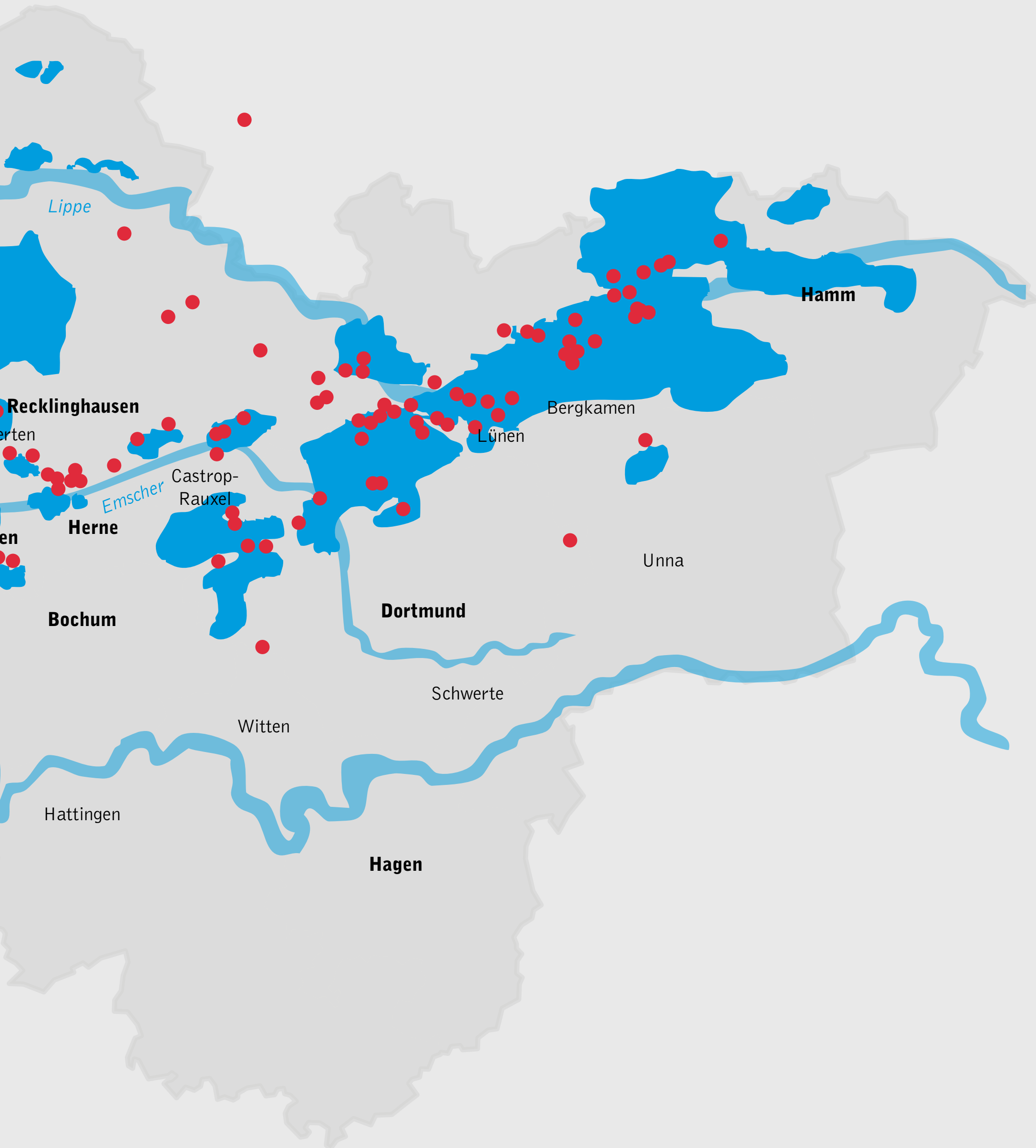


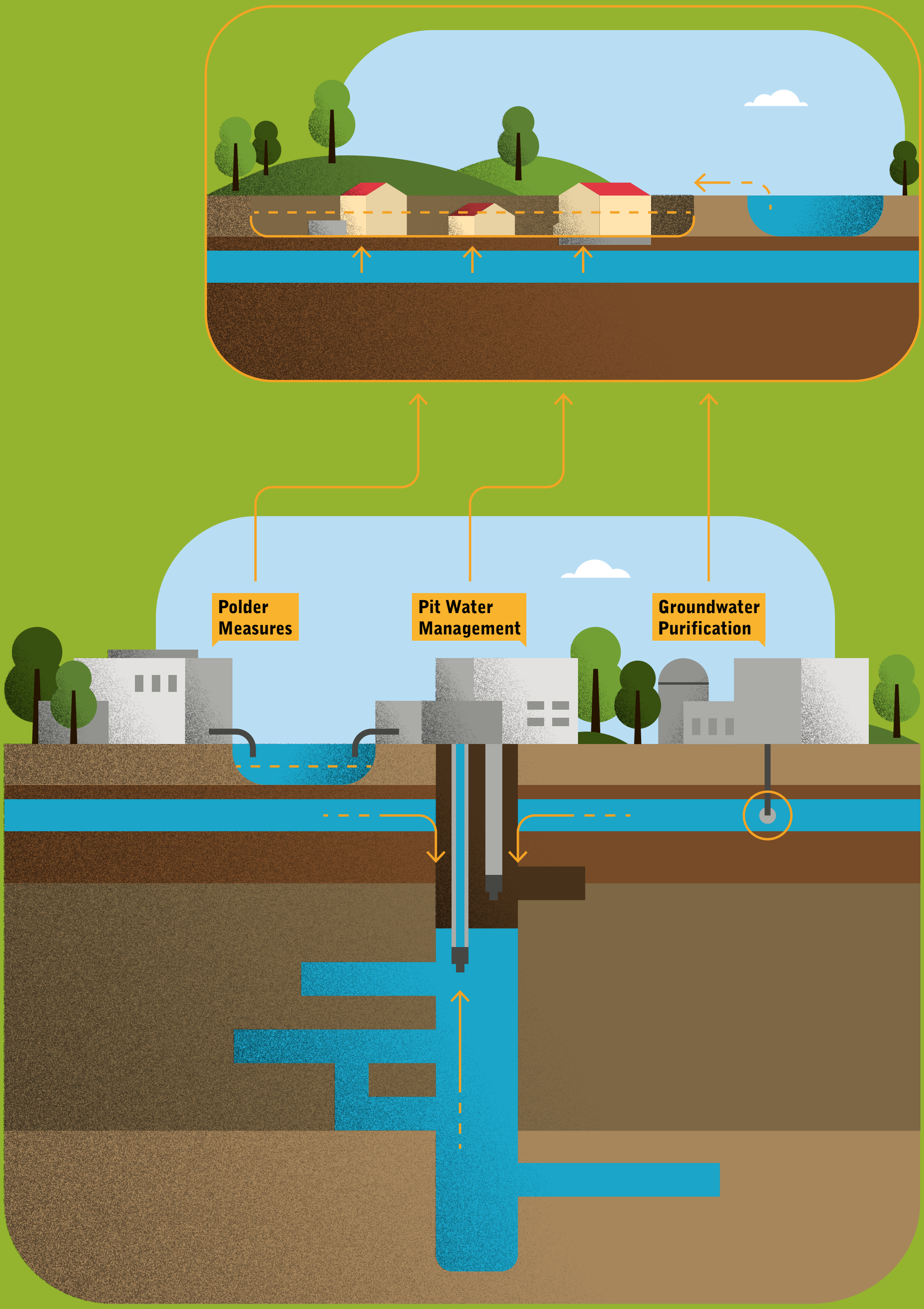
Figure 4: Pumps Ruhrgebiet
Location of pumps (red) in the Ruhr region highlighting the area that would be flooded if pumps would stop (deep blue).





Source: Own graphic; wikimedia commons, «Impactos a perpetuidad. El legado de la minería», co.boell.org, 2019.

Figure 5: Ruhrgebiet water management
A system of pumps keeping water away from the shallow aquifer



Source: Own graphic; based on a RAG-Foundation graphic.

Perpetual treatment requirements

Some perpetual impacts require mitigation strategies to be implemented without a foreseeable end and may even necessitate active treatments in perpetuity to keep parameters stable within acceptable values or prevent harm. Active measures, especially in such a complex sector such as mining, require financial, human, material, technological, energy, logistical and other types of resources.[1]

To illustrate this, we can imagine an area located over former underground mine tunnels that experiences subsidence below the phreatic level after their collapse. Such an area would accumulate water in its surface and therefore require pumping if flooding is to be prevented to allow for other uses (agriculture, housing, etc.). This is the case of Germany's former mining district of the Ruhr river, around which some areas have sunk 20 metres with respect to pre-mining levels. Currently, 993,000 cubic metres of groundwater per year are treated and 1 billion cubic metres have to be pumped each year to prevent surface flooding and groundwater mixing between contact water from the mines and shallow aquifers for water supply (RAG Stiftung, 2024).

To grasp the magnitude of such a significant volume, it is useful to do some comparisons. The volume of water that must be pumped out of the Ruhr area each year is roughly equivalent to 385 times that of the Great Pyramid of Giza. It is roughly equivalent to five full days' worth of the Rhine river's mean discharge, or almost two days' worth of the Danube. Finally, if it was spread over the area of the city of Paris, the water layer would be 10 metres deep.

How long will these pumps operate? For as long as the people in cities of the Ruhr area want to live there. Undefined persistence and irresoluble uncertainty.

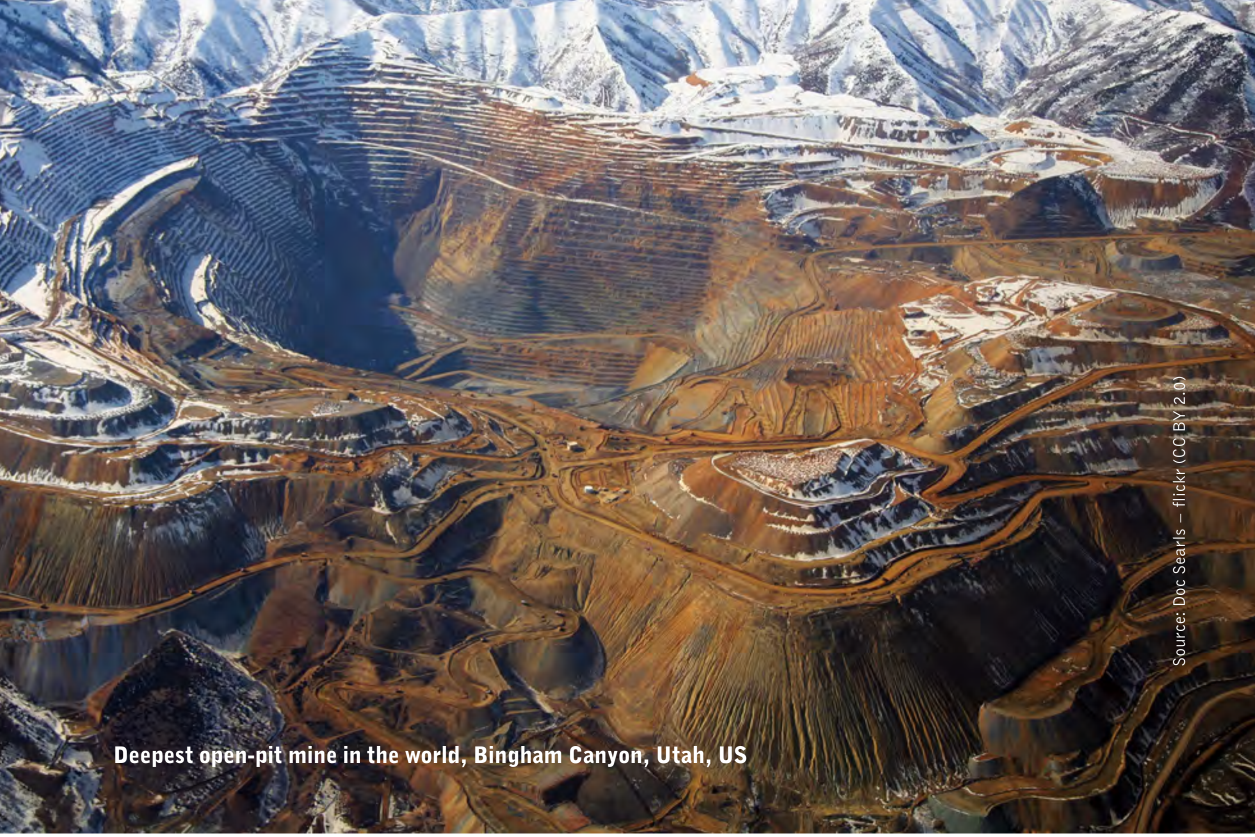
What it means for the mining sector

This section provides a general overview of key negative mining-related perpetual impacts. It begins with a proposed typology of dimensions and categories designed to systematise the approach to these impacts. Following this framework, the three categories within the biophysical dimension are examined in detail, with specific examples from the mining sector used to illustrate their relevance.

A typology proposal

Ángel et al. (2024) propose a typology to classify negative perpetual impacts in two dimensions, biophysical and sociocultural, which in turn encompass six categories, which are explained below.

1 For a comprehensive overview of active and passive treatment methods for mine water, the reader is referred to Wolkersdorfer (2023).



Source: Doc Searls – flickr (CC BY 2.0)

Deepest open-pit mine in the world, Bingham Canyon, Utah, US

Biophysical impacts

The first dimension is biophysical. It groups severe and irreversible impacts in both abiotic and ecological/biological non-human components of a geoecosystem. Most importantly, it groups three prevalent impact categories in the mining sector. As Carvalho (2017) suggests: «*Mining activities are very diverse and may have different ecological footprints.*» The three categories are water quality decrease, landscape modification and destruction of natural components. These are further elaborated below.

Water quality decrease

This term describes a complex set of impacts that take place when water (rainwater, groundwater, surface run-off) changes its physical properties and chemical load due to contact with mining infrastructure and/or mined materials. A typical example of this is pH variation. Mining effluents – commonly known as mine drainage – may be circumneutral but they may also exhibit pH values that consistently deviate from baseline or background values. These may be acid or alkaline[2] and they can favour the leaching of potentially toxic elements, such as heavy metals and/or metalloids.

Acid mine drainage commonly occurs when water comes into contact with sulphide-bearing rocks, and alkaline mine drainage occurs when the available materials

2 Meaning values that are lower or higher than a neutral pH value (7) respectively.

contain significant amounts of calcite and/or dolomite.[3] Although certain sources refer to acid mine drainage (AMD) as acid rock drainage (ARD), the latter is an overarching term that refers to the change in water's pH value due to the contact with rocks, sediments and other materials in any natural setting. ARD predominantly occurs at a much lower rate than AMD. Since ARD leaves out any reference to the root cause, using AMD would be similar to using «Earth's naturally occurring greenhouse effect» instead of «anthropogenic climate change».

Finally, It is important to stress that the substances required for these reactions to take place are generally liberated and not introduced, meaning that they are found naturally in the mined materials. In some cases, criticism towards mining projects focuses on introduced substances such as cyanide and mercury,[4] but it is indispensable to recognise that even in contexts where these two, or other reagents required for mineral processing are not present, instances of extremely grave pollution may take place.

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3 More detailed descriptions to the relevant reactions are available in the glossary.

4 Due to its harmful effects, mercury use in mining has been banned in most jurisdictions, so it is uncommon to find it as an introduced substance in legal mining and it is generally associated with ASGM. However, it may be present as a liberated substance.

Acid mine drainage from an abandoned copper mine in Kalavasos, Cyprus

Landscape modification

This term refers to any large-scale morphological alteration of Earth's surface due to mining activities (extraction, transport, transformation and disposal of large volumes of geological materials). They can take the form of positive relief features such as embankments, rock piles, tailings storage facilities (TSFs), dams, etc., or negative relief features such as pits, adits, etc.

Destruction of natural components

Given their economic impacts, some trade-offs may be accepted in the context of a mining project, among them compromising or destroying certain components of the natural system that fulfil important functions. For example, the removal of a mountain, the destruction of a lake or the extraction of an aquifer. The latter permanently prevents water storage and filtration, illustrating a perpetual loss in these and any other ecosystemic functions that it could have provided in the future. The imbalance of the natural groundwater dynamics resulting from subsidence in the Ruhr area and the subsequent need for perpetual active mitigation activities is a good example of a large-scale, irreversible modification of a complex system, and it falls under this category.

It is relevant to remark that, although the system components might not be completely destroyed, their functionality can be compromised by activities that do not account for the risks arising from inherent uncertainties or incorrect practices. Taking groundwater as an example, the impacts produced by mining prospection and

Source: uncredited – wallpaperflare (CC0 1.0 Public Domain)

Examples of large-scale landscape modifications: Barcarena tailings dam, Brazil

Examples of large-scale landscape modifications: Chuquicamata mine, Chile

Source: © abriendomundo – istockphoto

exploration activities may compromise quality and flows – both in quantity and direction – by connecting geological units through intense exploratory drilling, construction of infrastructure such as large tunnels or simply due to incorrect management strategies after mining activity cease.

The latter was the case at Mainsforth mine, located in the South Butterknowle mining area of Northeast England, where inappropriate hydrogeological assessments led contact water from the mine to mix with groundwater, resulting in the consequent pollution (Reker et al., 2019). It is also the case of the Berkeley pit, in Montana, where permanent monitoring and active measures must prevent pit lake water from reaching the shallow drinking water aquifer level (PitWatch – Berkeley Pit Information, 2024a).

Sociocultural impacts

The second dimension refers to all social, cultural, economic and health impacts and includes, but is not limited to, the destruction of sacred sites, the abandonment of cultural practices and limitations to natural resources (clean water, air, etc.) that might turn into irreparable harms, the loss of knowledge systems or «epistemicide» (Santos, 2016), the loss of languages – or «linguicide» – and livelihoods, and the onset and transmission of chronic and genetic hereditary conditions. Similar attempts of classification can be found in Mononen et al. (2022). These authors mention both positive and negative impacts of mining on two sub-groups: economics and employment (downstream enabling of industries, tax income and royalties, employment

This was once Mount Whaleback, now it is an iron ore mine in Pilbara, Western Australia.

and contracting opportunities, new economic activities and invesments, effects on livelihoods, and risks such as bankruptcy and dependence on the activity) and the socio-economic environment (new infrastructure, revitalisation of areas, loss of livelihoods and competition for land use, migration, safety perception, creation of conflicts).

Due to the subjectivity involved in their valuation and to intrinsic difficulties in finding quantitative indicators for some environmental effects, sociocultural impacts are arguably more cumbersome to assess than their biophysical counterparts. In some cases, the line between long-term and perpetual impacts might be blurry and depend on risk aversion, social values and other considerations.

For example, if the dynamics of a project creates a set of conditions that result in the disappearance of a whole ethnically and/or culturally differentiated human group, there is no question that the cultural traits specific to them will be lost as well.

There are instances where sacred sites have been destroyed by mining projects. A particularly serious incident took place on 24 May 2020 in Pilbara, Australia, where mining giant Rio Tinto, while blasting to extend Brockman 4 iron mine, destroyed one of the – if not *the* – most significant places for the Puutu Kunti Kurrama and Pinikura people (PKKP): the Juukan Gorge. This system of caves was a 46,000-years-old aboriginal heritage site. To understand its significance, it is convenient to cite the words spoken by a descendant of the PKKP people, Mr Burchell Hayes, to the Committee at the Parliament of Australia in charge of investigating the incident: «[Juukan Gorge] *is in the ancient blood of our people and contains their DNA. It houses history and the spirits of ancestors and it anchors the people to this country*» (Parliament of Australia, 2020). This and other statements, similar to others that have been made around the world, reveal a deep feeling of solastalgia (Albrecht et al., 2007).

However, in others cases, it is not so straightforward. If a cultural practice is abandoned, but its record is preserved and it would be theoretically possible to resume it at some point in the future, or if a town is relocated and the community struggles for years but eventually thrives in the new location, could these be considered examples of perpetual or even irreversible impacts? The sociocultural dimension is very complex, it involves emotions, valuation criteria and the subjective assessments of many stakeholders. A strategy that could aid decision-making in these cases is the application of a similar strategy, as in the precautionary principle.

An example of this is the approach to water treatment requirements in Colorado and other jurisdictions. In these cases, if no sufficient evidence exists to indicate a date at which the impact will cease or mitigation is no longer required, then the impact may be considered to be perpetual and the project cannot move forward.

A very significant and, at least partially quantifiable, sociocultural impact is the displacement and resettlement of communities located where mining projects are planned. It can be considered perpetual insofar as the original area where the community was settled disappears irreversibly. However, it also possesses the aforementioned associated complexities and must therefore be analysed on a case-by-case basis.

Destruction of St. Lambertus Church, North Rhine-Westphalia, Germany, on 9 January 2018 for the expansion of the Garzweiler coal mine.

Atrophy of vigilance

Source: Job Vermeulen – unsplash

Some countries have examples of recurrent mining-related resettlements spanning decades. One of them is Germany, in particular in the Middle Germany Lignite Mining District[5] (Arndt et al., 2022), the Ruhr river area and Lusatia, which have given rise to resistance movements to mine expansion, such as the movement «*Ende Gelände*».

The atrophy of vigilance as an ethical dilemma

The most relevant consequence arising from the two essential characteristics associated with perpetual impacts is the emergence of wicked institutional challenges, described as the «atrophy of vigilance» by Kempton (2003). The author highlights it as one of the four dilemmas posed by the prospect of perpetual management. This particular one refers to the discrepancy that exists between the time scale of the environmental impacts and the financial and government institutions that are supposed to manage them – the first one being much longer – thereby confronting us with the reality of a future filled with potentially orphan environmental liabilities and their corresponding harms.

Events 200, 500, 2,000 or even 10,000 years into the future could seem irrelevant for today's decision-making. However, overlooking and actively deciding not to prevent or adequately manage impacts – even if they are deemed to be too far in the future – poses an ethical dilemma with several considerations.

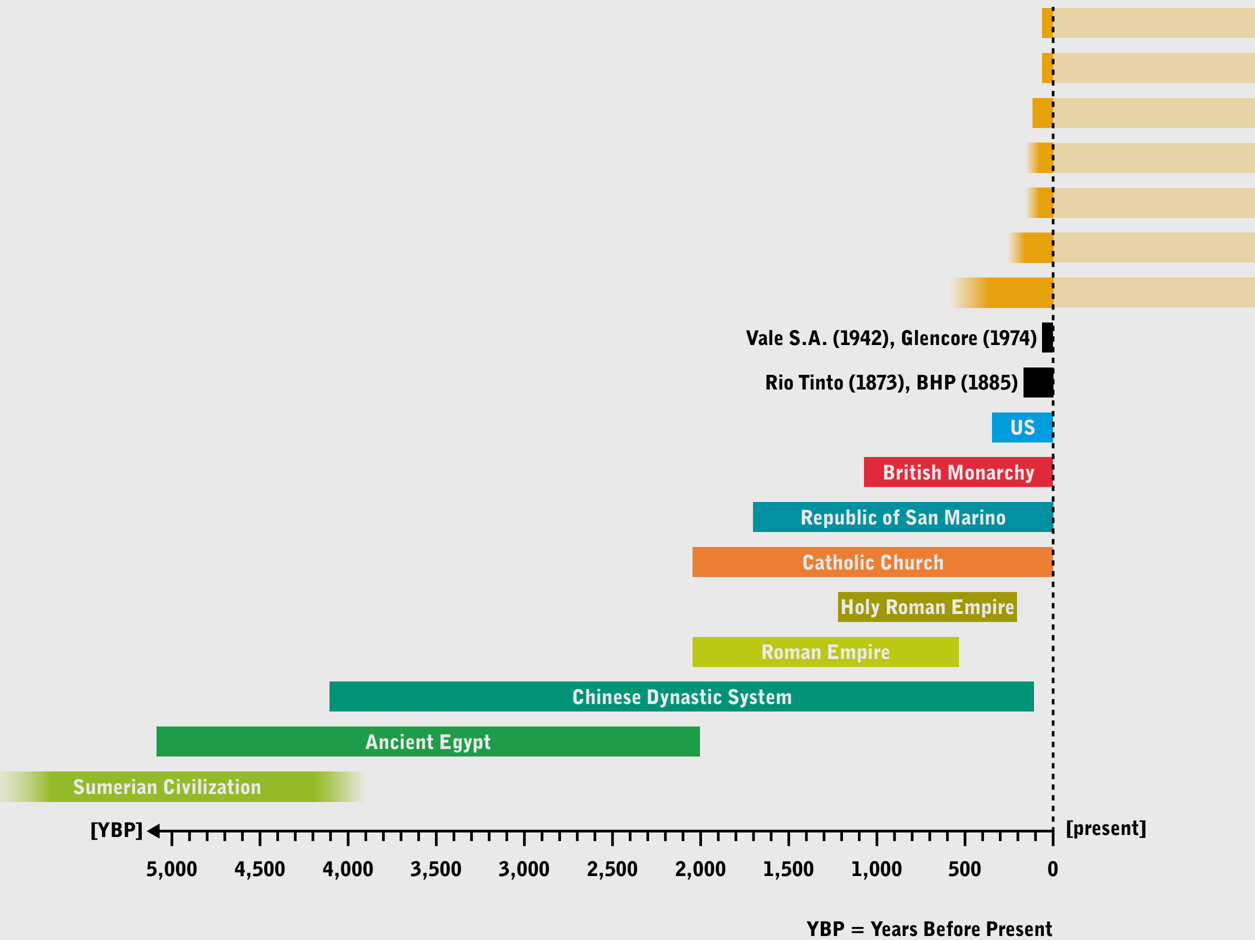
On a global level, the concept of stewardship, seen as an «ethical responsibility to the Earth» according to some currents of thought (Carnell & Mounsey, 2023), helps reinforcing the idea that, whether or not our current society, or even our species, avoids the worst consequences of some of our actions, we cannot simply turn a blind eye to them. On the concept of stewardship in the context of the Anthropocene, Rockström et al. (2024) even propose to create «comprehensive stewardship obligations» to restore and strengthen planetary resilience. The prevention of perpetual impacts that compromise the functioning of large planetary subsystems, such as tipping elements (Lenton et al., 2008), should also be taken to the local scale to prevent further damages to vulnerable systems and marginalised communities.

On a more concrete dimension, it is important to remark that, although these impacts may be expected to last for extremely long periods, they may also start and continue manifesting themselves while the activity that generates them takes place, right after it ceases, or after a relatively short latency period, as has been observed in some cases, such as the Buckhorn mine in the state of Washington, US (Okanogan Highlands Alliance, 2024a). For example, some types of water pollution and/or soil degradation or destruction may permanently compromise the livelihoods of the stakeholders depending on them.

A third consideration is that ignoring long-term and perpetual impacts is inconsistent with even the earliest definitions of sustainable development. Let us consider a narrow and anthropocentric interpretation of the one coined by Brundtland (1987).

5 Mitteldeutsches Braunkohlerevier

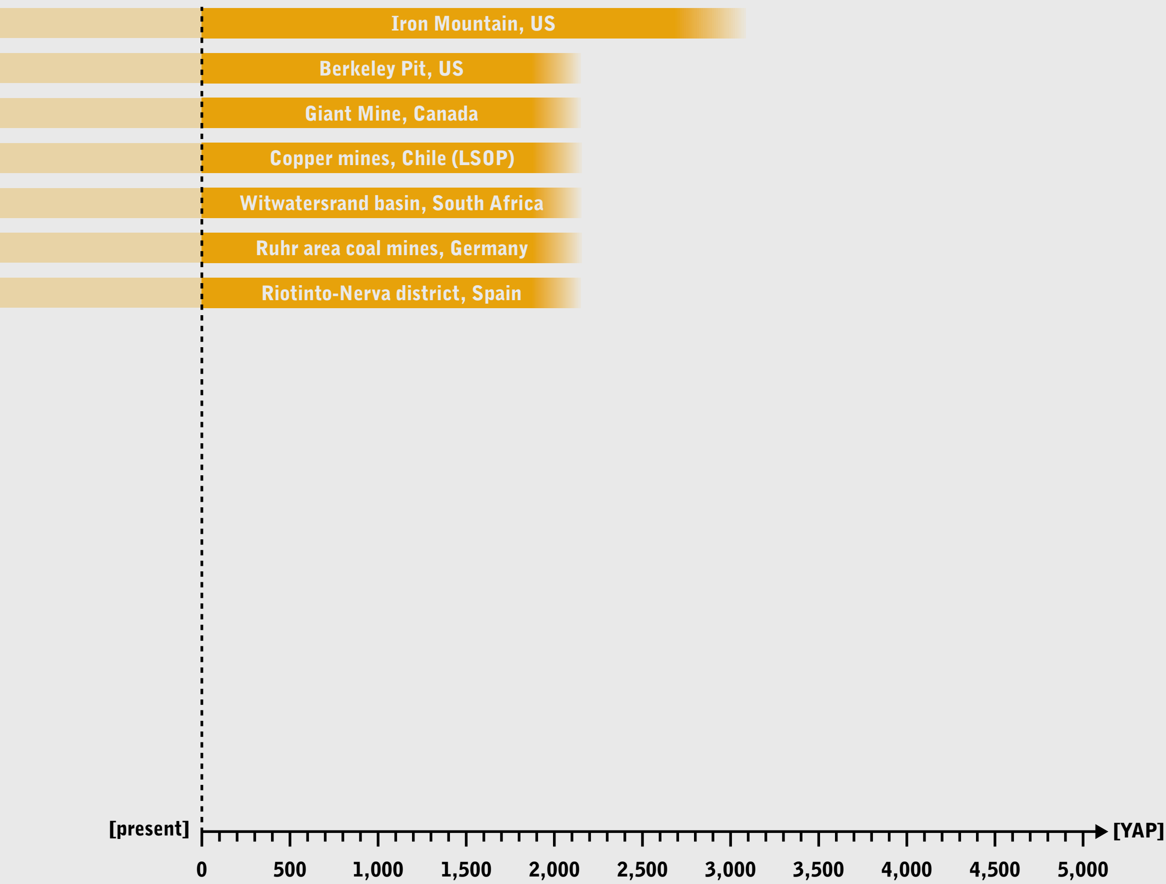
Figure 6: Long-term human institutions vs. Duration of water quality impacts at selected mines
Timeline showing the duration of some human institutions compared to the duration of the treatment/monitoring needs for some mining projects/areas with respect to the present day.



It defines it as «[…] *development that meets the needs of the present without compromising the ability of future generations to meet their own needs*». Even if the term «future generations» only refers to humans, there is a case to avoid perpetual impacts on the basis of the well-being of humanity's next generations at least for the coming centuries.

6 This is the case of the Giant Mine at Yellowknife, Canada, as highlighted by Raffensperger and Kuyek (2011).

Note: Due to their characteristics, all of the included projects/areas are expected to require some kind of perpetual management to preserve either chemical, physical or ecological stability, or security conditions be it because they comprise large-scale tailings dams or similar infrastructure, because of their geochemical characteristics or due to the nature of their rejects.[6] In terms of water quality, only Iron Mountain mine has concrete estimations of treatment requirements before the effluents comply with standards without it. Others, such as Berkeley pit, Witwatersrand and the Ruhr area, are assumed to be perpetual due to the continuous need for active remediation. In the case of Chile, as in any large tailings dam projects, it is assumed that at least monitoring will be required to keep geotechnical stability in check.



YAP = Years After Present

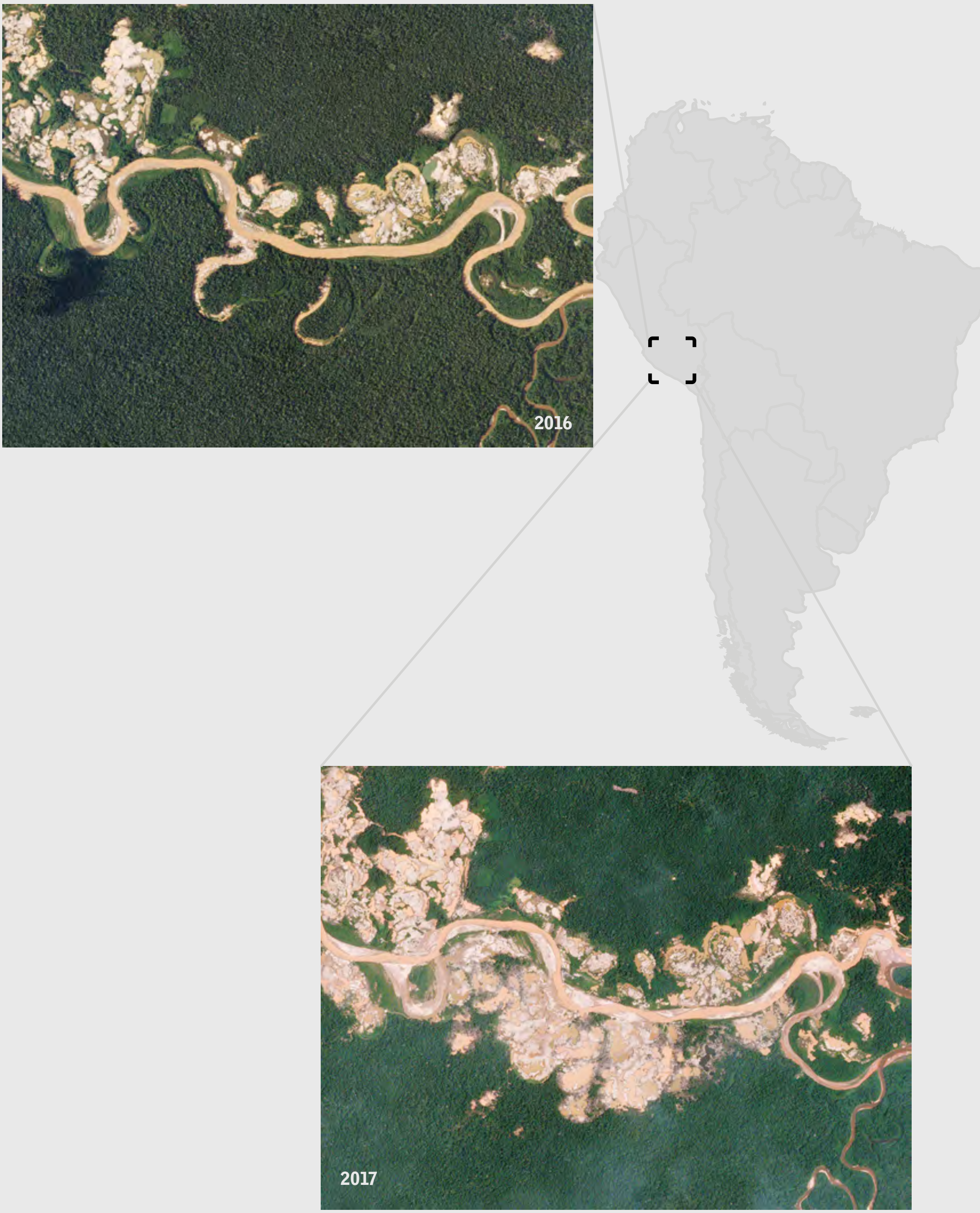
Source: Own graphic.

To show the discrepancy between the duration of human institutions and the need of treatment for a single mine, Kempton et al. (2010) present a figure similar to the one below. The version contained in this report shows the duration of some of the most long-lived political institutions of the last 7,000 years in the history of our species and compares that against the expected or estimated duration of management or treatment at mining projects or mining areas.

Figure 7: «La Pampa» gold mine 2016–2017

The sprawling «La Pampa» gold mine has grown quickly over the years. In 2016, however, the mine spilled south of the Malinowski River, illegally entering the Tambopata National Reserve – a protected forest. The Amazon Conservation Association used Planet data to publish a series of alerts which tracked hundreds of hectares of illegal expansion and mapped alterations to the course of the Malinowski River. The Peruvian government has intervened and is now actively targeting illegally cited mining equipment inside the reserve. [Map: canislupusarctos – wikimedia commons, (CC BY-SA 3.0)]

Source: Planet Labs, Inc. – wikimedia commons (CC BY-SA 4.0).



Source: Planet Labs, Inc. – wikimedia commons (CC BY-SA 4.0).

Perpetual impacts at different spatial scales

Local and regional

Understanding the scale of any project or activity is essential to grasp the onset and duration of the corresponding environmental impacts. It is also a criterion to determine if an impact should be considered to persist in perpetuity or not. Moreover, to establish the relevance of an impact, it is indispensable to define a corresponding scale or unit of interest, which is the resolution or level at which a phenomenon is considered to be significant.

Water pollution from mining illustrates this very well. Both effluent quality and quantity play a role in determining if the associated impacts will be perpetual. Quality is highly dependent on the geochemical characteristics of the deposit, on the separation and waste disposal methods and design, etc. Moreover, although there are no universal size thresholds for determining if a facility will generate perpetual impacts or not, the volume of potential pollutants is obviously an important factor. Holding all factors constant, there is a direct relation between the probability of generating perpetual water quality impacts and mine size.

Similarly, discharges from both active and abandoned facilities may be more or less concerning, depending not only on the chemical and physical characteristics of the effluents themselves, but on the characteristics of the receptor (soil, river, lake, sea). A discharge with a lower pollutant load may be equally concerning or have similar impacts on a smaller body of water as a more pollutant discharge on a larger one. If the scale of interest is considered to be a large-enough river basin, most polluting activities will not be of major concern due to natural attenuation, for example.

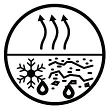
Not only are large-scale projects capable of generating significant impacts on a unit of interest, for example a basin. Cumulative impacts arising from a large enough number of smaller extraction units can also significantly negatively impact such a basin. This is the case in many places around the world, where sufficient artisanal and small-scale mining units can have a catastrophic effect on the biophysical and sociocultural dimensions. In the Peruvian Amazon, the Madre de Dios river and its affluents have been so starkly affected by this activity that – given the many difficulties (natural, institutional, social) – the restoration process, including removing the mercury from soils, may take decades or longer.

Global

Perpetual impacts are by no means restricted to the local or regional scales, nor to one specific industry. However, the scale at which we are modifying the Earth's systems is already exceeding the rates of most natural systems. For example, natural and anthropogenic greenhouse gas (GHG) emissions are in the same order of magnitude already. Out of the 54.33 to 75.50 Gt CO_2-eq (gigatons of carbon dioxide equivalent) estimated to constitute the annual global GHG emissions, about 36.2 Gt were estimated to be anthropogenic by 2016 (Yue & Gao, 2018). Data from 2023 shows that

Table 1: Tipping Persistence

Potential for causing abrupt changes if a tipping point is reached, and reversibility of tipping elements, with confidence intervals. The table is color-coded to ease reading and interpretation. The confidence levels of abrupt change and of the time scale are expressed in green, from light to dark, indicating lower to higher. Abrupt changes and reversibility are coded either with a plus or a minus, indicating the potential for abrupt changes (red) or not (green), and reversibility being unlikely (red) or likely (green). The time scale is coded in blue, from light to dark, indicating years (Y), decades (D), centuries (C), and millennia (M).

Tipping Element	Confidence of Abrupt Change	Abrupt Change Potential	Confidence of Time Scale	Time Scale	Reversibility
 Global Monsoon				Y D C M	
 Tropical Forest				D Y C M	
 Boreal Forest				D Y C M	
 Permafrost Carbon				C Y D M	
 Arctic Summer Sea Ice				Y D C M	
 Arctic Winter Sea Ice				Y D C M	
 Greenland Ice Sheet				M Y D C	

Tipping Element	Confidence of Abrupt Change	Abrupt Change Potential	Confidence of Time Scale	Time Scale	Reversibility
Antarctic Sea Ice					
West Antarctic Ice Sheet & Shelves				D C M Y	
Global Ocean Heat Content				C Y D M	
Global Sea-Level Rise				C Y D M	
Atlantic MOC				C Y D M	
Southern MOC				D C Y M	
Ocean Acidification				C M Y D	Deep Surface
Ocean Deoxygenation				C M Y D	Deep Surface

Source: Own graphic; Intergovernmental Panel On Climate Change (Ipcc), 2023.

anthropogenic methane emissions, mainly from the agriculture, fossil fuels and waste sectors, exceeded natural sources, amounting to 351 and 233 megatons/year, respectively (International Energy Agency, 2024).

Regarding mining, this sector is also responsible for a small but significant part of the global final energy consumption with 1.7 %, a figure that will likely increase to between 4 % and 12 % by 2060 due to three factors: future economic growth, renewable energy transition demand and the increasing final energy required per unit mass of mineral recovered[7] (Aramendia et al., 2023). Moreover, mining was estimated to have moved in 2020 about 54.9 billion tons of materials between metal ores and non-metallic minerals globally (United Nations Environment Programme, 2024), which is more than what is usually estimated for geological processes such as sediment load transport in all rivers in a year.

Data allows us to realise that our collective behaviour as a species is also causing perpetual impacts at the global scale. We are collectively modifying the planet to such an extent that the persistence of the changes at the planetary scale which we have made so far will exceed that of our species. Global warming, ocean acidification, land use changes, changes in the cryosphere and many others are effects that entail undefined persistence, irresoluble uncertainty and pose insoluble institutional challenges.

The Planetary Boundaries (PBs) framework, originally proposed by Rockström et al. (2009) and the research on Earth's tipping points and elements (Lenton et al., 2023) are probably the most comprehensive attempts made so far to assess our species' cumulative impact on the largest and most important processes of the planet and potential future biophysical and sociocultural dynamics.

These changes, arising from transgressing PBs, may force tipping elements, through positive feedback loops, into new stable states that the human species has never witnessed. Recent estimations included in the latest IPCC Working Group I report (AR6-WGI) suggest that some of these modifications may not be reversible for centuries, millennia or longer (Intergovernmental Panel on Climate Change, 2023). Although they could still be considered transitory from a geological perspective, they would certainly be perpetual in a human timescale. The following table contains information about estimated reversibility – and therefore, persistence – of some tipping elements if thresholds are crossed.

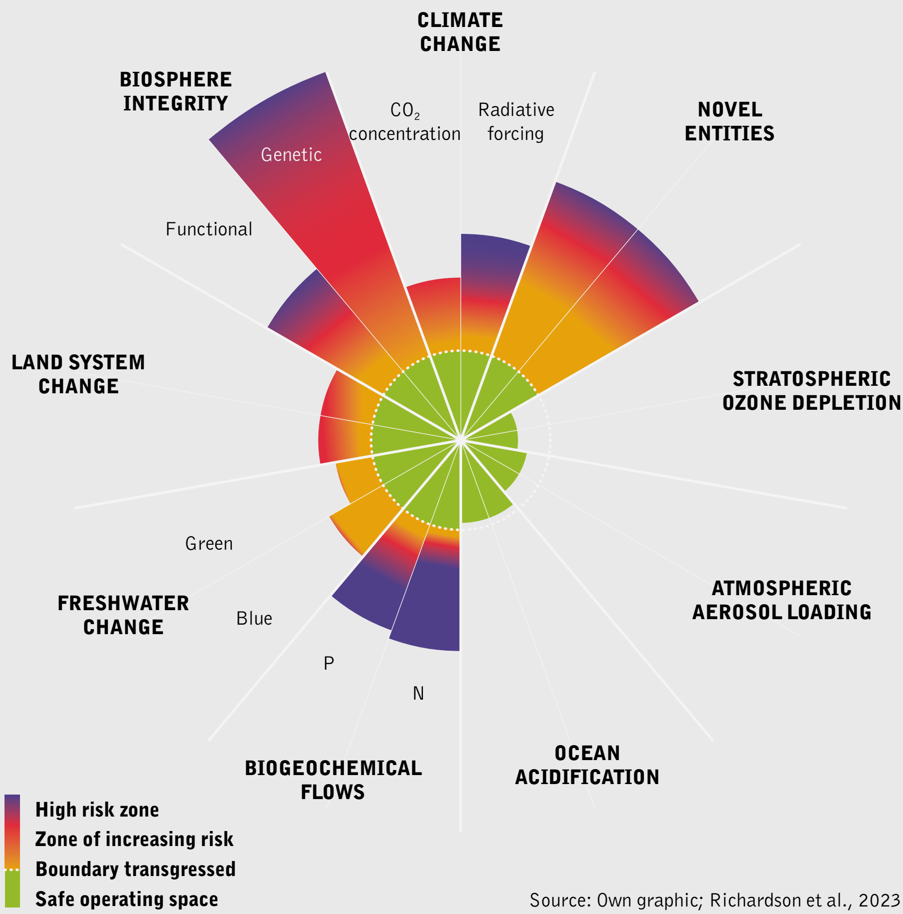
A multi-scalar approach to perpetual impacts allows us to understand the trade-offs between mineral resource extraction and climate change mitigation efforts while recognising the systemic nature of the current global crisis, thus leaving behind the carbon tunnel vision that justifies local and regional biophysical and sociocultural impacts in the name of fighting global warming. An important tool to achieve this is the aforementioned PBs framework.

Rising demand for transition minerals from weak or failed states lacking strong environmental and mining institutions may trigger or intensify environmental conflicts, especially in unequal societies, where mineral deposits overlap with vulnerable, impoverished communities. Such conditions often lead to cycles of violence – forced

7 Due to the decrease in deposit quality through time.

displacement, intimidation, armed resistance – and environmental degradation, including the expansion of large-scale mining infrastructure. The Global Atlas of Environmental Justice (Universitat Autònoma de Barcelona, 2024) has documented numerous cases of these dynamics. In Latin America, for example, Arce and Nieto-Matiz (2024) found that state coercion was linked to two factors: peaks in community mobilisation, particularly indigenous-led, and high economic potential of mining (lootability).

Figure 8: Planetary Boundaries
Graphical summary of the latest Planetary Boundaries assessment: 6 of the 9 boundaries have been transgressed.



Source: Own graphic; Richardson et al., 2023.

Considering that a significant portion of energy transition materials are located in Global South countries, which in turn suffer from poor or no environmental regulations and/or compliance, or that exhibit poor records in human rights, the issue of an increase in violence is particularly pertinent for the discussion. For example, 70 % of known cobalt reserves are found in the Democratic Republic of the Congo; 48.8 % of known nickel reserves are in Indonesia; 48.7 %, 64.6 % and 45.8 % of dysprosium, graphite and neodymium, respectively, are in China; and 73.6 %, 88.9 % and 35.8 % of platinum, iridium and manganese, respectively, are in South Africa (IRENA, 2023).

Although more attention is being paid to environmental justice issues around the boom in materials for the energy transition in recent years, there is mounting evidence which suggests that the onset of many types of violence during commodity booms is still an issue in many countries, with palm oil in Indonesia (Kenny et al., 2020) and coal extraction in Colombia (Moor et al., 2014; Bermúdez Liévano, 2024) being just a couple of relevant examples. It is therefore unlikely that a just transition to stay within the safe and just PBs (Rockström et al., 2023) can be achieved if such behaviours continue or if the other PBs are neglected in favour of CO_2 concentration and radiative forcing indicators.

As can be observed in the latest version of the PBs framework assessment, biosphere integrity,[8] both in functional and genetic terms, is the boundary that has been transgressed most severely. Even taking into consideration the methodological evolution of the assessment, it is possible to observe in past versions (2009, 2015) how biosphere integrity has consistently shown a higher risk level than the climate change boundary (Caesar et al., 2024). Therefore, risking an even greater loss of habitats and species to obtain additional materials – instead of pushing for reductions in consumption and efficiency increases – may not bring us closer to the target of solving the systemic crisis, but instead away from it.

8 Change of biosphere integrity is defined as «the decline in the diversity, extent, and health of living organisms and ecosystems, threatens the biosphere's ability to co-regulate the state of our planet by impacting the energy balance and chemical cycles on Earth» (Caesar et al., 2024).

Case studies: Practical examples of long-term and perpetual impacts

Nuclear waste management planning: Caring for the distant future

Although some jurisdictions and sectors still resist or deny the reality of managing perpetual impacts, others have acknowledged the need to protect and inform future stakeholders about potential harms that could last for millennia. Nuclear waste management is a prime example of long-term responsibility schemes, and it shares more similarities with mining impacts than one might expect. A brief context and examples from the sector are explored below to show that it is indeed possible and necessary to care for the distant future.

Duga OTH radar, Chernobyl, Ukraine

Source: Yves Alarie – unsplash

Impacts persistence in mining is so significant that Maest et al. (2005) state in their landmark report on water quality prediction in hardrock mines: «*The length of time over which a mine site will deviate from baseline or pre-mining conditions can be on the order of centuries to tens of thousands of years, as a result of potential delays in the generation or appearance of acid drainage [...] Therefore, the ‹future› at hardrock mine sites approximates the period of interest for nuclear waste disposal rather than that for more conventional industrial facilities.*»

In 2024, the German Parliament tasked its Scientific Services[9] with identifying areas in raw material extraction and energy production that may create perpetual burdens and determining who bears the costs. The consultation highlighted five sectors: hard coal extraction, lignite extraction, nuclear energy and waste management, solar and wind energy, oil and gas. Among these, hard coal extraction, nuclear energy and waste, and potentially lignite extraction were identified as having perpetual impacts (Deutscher Bundestag Wissenschaftliche Dienste, 2024), underscoring the long-term care similarities between mining and nuclear waste management.

High-level radioactive waste is stored in «permanent/deep geologic repositories» located hundreds of metres underground to prevent radiation leaks and ensure future inaccessibility. In Europe, four sites have been selected for such storage: Cigéo in France, Forsmark in Sweden, Nördlich Lägern in Switzerland and Onkalo in Finland, with only the latter currently being under construction (World Nuclear Association, 2024). In Europe, organisations such as the BGE, ANDRA and SKB[10] manage nuclear waste storage across Germany, France and Sweden (BGE, 2024; ANDRA, 2024; SKB, 2021; World Nuclear Waste Report, 2019).

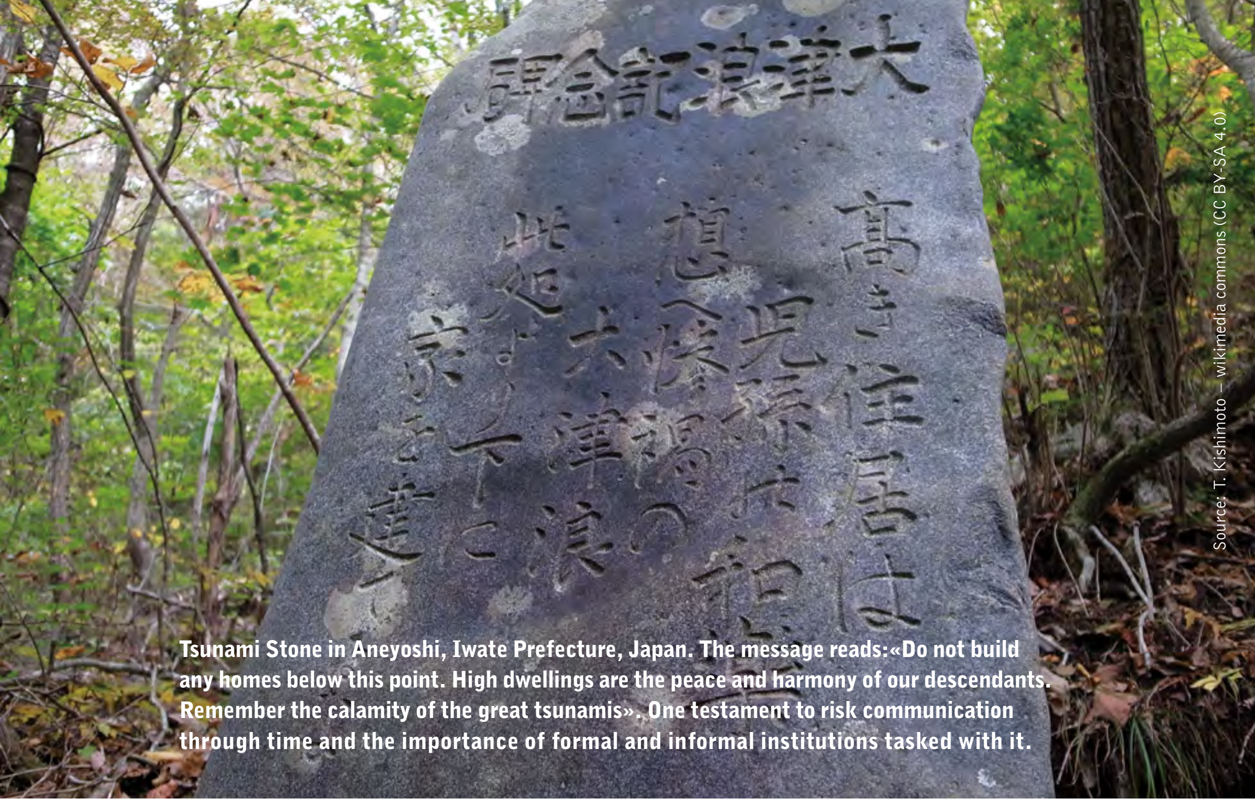
Key safety features for both operational and planned repositories include long-term isolation through passive safety measures, multiple barrier containment, structural robustness, suitable waste acceptance criteria and post-closure monitoring (OECD-NEA, 2020). Nuclear waste management exemplifies a regime designed for perpetuity, as it addresses both the essential characteristics of perpetual impacts and the atrophy of vigilance, even on longer timescales than with mining.

Posiva Oy's[11] Onkalo repository in Finland is designed to contain nuclear waste for at least one million years (Posiva Oy, 2024), and Germany's Repository Site Selection Act mandates similar protection durations (Bundesamt für Justiz, 2017).

9 The scientific services is an institution within the German Parliament that provides the elected members with relevant factual information for their tasks. It is composed by an interdisciplinary team and divided into eight thematic divisions.

10 Bundesgesellschaft für Endlagerung mbH, Agence nationale pour la gestion des déchets radioactifs and Svensk Kärnbränslehantering Aktiebolag, respectively.

11 Posiva Oy is a Finnish company in charge of handling and disposing the spent nuclear fuel generated by Teollisuuden Voima Oyj (60 %) and Fortum Power and Heat Oy (40 %), the companies that own Posiva Oy.



Tsunami Stone in Aneyoshi, Iwate Prefecture, Japan. The message reads:«Do not build any homes below this point. High dwellings are the peace and harmony of our descendants. Remember the calamity of the great tsunamis». One testament to risk communication through time and the importance of formal and informal institutions tasked with it.

Risk communication as an integral part of risk management

Failures in risk communication have led to disasters involving legacy mining infrastructures such as tailings dams. In Chile, limited awareness of tailings locations and risks has contributed to such events. Homes, farms and other infrastructure have been unknowingly built downstream from tailings, often obscured by vegetation. In February 2010, an 8.8 magnitude earthquake triggered the collapse of the Las Palmas tailings impoundment, burying and killing the Gálvez Chamorro family (Fundación Relaves, 2024). In response, citizens pushed the Chilean government to make available a comprehensive Tailings Dams Registry, including abandoned sites (Servicio Nacional de Geología y Minería de Chile, 2024).

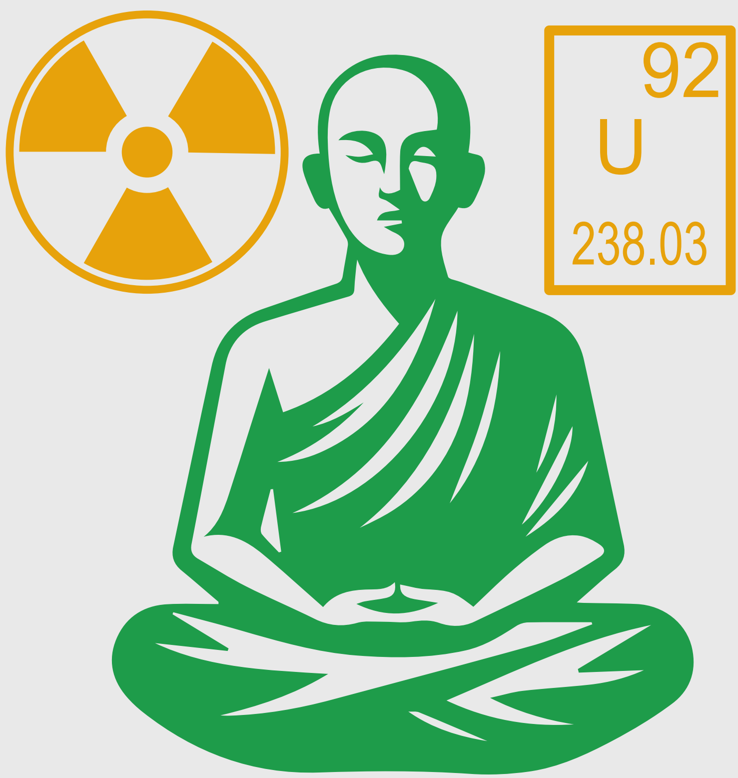
This is an example of instances where strong institutions, procedures and access to information could have avoided the loss of life. Therefore, a discussion on aspects related to the importance of risk communication, using the example of nuclear energy, is offered next.

Safely storing nuclear waste is only part of the challenge; communicating its perpetual risks to future societies, which may differ greatly from ours, is another. The gap between the civilisation that creates these risks and those that might endure them adds to the issue's deep uncertainty. Nuclear semiotics researchers work on ways to convey these dangers, proposing mechanisms such as religious taboos, genetically modified animals and hostile landscaping to deter future interaction with nuclear waste sites.

Mining risk communication efforts are not designed for such long timescales and sometimes fail even in the short and medium terms. For example, in South Africa's Mpumalanga province, abandoned mining pits have become drowning hazards for children and young adults (Human Rights Watch, 2022). Adapting nuclear semiotics principles could inspire urgently needed risk communication strategies for abandoned and post-closure mines – a concept that warrants further exploration.

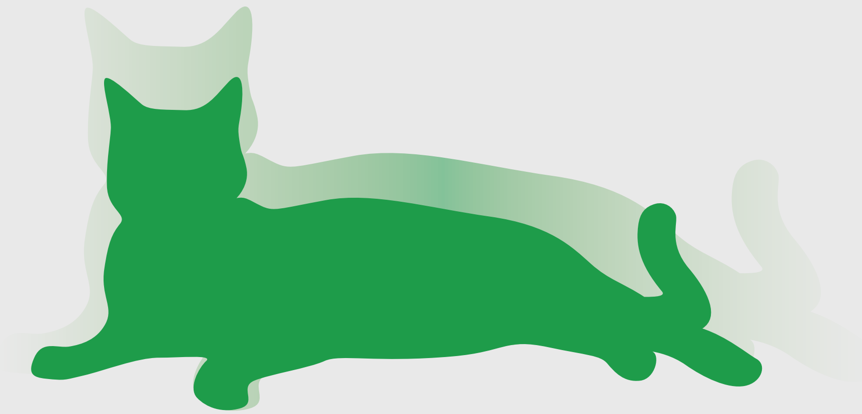
The first proposal, often called the «atomic priesthood», was initially mentioned by Weinberg (1972) and later developed by semiotician Thomas Albert Sebeok for the Human Interference Task Force. Sebeok (1984) suggested that an educated elite should safeguard and transmit scientific knowledge about nuclear repositories while conveying it to society through folklore – myths, legends, rituals and superstitions – to instil a lasting fear of these sites.

Figure 9: Conceptual representation of the atomic priesthood



Source: Revised and reimagined; based on: freepik (©), and wikipedia (Public domain and CC BY-SA 2.5).

Figure 10: Conceptual representation of the ray cat



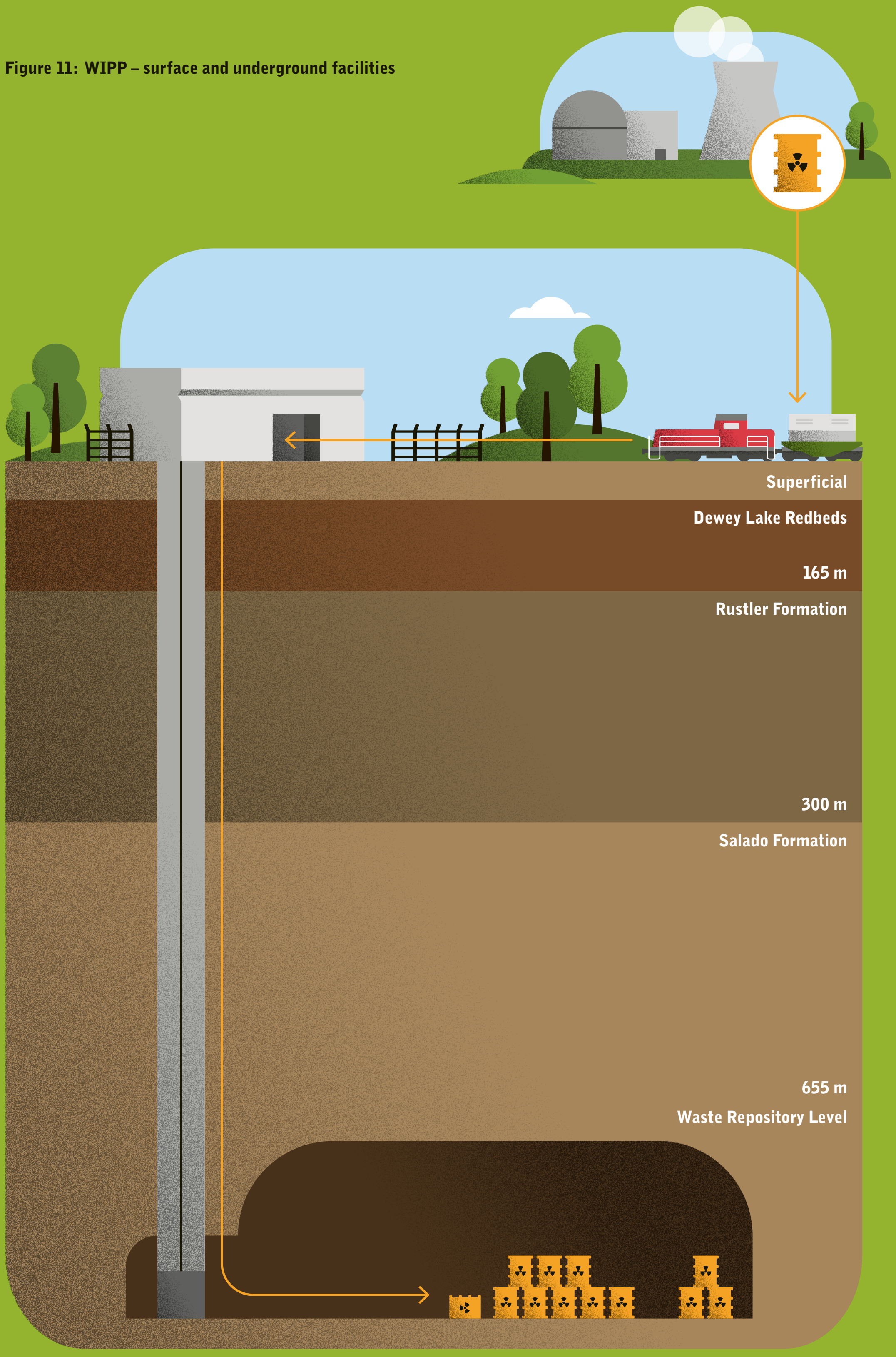
Source: Revised and reimagined; based on: V.G.Design – shutterstock (©).

The second, more controversial proposal, known as the «ray cat», was developed by Françoise Bastide and Paolo Fabbri. It involves genetically modifying cats to change colour when exposed to radiation, coupled with folklore – stories, songs and poetry – informing people that if their cat changes colour, they should relocate (OECD-NEA, 2019).

Finally, «unwelcoming landscaping» involves constructing large, ominous landmarks near repositories to warn of potential dangers. A well-known example is the «Landscape of Thorns», designed by Michael Brill and Safdar Abidi in 1991, featuring a field of thorn- and needle-like structures rising from the ground (Trinity College Dublin, 2024). Brill and Abidi's project, along with others, aims to evoke fear, unease and a sense of threat.

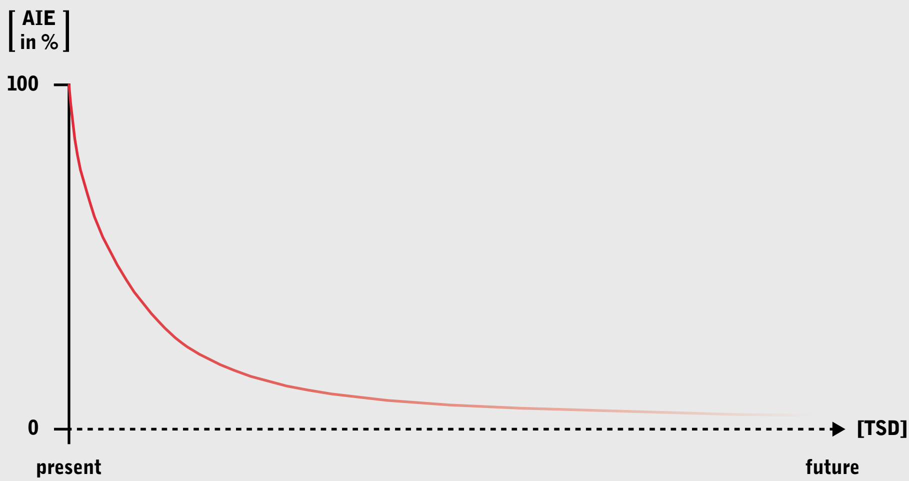
Even with arguable shortcomings, nuclear waste management strategies clearly show that we can think in terms of extremely long periods of time, overcoming psychological distance, caring even for distant future societies and/or life forms, and even eliciting institutional responses to achieve the goal of protecting them. Because mining is a much closer phenomenon to us than nuclear risks, both in time and space, it should be possible to establish management systems to comprehensively avoid and/or mitigate perpetual impacts.

Figure 11: WIPP – surface and underground facilities



Source: Own graphic; based on a DOE graphic.

Figure 12: Psychological Distance
A diagrammatic representation of decreasing importance given to a topic in function of an agent's perceived distance in time, space and to self. The X-axis represents «Temporal & Spatial Distance» (TSD) and the Y-axis shows «Attention, Interest & Engagement» (AIE) to negative effects.



Source: Own graphic.

Berkeley Pit (Montana, US)

The Berkeley Pit stands as one of the world's most iconic and well-documented case studies on mining impacts, not only in the United States but worldwide. It offers a unique convergence of elements such as a history of vast underground mining combined with more recent large-scale open pits, a large tailings impoundment and a decades-long history of robust monitoring. Moreover, the need for active measures and the risk of polluting the groundwater that the nearby town gets its water from have made monitoring so much more relevant in an already regulated environment with strong institutions. These factors make the Berkeley pit an invaluable reference for understanding the complexities and long-term consequences of mining.

In 1955, copper prices soared to levels that would only be reached again in 1974 and 2006. This made it more attractive and feasible for companies to expand the existing mines to lower grade ores, which in Butte, Montana, meant moving from underground mining, which had started in the 1860s, to large-scale open-pit mining (Ripple, 2024). That year, the operator of the mine, Anaconda company,[12] started to excavate the Berkeley pit, carving what was once known as «the richest hill on Earth» and destroying the upper levels of several of the shallower historic mines.

12 Anaconda Company was bought by Atlantic Richfield Company in 1977.

According to the Montana Bureau of Mines and Geology's (MBMG) Open-file report 761, the Berkeley pit operated from 1955 to 1982, with a total estimated extraction of 320 million tons of ore and 700 million tons of waste rock. In 1980, the East Berkeley pit was opened and extraction continued until 1983, when the Anaconda company ceased all activities in Butte. In 1982, the operator ceased groundwater pumping out of neighbouring underground Kelley mine,[13] and this process led to the flooding of the Berkeley pit. In 1985, a portion of the operation was sold to Montana Resources, which resumed mining in the East Berkeley pit, now renamed Continental pit, in July 1986 (Montana Bureau of Mines and Geology, 2023). Since 1982, a water level monitoring programme was created, accompanied by the US Environmental Protection Agency (EPA) and the MDEQ. The former issued a Record of Decision in 1994 containing provisions for:

- Continued monitoring and sampling of groundwater and surface water in 73 monitoring wells and 12 mine shafts,
- Diversion of Horseshoe Bend Drainage,[14]
- Incorporation of the Horseshoe Bend Drainage into Montana Resources' operations for treatment,

13 The pumping station was located at approximately 1097 meters below the surface.
14 One of the main drainages and later, a treatment plant. That particular infrastructure drained into the Berkeley pit, and therefore this measure was taken to slow down the filling rate.

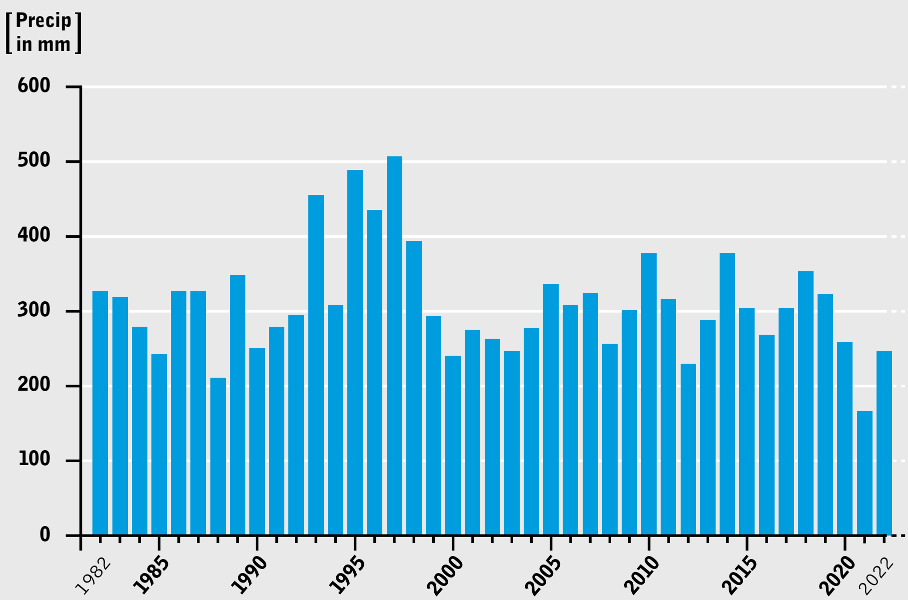
- Construction of a water treatment plant,[15]
- Definition of a maximum water level, also known as Protective Water Level (PWL) for the pit; if level was exceeded, pumping was required to protect groundwater quality at the shallower aquifer.[16]

In 2002, the US EPA issued an update of the monitoring network, which included 75 sites, 56 monitoring wells, 12 mine shafts and 7 surface water sites.

Environmental factors: Precipitation

Just like any other mine site, the state of the Berkeley pit highly depends on the dynamics of the surrounding environment. It is therefore extremely important to monitor environmental variables and to understand how these may affect the pit's physical and chemical stability, especially considering the potential impacts of climate change.

Figure 13: Berkeley Precipitation
Precipitation data from the Berkeley site 1982–2022. Precipitation influences the quality and quantity of mine drainage and is an important factor that affects management alternatives.



Source: Own graphic; Montana Bureau of Mines and Geology, 2023.

15 In case any future changes, like a shutdown, prevented the treatment of the Horseshoe Bend Drainage water.

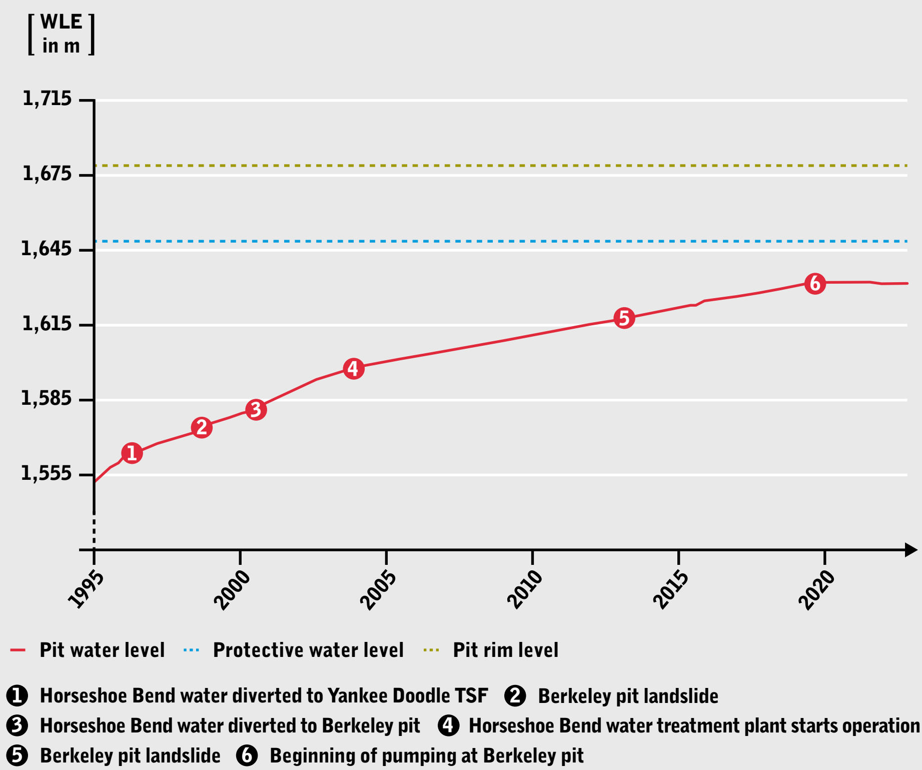
16 In order to adequately monitor the state of the system, 14 points of compliance (POC) were defined.

One key variable, both for open-pit and underground mines, is precipitation. This is why the reports from the MBMG offer periodic updates on it. Although the trend is very modest, the area of Butte has received below average precipitation for 7 out of the 10 last years, up until 2022. Changes in precipitation intensity, frequency and distribution will affect local conditions at the mine site, and therefore management strategies must be changed accordingly.

Water level at the Berkeley Pit

Leaving out the unlikely scenario of a catastrophic failure at the Yankee Doodle tailings dam, the main threat posed by the mining infrastructure to the people of Butte is groundwater pollution. This would occur in the event that the level of the water inside the pit reaches the level of a shallow aquifer from which Butte sources its water.

Figure 14: Berkeley Pit Water Level, 1995–2023
The X-axis represents the years, while the Y-axis shows the water level elevation (WLE) in meters. The values presented are from single measurements taken in January of each year. Also included are the most important events influencing level variations.



Source: Own graphic; Montana Bureau of Mines and Geology, 2023.

In light of this, a PWL, which the water level in the pit must never cross, was defined at 1,648.9 metres.[17] Additionally, water began to be pumped out of the pit on 26 September 2019, which stabilised the level at about 1,630 metres, that is, 18 metres below the PWL. Many other events have influenced the water level increase of the pit through the years, which shows just how difficult it is to manage a system of that magnitude. Such a complex system requires active mitigation measures such as pumping and water treatment in perpetuity only to avoid the materialisation of environmental risks.

Water quality monitoring

In terms of water quality, the applicable water standards are defined by the Montana Department of Environmental Quality (2019), and there are several networks of monitoring wells around the mining infrastructure that are periodically monitored to compare their values.

Observations from the data available at the Montana Bureau of Mines and Geology (2023) will be made in the following lines. Since there are several reported observations and it would be impractical to describe and discuss the results of each here, only some of those concerning the Berkeley pit will be assessed. These can be seen in the figure below.

17 All values are given in meters above sea level.

Wells around the Berkeley pit show a wide range of behaviours in terms of groundwater quality. A condensed version of this will be provided. AMC-6 exhibits a downward and stable trend in the concentration of pollutants; however, cadmium and zinc periodically exceed the state's standards. Moreover, AMC-8's behaviour is described as variable, with sulphate, iron and zinc not showing a clear trend and periodical exceedances of cadmium. AMC-12 not only shows a variable behaviour, but also exceedances of cadmium, copper, nickel, zinc, iron and manganese.

LP-9 showed a rather significant increasing trend in the concentration of sulphate from just under 5,000 mg/L in 1992 to 20,000 mg/L in 2002; then the values of both stabilised until 2007, when a decreasing trend that lasted to 2022 started with a last reported value of 10,000 mg/L. Zinc shows the same behaviour in time with concentrations of 200,000 µg/L in 1992, to a peak of about 2,250,000 µg/L in 2007, and then close to 750,000 µg/L in 2022.

Table 2: Numeric water quality standards for some pollutants of interest in the Berkeley pit area

Compound	Category	Aquatic life (µg/L)		Bio-concentration factor (µg/L)	Human health (µg/L)	
		Acute	Chronic		Surface	Groundwater
As	Carcinogen	340	150	44	10	10
Fe	Harmful		1,000			
Zn	Toxic	37 at 25 mg/L (hardness)	37 at 25 mg/L (hardness)	47	7,400	2,000
Cd	Toxic	0.49 at 25 mg/L (hardness)	0.25 at 25 mg/L (hardness)	64	5	5
Ra-226, Ra-228	Carcinogen/ Radioactive				5 pCi/L	5 pCi/L
Al	Toxic	750	87			

Source: Montana Department of Environmental Quality (2019).

LP-16 showed downward trends in general but also exceedances in cadmium, copper and zinc, while Kelley well's concentrations of sulphate, zinc, aluminum, iron and arsenic increase dramatically in the 2003–2004 period and then had a gradual and steady decrease from 2005 to 2022, when the two latter elements were, according to the last report, in concentrations of about 2,600 mg/L and 4,500 µg/L, respectively. Anselmo showed elevated concentrations of iron, with the last data point showing about 26 mg/L; low concentrations of copper; zinc doubling between 2017 and 2018 before declining; cadmium relatively stable at 2 µg/L; and arsenic showing a significant increase to values above 250 µg/L from 2002 with occasional lows, and then a decrease from 2014 to present day, reaching almost 200 µg/L.

It is important to mention that, from the vast well monitoring network around Berkeley pit and in the underground mines, the last MBMG report shows that 20 out of 23 wells show exceedances in one or more parameters, and predominant trends are characterised as either variable, that is, no clear trend observed, or stable. Additionally, radium (226 and 228) is one of the pollutants present naturally in the rocks of the deposit, and it has been routinely monitored since 2003. Sixteen wells, mainly those located between the Berkeley and Continental pits, show exceedances of DEQ-7 values.

Economic retrieval of materials

Some of the elements in the waters of the abandoned mines, both underground and open pit, are in such large concentrations that they could be recovered economically. This is the main thesis of the MBMG and Duaime (2023), who pose the idea of further exploring the potential for rare earth elements (REEs).

But this option is not limited to this group of elements. Such is the concentration of metals in the pit's water that, in 2024, a Montana Legislative Committee requested the US Congress to support an initiative to extract the REEs present there (Eggert, 2024). Similar to the produced ore, zinc is found in high concentrations in waters throughout the district. Dissolved zinc concentrations in mine waters range from 630 parts per million (ppm) in the Berkeley pit to 150 ppm in the Kelley mine shaft, to 50 ppm in the Steward mine shaft. Economic recovery levels highly depend on extraction methods, but one indication may be the waste sludge generated by the water treatment. Zinc concentration in the sludge, for example, is about 4.3 %, and minimum ore grade is about 3 %. Similar to future treatment and costs, this is an ongoing discussion at the mining district.

Table 3: Estimated concentrations of REEs in matrices at the Berkeley Pit area (in µg/L)

Site	Nd	Eu	Tb	Dy	Er	Y	Ce	La	Total REEs
Berkeley pit	629	39	38	250	155	1411	1303	330	4,950
Leach pad water at Montana Resources facility	411	21	19	122	72	NA	674	150	1,890
Horseshoe Bend Sludge	50,000	3,200	3,100	21,000	13,000	113,000	102,000	26,000	397,820

Source: Montana Bureau of Mines and Geology and Duaime (2023).

An ongoing issue

The Berkeley pit, the Continental pit and the Yankee Doodle TSF will exist forever. All of the infrastructure will need to be monitored, maintained and managed in perpetuity. In this case, active mitigation measures in the form of water pumping and water quality treatment are indispensable. Such a case is a very good example of the negative legacies of mining and the uncertainties that they entail.

Other cases

Although well-documented cases with proven perpetual impacts are rare, numerous large-scale mining sites around the world present reasonable expectations for long-term or even perpetual care needs. Often, these are large-scale open-pit sites with significant TSFs. In them, physical, chemical and/or ecological stability must be carefully monitored to prevent compromises over time. Even if extensive mitigation measures are not deemed necessary post-closure, routine monitoring remains essential to detect risks to environmental and human health, particularly in cases where sensitive receptors are nearby.

Open-Pit Metals Mines

Large open-pit mines for metals extraction – particularly for example in Chile, the United States, Poland, China and Brazil – frequently produce vast quantities of waste rock and tailings. These structures require regular assessments and maintenance to mitigate risks associated with AMD, heavy metal leaching and geotechnical stability of tailings dams. Examples in Europe are:

- Aitik mine (Sweden): One of Europe's largest open-pit copper mines, Aitik entails massive waste rock and tailings storage areas. Long-term geotechnical risk management is vital, with a focus on slope stability and water pollution control.
- Żelazny Most TSF (Poland): This copper tailings impoundment is one of the largest in Europe. It requires ongoing structural reinforcement to minimise the risk of failure and leaching, potentially extending well into the future.

Coal Mines and Long-Term Water Quality Challenges

Coal mines, particularly in countries such as China, Germany, Indonesia and Colombia, may present prolonged challenges to water quality management and groundwater levels in the distant future:

- Germany's Lusatia and Ruhr coal mining regions: Centuries of lignite mining have left behind pit lakes that necessitate ongoing water treatment to prevent widespread pollution in aquifers and nearby rivers.

- China's coal mining sites: With the world's largest coal industry, China faces significant AMD issues, with potentially long-lasting or perpetual impacts on several major river systems.

TSFs in Gold and Copper Mining

Large-scale gold and copper mining operations often utilise tailings dams with significant structural and chemical challenges that require monitoring for as long as the structures exist:

- Escondida mine (Chile): As the world's largest copper mine, the TSFs of this project are substantial and require constant water quality and seismic risk monitoring.
- Brazilian iron ore and gold mines: Facilities such as Samarco and Brumadinho have highlighted the risks associated with tailings dam failures. Even where dams are well-maintained – which is not always the case – monitoring remains essential in light of risk factors such as heavy rains and seismic events.

Żelazny Most tailings dam in Poland

Governance and Management

As the awareness of perpetual mining impacts has grown among experts and decision-makers, various institutions and strategies have emerged to manage them, with mixed success. Soft approaches, based on weak sustainability, allow projects with significant or perpetual impacts to obtain environmental licences under specific frameworks, often requiring financial provisions for long-term care, stricter oversight, remediation measures and enhanced environmental standards, but this still leaves open questions relating to institutional strength in the long-term.

In contrast, a hard approach, rooted in strong sustainability, seeks to prevent projects with severe risks – such as those requiring perpetual water treatment, involving resettlements, threatening endemic or endangered species, or damaging valuable natural or cultural sites.

The following section examines notable global policies and regulations addressing long-term mining impacts. While not exhaustive, it highlights key strategies that may serve as lessons or cautionary examples for other jurisdictions.

North America

United States

The US structural policy for addressing environmental liabilities is the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA). Dating back to 1980, it created the most important environmental damage remediation and mitigation fund in the country, known as the Superfund. Administered by the US EPA, this financial fund is dedicated to mitigating and remediating contaminated sites in the country (US EPA, 2024).

CERCLA obliges polluters to carry out management activities or to pay the US EPA for activities that the agency considers necessary and then carries out. The list of contaminated sites to treat under this act is called the National Priorities List, which is updated periodically and contains several mining projects that are estimated to require water treatment in perpetuity.

Since those days, a great deal of progress has been made at the state level to avoid and/or manage impacts in perpetuity. Recent and current discussions are motivated by the realisation of the onerous costs associated with perpetual impacts. According to Earthworks, the United States spent between USD 57 billion and USD 67 billion in 2013 on water treatment at sites contaminated in perpetuity by mining. Only in 40 mines did the annual water volume amount to between 17 and 27 billion gallons (Sumi & Gestring, 2013), that is, approximately 64.35 to 102.21 million cubic metres.

Climax Mine, Colorado, United States

Source: © milehightraveler – istockphoto

In light of the evidence, the General Assembly of Colorado, one of the states with the longest mining tradition in the United States, passed Bill HB 19-1113 on 4 April 2019. This bill banned any type of mining project unable to demonstrate that it would not require water quality treatment in perpetuity, and that it would not offer robust-enough financial guarantees (Protect Water Quality Adverse Mining Impacts, 2019). It is expressed in the bill as follows (Section 1-V7gII): «*Reclamation plan for a new or amended permit must demonstrate, by substantial evidence, a reasonably foreseeable end date for any water quality treatment necessary to ensure compliance with applicable water quality standards.*»

The wording of this bill is particularly interesting and potentially useful in other contexts. It explicitly requires an evidence-based estimation provided by the operator for an end date with two characteristics: reasonability and foreseeability. These could be interpreted as «not excessively vague or in the distant future». Moreover, it requires such an end date to be grounded on sound and enough (substantial) evidence to make a decision and establish a clear goal (standard compliance without treatment).

In the same year, New Mexico passed Ordinance 2019-2, amending section 11.14 (Regulations for mineral resource extraction and processing) of the Sustainable Land Development Code (Santa Fe County, 2019), which constitutes another attempt to ban perpetual treatment, as follows: «*11.14.3.1 Reclamation in accordance with a proposed reclamation plan shall be economically and technically feasible and will not require perpetual care.*»

This code also includes several mentions of perpetuity in the context of mining, for example, in Art. 11.14.6.7 (Facilities for Storage, Processing and Disposal of Ore, Spent Ore, Waste Rock, Tailings and Other Geological Materials), it requires that the design of the liners for such facilities have the «*[…] ability to remain functional in perpetuity*». It is notable that it uses the term to refer to an extremely long, albeit finite period, since similar uses have sparked controversy, as is shown in cases below.

Latin America

Colombia

Public institutions in Colombia have dismissed post-closure impacts for a long time. Responses to several inquiries from the author of this report concerning the topic of perpetual impacts – answered by ministries and agencies between 2017 and 2022 – reveal their unwillingness and/or unpreparedness to address the issue. Some relevant quotes from these are[18]:

- «*It must be established that after the closure and abandonment stage of mining operations, there is no follow-up environmental liabilities remediation*» (ANM, 2017);
- «[…] *the country lacks regulations on environmental liabilities, and therefore it does not have mechanisms or instruments to cover remediation costs, nor a specific liability regime to manage mining environmental liabilities*» (MADS, 2017);

18 Translated by the author.

Extraction at El cerrejón coal mine, La Guajira, Colombia

Source: Hour.poing – wikimedia commons (CC BY-SA 3.0)

«*In environmental regulation, there are no specific norms that allow for identifying those liabilities and environmental damage in the long-term or in perpetuity* [...] *nor management mechanisms* [...]. *Finally, it is pertinent to point out the convenience of using the term ‹long-term› or ‹perpetual liability› or ‹damage› since the term ‹perpetual› refers to that of very long or infinite duration, and if an adequate management is carried out, it should not be considered as such*» (MADS, 2019).

Colombia suffers from a lack of adequate environmental regulations and oversight, particularly in the mining sector. The Mining Code requires financial insurance policies to be kept for only three years after the concession contract expires (Government of Colombia, 2001; MME, 2022), regardless of local environmental quality. Environmental guidelines are based on outdated documents, and no clear impact prediction methodologies are in place for some matrices – specific Terms of Reference for mining projects (ANLA, 2016) were only finally issued in 2016.

This document contains provisions on water quality prediction requirements, but these are non-specific and refer only to static and dynamic[19] tests in general, Toxicity Characteristic Leaching Procedure (US EPA, 1992) and the Synthetic Preparation Leaching Procedure (US EPA, 1994) being the only specific methods mentioned (ANLA, 2022). Issues such as test duration, representativeness of samples, compliance period evaluated etc. are mostly left for the proponent of the project to decide. In this sense, there is little clarity for evaluators about the acceptability of EIS results. If we add to that the lawfare in which companies have engaged in the past in light of rejections of environmental licences, it is clear that the evaluators lack the appropriate tools to exert their oversight and regulatory obligations.

Much like in many Global South countries, institutional capacity is a major concern. Expertise is still lacking in ministries and agencies to evaluate the environmental impacts of large-scale mining projects. Public institutions often resort to external experts in universities and research institutions, for example, to provide expert advice on EISs. However, since these institutions usually are hired by the private sector in the context of mining projects as well, there is an incentive to facilitate and promote their development. When consulted by a concerned civil society organisation about the regulator hiring external experts to evaluate EISs, ANLA responded[20]: «[...] *after an internal review, this entity confirmed the lack of available experts specialized in hydrogeology, hydrology, geotechnics, geochemistry and applied ecology*» (ANLA, 2019; Ángel, 2020).

Another example of the unpreparedness is the absence of a legal definition of environmental liability, a situation only resolved in September 2023 with the coming into force of Law 2327, which additionally created relevant management elements such as a dedicated public policy, a national management committee, a national management strategy, a public cadaster and registry, and related protocols (Government

19 Kinetic.

20 Translated by the author.

of Colombia, 2023). The lack of this legal definition prevented institutions from acting upon the issues related to mining, as can be read in the answers provided above.

Several proposals to reform the Mining Code and other mining-related regulations have been made since its issuing in 2001, among them the proposed new Mining Law of 2024 (MME et al., 2024), which does not explicitly mention perpetual impacts. However, it establishes new principles such as prioritisation of water uses and also mandates the issuing of future regulation of financial insurances as well as updates on closure standards. This law was still in the draft stages when the present report was being written.

Peru

In 2003, the Congress of the Republic of Peru passed Law 28090 on mine closure, which was subsequently regulated by Supreme Decree No. 033-2005-EM, which in Article 31 defines the responsibility period of the operator to be not less than five years after the mine closure. It also provides the conditions for the termination of the operator's responsibility for the physical and chemical stability of the infrastructure. Additionally, it explicitly alludes to perpetual management when referring to financial guarantees, as follows[21]:

> «[…] *an amount at present value will be subtracted from the guarantees corresponding to the projected additional post-closure time which as necessary or in perpetuity as required, to the effect that the State, directly or through a third party, is responsible for maintaining the established post-closure measures.*»
>
> (Gob.pe, 2005)

In addition, the country has a robust institutional framework that includes the public company Activos Mineros S.A.C. (AMSAC), which, among other activities that include supervising the operators' compliance with contractual obligations, is in charge of «*conducting remediation of mining liabilities that pose a high risk to human health and security, and risks to the environment*» (Gobierno del Perú, 2024).[22] This entity operates under the scope of the National Fund for the Financing of the State's Entrepreneurial Activity (FONAFE). Such a legal and institutional framework provides greater protection against the occurrence of impacts following mine closure and, together with international cooperation, ensures that they are eventually managed, minimising the risk to communities and the environment.

Costa Rica and El Salvador

These two cases are presented together due to their shared hard approach towards certain types of mining. This approach is more controversial and legally precarious

21 Translated by the author.
22 Translated by the author.

due to the potential for lawsuits from companies seeking to develop mineral deposits. As a result, it is less favoured by governments.

This was the case of Costa Rica's Legislative Assembly, which approved Law 8904 in December 2010, banning the granting of any future exploration and extraction concessions for open-pit metals mining (Attorney General of Costa Rica, 2010). The decision was contested by the Costa Rican Association of the Mining Industry with a lawsuit at the Constitutional Court and swiftly dismissed by the tribunal in January 2013 (Salazar, 2013). Since then, several attempts have been and are being made to reverse the Legislative Assembly decision, without success (Alfaro, 2019; Lobo Segura, 2024).

One of the most decisive measures to prevent the impacts of mining was proffered in El Salvador, with the approval of Decree 639 in March 2017 banning metallic mining (Legislative Assembly of El Salvador, 2017).

This ban was motivated by the results of a strategic environmental assessment conducted in 2011 by the Ministry of Environment, which had previously motivated a moratorium in the sector and pointed out the need for better legislation; higher environmental, geological and mining information quality; documentation of the onset of environmental conflicts and of institutional shortcomings of resource planning and management. The decree explicitly mentioned some of the risks associated with the activity in the following manner [23]:

> «[...] *mining activities constitute a threat to the health of the country's inhabitants, it entails severe environmental risks, characterized by endangering forests, soils and water resources due to [the liberation of] acid drainage, heavy metals and highly toxic wastes, such as mercury, cyanide and others...by consuming significant amounts of water in all phases of the operation with the likelihood of destroying landscapes, polluting the air and generating social conflicts.*»
>
> (Legislative Assembly of El Salvador, 2017)

Europe

European Union

The EU has issued several Directives addressing environmental issues related or applicable to mining, and some of them also contain provisions for long-term impacts – a sample of these Directives are discussed here. Due to the legal nature of the Directives, they are fairly broad and general. Nonetheless, they provide guidance and a useful general framework for the Member States. Probably the most relevant pieces of legislation for perpetual impacts from mining activities are the Directives on Water Framework, on Environmental Liability, on Environmental Assessment, on the Management of Waste from Extractive Industries and on Critical Raw Materials (Directive 2024/1252), which is very relevant to the current mining context in light of the energy

23 Translated by the author.

transition and the urgency for new materials. This Directive mainly aims to enhance the security and sustainability of the EU's critical raw materials supply.

Another interesting piece of legislation that applies to the mining sector is Directive 2012/18 concerning the control of hazards from major accidents involving dangerous substances due to its relevance for TSFs, which are explicitly mentioned in it. Operators, among others, are required to create a Major Accident Prevention Policy containing preventive measures to avoid similar scenarios; detailed safety reports and plans; coordination mechanisms, for example with land-use planning authorities; and materials fostering public information and participation, among other provisions (Directive 2012/18/EU, 2012).

The Water Framework Directive was adopted on 23 October 2000 and is the culmination of several efforts by the European Council since 1991 to protect the quality and quantity of water over the long term in the Community. It starts by recognising water as a heritage rather than a mere commercial product, and by declaring the objectives of preventing deterioration; promoting sustainable, balanced and equitable use; guaranteeing the protection of the marine environment; and ensuring progressive pollution reduction (Directive 2000/60/EC, 2000).

Crucially, the Directive's progress is assessed in a report by the Commission every six years, and it is supported by two complementary Directives: The Groundwater Directive (GWD, 2006/118/EC) and the Environmental Quality Standards Directive (EQSD, 2008/105/EC), which contain relevant provisions on transboundary pollution as well as the requirement to define mixing zones to assess the extent of a pollutant discharge, and it expands the specific lists of pollutants, among other things (Directive 2006/118/EC, 2006; Directive 2008/105/EC, 2008).

Directive 2004/35/EC on Environmental Liability establishes a framework based on the «polluter pays» principle, enshrines preventive action, regulates cost allocation and contains the general principles of the matter. Importantly, Annex II Section 2 addresses land damage as follows:

> «*The necessary measures shall be taken to ensure, as a minimum, that the relevant contaminants are removed, controlled, contained or diminished so that the contaminated land, taking account of its current use or approved future use at the time of the damage, no longer poses any significant risk of adversely affecting human health. The presence of such risks shall be assessed through risk-assessment procedures taking into account the characteristic and function of the soil, the type and concentration of the harmful substances, preparations, organisms or micro-organisms, their risk and the possibility of their dispersion. Use shall be ascertained on the basis of the land use regulations, or other relevant regulations, in force, if any, when the damage occurred.*»
>
> (Directive 2004/35/CE, 2004)

Although this Directive does not explicitly deal with issues related to a sector in particular, it emphasises, throughout its articles, the need for the long-term stability of the ecosystems' structures and functions. As stability is a time-dependent concept, it is closely related to the topic of perpetual impacts. However, Directive 2011/92 is more specific regarding principles of environmental licensing and the types of infrastructure to which they apply, including open-cast (open-pit) and underground mining (Directive 2011/92/EU, 2011).

Finally, Directive 2006/21/EC on Management of Waste from Extractive Industries is probably the main high-level piece of legislation regarding this issue and a regulation of pivotal importance for the discussion on perpetual impacts in Europe. It requires post-closure facility management based on the best available techniques, encourages backfilling as much as technically and economically feasible and also designs that minimise or avoid monitoring, control and management. Particularly interesting is the section on waste facilities, for it requires permitting and periodic revisions of the permits that may include their reconsideration and update.

However, the permit application does not always require an EIA, and the considerations listed do not include any references to long-term or perpetual impacts or care. A positive aspect is the existence of an entire article dedicated to public participation, in which opinions and comments from the concerned citizens are guaranteed to be part of the decision-making process.

Finally, the classification system is a major aspect of this Directive. Annex III contains the criteria to declare a facility as Category A, which requires special management and care. Most large-scale mining infrastructure would fall into this category.

Incumbent Directives do not explicitly mention the issue of perpetual impacts, but they point out some of the main issues related to long-term or perpetual care to Member States. The national regulations, plans and policies to realise these guidelines are the responsibility of each jurisdiction and deserve in-depth, individual assessments. Some states, such as Germany and France, have dealt with perpetual costs for years in the nuclear waste sectors. Germany and Spain have perpetual legacies from mining in regions such as Lausitz, the Ruhr area, and Huelva, for example. We can see clear differences in the approaches across Europe, from those that clearly recognise and manage the issue to more ambiguous, vague or idle approaches. These are also worth individual assessments to provide state-specific recommendations.

Key messages

This section shows that approaches to managing perpetual impacts are extremely diverse, and they are highly dependent on each national or regional context. Attitudes towards this and other environmental issues also depend on structural factors such as regulatory and policy strengths, institutional and technical advances in environmental issues and even cultural traits.

However, there are issues present in all cases to pay attention to, such as the importance of financial assurance. These mechanisms are vital in order to at least offer a safeguard to stakeholders in the future. Avoiding long-term costs is crucial for the fiscal sustainability of communities in the vicinity of the projects. In some cases, even the state would have issues assuming these costs in perpetuity. A second indispensable requisite is evidence-based regulation. Careful, protective and tailor-made policies, standards and regulations are key to prevent harms. A third element was mentioned at the beginning of this section. Institutional capacity, if present, may even solve some of the other shortcomings, but if it is absent, it may become a cluttered funnel in which processes become stuck. Monitoring, mitigation and remediation activities may fall victim to such conditions.

Regional cooperation and knowledge transfer is also key. Collective exercises of regulations drafting, although challenging, build upon the expertise of the countries with the most advances in each field. Sharing know-how may spark future synergies in dealing with these cumbersome impacts.

As in every case, there are some open questions, for example:

- Are there any innovative and effective ways in which countries can improve their institutional capacities to manage and monitor environmental impacts, particularly in regions with limited expertise? (Cross-regional collaboration)
- What are the most effective ways to enforce long-term financial responsibilities from operators, especially in countries with weaker regulatory frameworks?
- How can regional frameworks or strategies, such as the recently published UN principles, be adapted for other contexts in meaningful ways that work and prevent perpetual costs?
- Under what circumstances are mining bans the most reasonable option?

Conclusions

- Perpetual impacts, whether referred to as such or not, are a reality that must be addressed. Efforts on the subnational, national and regional levels have been underway for many decades – only during some years or not at all, depending on the jurisdiction. In the latter case, additional urgent efforts are needed in light of the increasing number of mines, the urgency for energy transition materials and the general decreasing quality of the deposits worldwide.
- Historically, there has been an imbalance in the acknowledgment of perpetual impacts in jurisdictions of the Global North and the Global South. Whereas in the former, institutional strength forces operators to assess and disclose the full extent of their impacts, in the latter, these are usually downplayed or disregarded in the context of EIAs and public discussions.
- Transparency and proactivity in communicating these risks to decision-makers and the general public is a *sine qua non* condition when considering whether operators are in compliance and observance of their due diligence obligations.
- In order to prevent and/or manage perpetual impacts, it is indispensable to acknowledge them first. Where needed, appropriate regulations and policies must be drafted, and standards for specific sectors that are prone to generate them must be put in place.
- One such sectors is mining. As it is a chronically under-regulated industry in certain cases, some stakeholders have allowed perpetual impacts to materialise, both in contexts where governance tools were present as well as in more vulnerable contexts.
- Regulatory gaps or faulty oversight have created situations in which these impacts have veered towards both intergenerational injustices in Global North countries due to environmental and social harms, as well as injustices between Global North and Global South countries due to hidden long-term financial costs (Sydow et al., 2021).
- The pressure that the anthropogenic climate crisis puts on decision-makers may elicit approval for projects without accounting for their full impacts, not only on the local scale, but also the global scale, stressing PBs such as biosphere integrity even further. The disturbance of this boundary constitutes one of mining's most well-known negative consequences.
- So far, the discussion – where it exists – around perpetual impacts is centred on the biophysical dimension, and little importance is being given to sociocultural impacts on the local scale. It is urgent to open up the discussion to prevent human rights violations, among other harmful effects, especially in the context of the boom in energy transition materials.

Recommendations

The following discussion is based on recommendations issued by Ángel (2019). These have been revised and updated in light of the European context; since some raw materials supply chains in Europe have a strong external component, these recommendations are being issued while considering the contexts of the jurisdictions in which these materials come from or might come from in the future.

Increasing independence in ecological and social baselines

Environmental impact statements (EISs) contain valuable information about the context of projects. These statements are generally made by the proponent directly or commissioned by it. They are then passed to the regulators for assessment before a decision is finally reached on whether the project should go ahead or not and the rationale behind the verdict is offered. Depending on the country's regulations and institutional capacity, EISs and their assessments can be more or less robust, as shown by some of the examples in this report.

Their scientific quality is in itself an issue in many states. This may not be an issue in highly regulated contexts, such as in most of Europe, where environmental standards are generally enforced and information of sufficient quality is available, but it is certainly a factor to consider if states with suboptimal environmental standards and procedures are part of the supply chain for a particular material (Sydow et al., 2021).

A second issue to consider when dealing with the quality of EISs is the independence of the various actors. Many regions and countries lack a clear separation between the proponents, their contractors, research institutions and universities, and even the regulators themselves. This has been evident in the context of water quality prediction, whereby consultants that provide favourable predictions are rewarded, and the ones that do not are punished (Earthworks, 2006).

It is therefore desirable for an EIS not to be elaborated upon by the proponent, nor should there be a direct client/customer relationship between the latter and the consultant(s) in charge of the EIS. Ideally, the proponent would allocate resources into a state-managed fund, from which a public environmental authority would then hire the services of one or more consulting companies to conduct the full environmental assessment. In this way, the final result is not influenced by any pressures applied from the interested party. Although the structure of the environmental assessment process is country-specific, whether there are **guardrails in place or not could be a factor when choosing suppliers for raw materials.**

In an even more ambitious scenario, **a consumer country's environmental authorities could perform rapid assessments to detect any potential**

environmental shortcomings that may cause unintended consequences in the extraction area, or even violations of the Free, Prior and Informed Consent (FPIC) process, and issue recommendations before buying from such country. This could be especially relevant in contexts such as the EU, where projects may be granted «strategic» status. In these processes, the shortcomings of the EIAs could be evaluated to highlight issues of special concern that would be important to evaluate during a rapid assessment.

Although such a hard top-down initiative might be seen as controversial or colonialist, any additional instances of oversight and control could prove beneficial to the affected communities, and any omissions in the assessments could be easily highlighted during the environmental licensing procedure. Additionally, any posterior exceedances in environmental parameters or violations to agreements with local communities could be brought up to legal instances of the consumer country for a revision of commercial relations. An independent, well-informed, robust, socially inclusive and multilateral EIA process can prevent severe environmental and social conflicts during and after a mining operation, even in the long term or in perpetuity. The discussion on perpetual impacts could and should lead to an overall improvement in the quality of EIA regulations to achieve the aforementioned characteristics.

It is important to stress that these shortcomings, omissions or other potential violations do not necessarily occur in conflict contexts, and therefore legislation such as the Regulation on mineral imports from conflict areas (Regulation (EU) 2017/821, 2017) may be inapplicable in many cases.

Focusing on water quality modelling

As described above, some jurisdictions have strict water quality prediction regulations, whereas for others, this requirement is vague at best. In many other contexts, especially in weak or failed states with very limited institutional capacity, it may be less rigorous, inconsistently applied or it may not even exist. This is also the case for other potentially perpetual impacts such as landscape destruction, which in turn can lead to other impacts. In countries such as South Africa, abandoned pits have caused innumerable issues, among them the frequent drowning of children in abandoned mines that lack any safety measures to prevent this (Human Rights Watch, 2022), as mentioned in sections above. **Due to the severity of these impacts, special attention has to be put on assessing their likelihood in the EIS.**

As previously stated in this report, even if water quality indicators can be kept within acceptable ranges, the costs associated with active (and sometimes even with passive) treatment systems that should work theoretically in perpetuity are in themselves an often overlooked impact. Even if the financial mechanisms to install and operate the systems exist, disruptions due to corruption or similar circumstances would not be unreasonable in such contexts, and the biophysical impacts may materialise in the medium or long term anyway. **It is therefore pivotal to assess these political variables if state-mediated mitigation mechanisms for this or any other potentially perpetual impact are proposed.**

Demanding the use of verifiable methodologies

A proponent of a mining project may use methodologies to characterise either the mineral deposit and/or its biophysical and social context in the EIS that may not be available for independent verification due to commercial hurdles, for example. This is sometimes argued due to the use of proprietary models, extraction or processing techniques, or confidential information protected by commercial secrecy, etc. Directive 2011/92/EU (2011), for example, contains provisions both on transparency and data availability (Art. 6 Par. 2) as well as on the need to respect the aforementioned confidentiality (Art. 10). Proprietary tools are often preferred due to their higher levels of complexity and extensive development and testing. Even if this is the case, any scenario where the results cannot be verified should be prevented.

These two approaches may be in tension due to the nature of environmental studies, which take raw data and process it to make predictions. Even if the data is known, a processing technique that is not transparent prevents external parties from verifying the results as the proponent. For example, a mining company might arrive at the conclusion that its project will not require water treatment after closure by using a proprietary code developed by a consultant of the mining sector. In such a case, the robustness of the prediction becomes impossible to validate, even if the process is correctly described in the EIS. The former example is not hypothetical and has actually been raised as an existing issue in the United States (Maest et al., 2005), where sometimes even the regulators cannot access the models used in water quality prediction.

Both the raw data and its processing should be transparent, available and the results replicable for regulators and the general public to assess the robustness of the proponent's conclusions.

Requesting a Perpetual Impacts Statement

This is probably the most straightforward and simple of the recommendations. It suggests **establishing a requirement in the EIS of clearly stating whether the proponent estimates that the project will generate perpetual impacts and the associated management requirements (financial, technical and human requirements, among others).**

Such a requirement unequivocally transfers the burden of any incorrect estimation to the proponent/operator in an elegant and succinct way, allowing the regulators to take legal action if they believe that the resulting environmental state was not predicted accurately enough.

Assessing the existence of financial mechanisms

Similar to the US Superfund, **any company that wishes to conduct economic activities that entail significant risks for human health and/or the environment should be required to contribute a non-reimbursable fee to a financial fund for mitigation and remediation efforts** where operators are unable to assume the costs, where responsible parties cannot be found or where the responsibility has ceased. The issue of resource availability for mitigation and remediation efforts has been addressed at the national level in Europe with initiatives such as Poland's National Fund for Environmental Protection and Water Management and the many German programmes for the rehabilitation of industrial areas, some of which are mentioned in this report.

These funds provide additional certainty that orphan environmental liabilities will be appropriately taken care of in the jurisdictions where they operate. Therefore – and provided the aforementioned conditions regarding oversight and corruption are in place – they could constitute a viable alternative for the cases where perpetual impacts requiring active mitigation have taken place. **The existence and operative record of such financial mechanisms could be used as an indicator on whether a supplier country has an adequate framework to address perpetual impacts.**

Having said that, these financial tools are in themselves part of active mitigation efforts, since they provide resources but require financial stewardship, and therefore they should be viewed as a palliative tool rather than a mechanism to legitimate unacceptable harms. In this regard, the legacy fund proposed by the United Nation's Panel on Critical Energy Transition Minerals could help finance the efforts to address some of the already existing impacts, but it does not address future ones. Whether it can address the existing ones in their full complexity and magnitude is yet to be seen.

Performing independent financial assessments

EISs contain not only a description of the project and a characterisation of its context as well as estimations of the impacts, but they also entail descriptions of any mitigation and/or remediation actions to be undertaken by the proponent. These actions must not only be technically but also financially feasible. Meaning that even if an activity can be carried out in principle, if the financial conditions of the project do not permit it, then they cannot be accepted as part of a credible mitigation or remediation plan. For example, a mining pit, no matter how large, can be backfilled, provided that the appropriate resources are available. However, doing so may require more resources than can be provided for by the revenues generated from the mine over the project's lifespan, and therefore it is not always a financially sound alternative.

These plans must cover several scenarios, depending on the expected and unexpected variations in the quality of the environment at the mine site, and they must carefully consider commodity prices and other macroeconomic factors. **Regulators must have the capacity to assess the sustainability and credibility of any financial plans presented by the proponent,** and also to conduct rapid assessments of the financial provisions and stability of projects along supply chains.

Promoting circularity and reducing overall resource consumption

The principles of refuse, reduce, reuse, repurpose and recycle, in that order, must be at the core of policies and regulations that deal with projects in the extractives sector due to their non-renewable nature – even more so if they are classified as critical or strategic. **Structural approaches towards the avoidance of perpetual impacts require pushing for an overall consumption reduction whenever possible – to achieve a sustainable and just energy transition while avoiding the worst impacts of the systemic crisis.**

There are multiple misrepresentations of circularity, such as the ICMM's 2023 factsheet on circular economy, in which virgin extraction and the representation of a linear economy are seen as part of the cycle, in addition to circularity being reduced to the reuse of materials and the reduction of waste in mining activities, but there is no mention of post-extractivism (ICMM, 2023). On the other hand, there are some interesting attempts to retrieve already mined materials to reduce virgin extraction, in what is known as «secondary mining» or «re-mining», such as the already mentioned recovery of REE from the water of the mines in the Butte mining district (Montana Bureau of Mines and Geology & Duaime, 2023) and the European UNEXMIN project, which is aimed to deploy flooded mines with drones to assess the retrievability of cobalt, graphite, lithium and nickel (UNEXMIN, 2024). These types of initiatives offer alternative pathways to virgin extraction and are necessary to increase the available material base from a real circularity perspective.

Sustainable closure designs

Closure plans must be carefully designed and implemented to ensure a reasonable and sustainable allocation of resources. The activities required to execute these plans must avoid creating additional imbalances in the biophysical and sociocultural conditions of the directly affected area and its surroundings.

The flow of crucial resources such as water must not be suddenly changed on the basis of avoiding an even larger impact, and competing uses have to be carefully assessed. A notable example is the rapid flooding of mining pits to mitigate severe acid mine drainage. In cases where downstream communities rely on water resources diverted by mining infrastructure, viable alternatives must be provided to preserve essential ecosystem functions without compromising local livelihoods.

Being bold

Considering their severity, **banning extractive projects that entail certain perpetual impacts is a reasonable response, especially in particularly vulnerable settings.** In this scenario, it is important to reiterate that the willingness to accept perpetual impacts should largely depend on the context, preferences and capacities of each case, and that because extraction always entails permanent impacts to a certain extent, it is important to apply this category cautiously. This means that if the derived consequences of the impacts are deemed to pose an unacceptably high danger to the health of the ecosystems or the people, or if the burden – financial or otherwise – is deemed too great for future generations to carry, the proposals should be rejected.

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ECOLOGY
VOLUME 51

From Boom to Burden
Perpetual Impacts and Mining

Worldwide the economies are rapidly increasing the demand for minerals. Although some policies are focusing more on recycling, many others are aiming to open new mining projects. Since the start of Russia's war of aggression against Ukraine, the race for raw materials has intensified. In this rush for coveted minerals and metals such as copper, gold, bauxite, lithium and others the long-term consequences of this extreme intervention in landscapes and ecosystems are often lost from focus.

This report strives to shed light on the various biophysical as well as sociocultural long-term impacts of mining, which can mean too massive long-term monetary costs for states and further generations.

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