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Consideration of the risks per-fluoroalkyl and poly-fluoroalkyl substances pose in adopting suitable mine closure rehabilitation milestones and completion criteria

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Abstract

There are a number of activities associated with mining operations that may result in release of a range of constituents of potential concern (COPCs) into the environment. However, impacts associated with per- and poly-fluoroalkyl substances (PFAS) have the potential to require investigations (and potentially remediation) with cost, time and reputation implications over and above 'conventional' contaminants, due to the nature and behaviour of PFAS. These manufactured chemicals are known to be persistent in the environment, bioaccumulative in organisms and toxic at relatively low concentrations (PBT). As COPCs are most commonly discussed in relation to fire training activities at defence facilities and airports, the risks and liabilities to mine operators from PFAS related issues are not fully understood or adequately quantified. Undertaking environmental due diligence audits of mine operations (as the first stage of assessment) will provide a sound basis to develop a conceptual site model (CSM), in turn enabling order of magnitude (OoM) provisioning and scheduling in order to plan for any remedial and management measures associated with PFAS.

Given the PBT nature of PFAS and the disturbed hydrogeological and hydrological systems associated with mine sites, there are potential risks to air, water and soil quality (and therefore rehabilitation success) that, if not better understood, may limit the practical adoption of appropriate remediation and monitoring measures to achieve relinquishment. Such risks include long-term uncertainty in water quality projections, particularly if a mining void is left as a permanent sink for groundwater or if the site is near a sensitive receiving environment. The implications this may have on setting reasonable and effective rehabilitation milestones and completion criteria are not fully understood, and if not appropriately considered, may also limit the assessment of reasonable residual risk posed.

Key aspects to be discussed include (1) why the presence of PFAS (compared with 'conventional' contaminants) may require longer-term planning; (2) what are the long-term risks PFAS poses in terms of achieving relinquishment/accepted post-mining land-use (PMLU); (3) how can these risks be appropriately managed, including a proposed framework for creating appropriate rehabilitation milestones and completion criteria in terms of PFAS; and (4) implications for capturing sufficient closure provisioning based on the unique requirements for PFAS investigations, waste management and remediation.

Keywords: *per-fluoroalkyl and poly-fluoroalkyl substances, contaminated land, remediation, mine closure planning*

1 Introduction

Per- and poly-fluoroalkyl substances (PFAS) are an emerging contaminant class comprised of highly fluorinated synthetic organic compounds that are extensively used because of their resistance to heat, water and oil. They have been used in products as wide ranging as aqueous film forming foams (AFFF) for firefighting, semiconductors, hydraulic fluids, surfactant coatings for textiles, paper products and cookware, industrial and household cleaning products, pesticides and insecticides (CRC CARE 2016; United States

Environmental Protection Agency [USEPA] 2022). Whilst only developed in the mid-20th century, due to their useful properties and widespread application this group of manufactured chemicals is now ubiquitous in people, wildlife and ecosystems globally. PFAS are receiving increasing attention from scientists and regulators due to widespread detection in the environment, and also because many PFAS compounds have been found to be persistent in the environment, bioaccumulative, and toxic at relatively low concentrations (PBT) (NTP 2016; Concawe 2016; Agency for Toxic Substances and Disease Registry [ATSDR] 2020). They have also been found to be highly mobile in the environment (particularly in water).

In the mining industry, the primary source of PFAS is AFFF. AFFF is used in fire suppression systems on mobile plant and in workshops, and in emergency response team (ERT) firefighting training facilities. Whilst the sources of PFAS on mine sites are likely to be localised, the highly mobile nature of PFAS and the operational activities at mine sites (e.g. earth moving, dust suppression and dewatering) can result in widespread distribution.

A comprehensive understanding of the nature and extent of PFAS impact is required, along with a well-developed conceptual site model (CSM) in order to assess risk and, if necessary, implement remedial measures. Investigations and remedial strategies (including remediation pilot trials, commonly required) can take longer than conventional contaminants to complete and, given the very low (nanogram level) trigger values established for the protection of aquatic ecosystems, there are real challenges associated with achieving relinquishment of sites for many proposed post-mine land-uses (PMLUs).

This paper explains why it is important to assess and understand liabilities associated with PFAS contamination, well in advance of planned site closure, and outlines a framework that can be used to mitigate risk.

2 Background

The PFAS group consists of thousands of different compounds with a wide range of physical and chemical properties, however all contain carbon-fluorine bonds which resist degradation. They are often described as long-chain or short-chain molecules (in terms of the number of carbon molecules in the chain). The long-chain PFAS chemicals perfluorooctanoic acid (PFOA) and perfluorooctane sulfonate (PFOS), also known as C8 chemistry due to both containing eight carbon molecules, are two of the most widely used and studied chemicals in the PFAS group. As mentioned previously, many PFAS compounds, particularly PFOA and PFOS, are known to be persistent in the environment, bioaccumulative in organisms and toxic at relatively low concentrations (PBT) (NTP 2016; Concawe 2016; ATSDR 2020). Additionally, PFAS are highly mobile within water and leachable from soil (Mei et al. 2021), and several are also sufficiently volatile to be considered long-range trans-boundary air pollutants (EEA 2017; Kurwadkar et al. 2021).

PFAS exposure can occur through various pathways and its severity depends on proximity to the source, PFAS concentration at the source and frequency of exposure (Kurwadkar et al. 2021). The scientific literature on PFAS has increased considerably in the last decade, with PFAS (particularly PFOA and PFOS) being linked to a wide range of health risks in both human and animal studies including cancer (kidney and testicular), hormone disruption, liver and thyroid problems, reproductive harm, and abnormal foetal development (ATSDR 2020). There is evidence from peer reviewed human and animal studies that PFAS exposure may also reduce antibody responses to vaccines (Grandjean et al. 2017; Looker et al. 2014) and may reduce infectious disease resistance (NTP 2016), i.e. reduce the ability of the body’s immune system to fight infections, which includes reduced vaccine response.

Due to these findings, in the past decade global manufacturers have phased out long-chain compounds (PFOA and PFOS), replacing them with novel, short-chain PFAS. However, due to their persistent nature, PFOA and PFOS are still commonly found in the environment and people. Further, the behaviour and effects of novel (short-chain) PFAS are not well understood (USEPA 2022). Studies to date have found that several of the novel PFAS and their degradation products are also persistent in the environment, have been found to accumulate in and contaminate surface water and groundwater, including potable supplies (Eschauzier et al. 2012; Sun et al. 2016; Gebbink et al. 2017), and accumulate in plants (Ghisi et al. 2019), potentially increasing human dietary exposure.

Generally, the focus on PFAS has been directed at specific industries where PFAS use has been/still is prevalent (defence, aeronautics, manufacturing, etc.) and consumer products. However, a variety of PFAS compounds are used within the mining industry; the primary source being the use of AFFF, both for emergency response training activities, and for fire suppression associated with mobile plants and with fuel storage. Minor sources of PFAS associated with mining activities may also include mist suppressing agents, wetting agents, fluorinated surfactants (for ore extraction processes) in drilling fluids, or as fluoropolymers in pipework.

PFAS are more complex to assess, manage and remediate compared to conventional mining contaminants such as hydrocarbons and metals. PFAS is highly soluble in water, noting that solubility decreases with increasing chain length. The solubility of PFOS and PFOA and their potential for natural degradation in the environment, is compared with the same properties of selected conventional contaminants in Table 1, below. Whilst PFOA and benzene both have very high solubilities (meaning that they can both be readily dissolved and transported in water and have the potential to result in large groundwater plumes), benzene degrades readily in the environment (resulting in natural attenuation) compared to PFOA, which exhibits little to no degradation (via biotransformation).

Table 1 Properties affecting fate and transport – PFAS compared with conventional contaminants

Chemical	Solubility[1] (mg/L)	Degradation
Perfluorooctanoic acid (PFOA)	4,340[2]	Little to none
Perfluorooctane sulfonate (PFOS)	910[2]	Little to none
Perchloroethylene (PCE)	200[3]	High
Benzene	1,790[4]	High
1,4-dioxane	Miscible	Biodegradable
Benzo(a)pyrene	0.0016[4]	Little to none

[1] Solubility as an anion. In the environment, PFOA is a mixture of neutral and anionic forms, and PFOS is an anion; [2] ITRC (2021); [3] Howard et al. (1991); [4] May et al. (1983)

PFAS is also more readily leached from soil into groundwater, facilitating widespread migration, noting leaching rates also reduce with increasing chain length. Transport of PFAS through the subsurface will depend on soil type and geochemistry (particularly presence of organic carbon and pH, which can both influence sorption of PFAS), as well as the PFAS chain length. Further, precursors of PFAS species that are able to be identified by current commercial analytical methods show a higher tendency to adsorb than their breakdown products. This may lead to a secondary source 'reservoir' of PFAS in soils or sediments that could biotransform over time into PFAS species that drive risk, such as PFOS or PFOA.

The persistence of PFAS, along with their low to moderate rates of sorption to soils and their solubility, means that many PFAS are highly mobile and can result in very long groundwater plumes (kilometres in some cases). Coupled with the operational water movements typical at a mine site, such as dewatering, water transfer and dust suppression, the potential for widespread low-level PFAS contamination is significant.

Additional complexity also arises in the sampling and analysis of PFAS. Given default guideline values are often very conservative, and within Australia are currently established for the protection of aquatic ecosystems (namely, 99 percent species protection value for PFOS, 0.00023µg/L (ANZG 2018)), super ultra-trace analysis is required in order to assess the potential risk to aquatic ecosystems. Given the ubiquitous nature of PFAS, used in everyday products ranging from food wrappers, cosmetics, sunscreen, insect repellent, weatherproof clothing and footwear, the risk of introduction of PFAS from other sources must be recognised and carefully managed by the sampler. This also extends to sampling equipment and bottles; with tubing, certain types of HydraSleeves™, and a number of other items and sample bottles used for sampling other contaminants being potential sources of PFAS.

Further analysis (with associated cost and time implications), other than the extended PFAS suite of analytes, should also be undertaken in order to attempt to assess the presence of precursors and the overall mass of fluorine. Given that commercial analytical suites can generally only identify 30–50 PFAS species, and it has been estimated that there may be 5,000–10,000 chemical substances (USEPA 2018), analytical suites such as Total Oxidisable Precursor (TOP) Assay and Total Organic Fluorine (TOF) are valuable in assessing the presence of precursor species and the overall potential mass of PFAS.

3 Regulatory overview

The regulatory response to PFAS is still evolving, with PFAS only recently being designated a contaminant of emerging concern despite first being synthesised in the 1940s (Aminot et al. 2019), their now widespread occurrence, and studies dating back decades that demonstrated the toxic effects of long-chain PFAS. In response to the growing body of evidence on the existing and potential harmful effects of PFAS (long- and short-chain) on humans and the environment, regulatory bodies of several countries (including Australia, Canada, the United Kingdom, Germany, Norway and Sweden) have recently recommended a series of advisory values for protecting the environment and human health (Kurwadkar et al. 2021).

Further, the USEPA has submitted a proposal to designate PFOA and PFOS as hazardous substances under the Comprehensive Environmental Response, Compensation and Liability Act (CERCLA), which, if accepted, will change the regulatory status of PFAS and force parties responsible for PFAS contamination to pay for remediation (Rangaswami 2022). In Europe, the European Commission (EC) has declared PFAS as emerging organic contaminants, and PFOS and its derivatives as priority hazardous substances. The United Nation's Environment Programme (UNEP) Stockholm Convention (2001), an international treaty that aims to eliminate or restrict the production and use of persistent organic pollutants (POPs), included many PFAS on the POPs list and restricted the use of firefighting foam containing PFOS and its salts (Annex B) and PFOA and its salts (Annex A), if all the releases arising from such activities are not contained (Kurwadkar et al. 2021). The Rotterdam Convention (1998), which addresses the international trade of certain hazardous chemicals, included PFOS and PFOS precursors on its list as part of Annex III, which means they are either banned or severely restricted for health or environmental reasons (dependent on the country, as can be found within the Decision Guidance Documents provided by the Convention). The inclusion of PFOA has been recently recommended by the Food and Agriculture Organisation (FAO) and UNEP (Secretariat of the Basel, Rotterdam and Stockholm Conventions 2020).

Whilst not having any Commonwealth laws that directly relate to PFAS, Australia has ratified the above conventions and currently, importers and manufacturers of PFAS must comply with legal obligations under the *Industrial Chemicals Act 2019* (Australian Government 2019), with controls on PFOS and PFOS precursors as per Annex III of the Rotterdam Convention. However, Australia is yet to ratify the listing of PFOS and PFOA under the Stockholm Convention because Australia is yet to meet the associated management obligations. The Australian Government is working to establish a National Standard for the Environmental Risk Management of Industrial Chemicals. This National Standard will set a nationally consistent environmental management approach for the use and disposal of industrial chemicals, including PFAS. The Commonwealth Environmental Management Guidance is another policy document that is in draft and will assist Australian Government agencies to assess and manage PFOS and PFOA contamination.

Currently, guidance for assessing and managing contaminated land (in general) at a national level in Australia includes the established National Environment Protection (Assessment of Site Contamination) Measures (ASC NEPM) (1999, amended 2013), created under the *National Environment Protection Council Act 1994*, and specifically for PFAS, the PFAS National Environmental Management Plan (PFAS NEMP) which was developed by the Heads of Environmental Protection Authorities (HEPA) in Australia and New Zealand, and was first published in 2018 (updated in 2020). The ASC NEPM provides the framework and methodologies for a risk-based approach to contaminated land assessment and is appropriate for providing a general approach to planning PFAS assessments. The PFAS NEMP specifically provides nationally agreed guidance on the management of PFAS contamination in the environment, including prevention of the spread of contamination. The PFAS NEMP reflects the current state of knowledge and is a dynamic document (currently being updated to reflect new scientific evidence and guidance), and it promotes collective action on PFAS by the Commonwealth, state and territory, and local governments around Australia.

Regulation of the use, release and disposal of PFAS in Australia is primarily a state and territory responsibility. As such, regulations vary in applying restrictions around the use and management of products containing PFAS, particularly AFFF. For example, Queensland phased out AFFF containing long-chain (>C6) PFAS between 2016 and 2019, and South Australia has completely banned the use of fluorinated AFFF since 2018. Meanwhile, other states have commenced staged banning processes and/or have implemented a means of prioritising assessments of sites, and regulations around waste transport and disposal of PFAS-impacted materials. Similarly, contaminated land regulation is also the purview of the state and territories and varies between them. However, all jurisdictions have laws with respect to the assessment and remediation of contaminated land, which would also apply in the case of PFAS contamination.

4 Current situation within the mining industry

The number of abandoned or orphaned mine sites with ongoing contaminated land issues across the globe is estimated to exceed one million (though this is an imprecise estimation, as most countries often have no available data on the number of abandoned mines). Within Australia, it is estimated that there are at least 50,000 (Bennett 2016). Recent reforms to improve rehabilitation and financial assurance outcomes in the resources sector have highlighted the changing mindset around acceptable mine closure, and the subsequent need to understand environmental liabilities and plan to appropriately manage them.

Mine operators have a responsibility to manage and/or remediate contaminated land incorporated in their license to operate and may have the obligation to notify the relevant authority if contamination exceeding defined thresholds of environmental harm is identified on the site (depending on jurisdiction). Traditionally, mine operators have delayed management and remediation of contaminated sites to coincide with decommissioning and closure activities. This may have been the most efficient approach for sites impacted by hydrocarbons, given that decommissioning of the fuel infrastructure at closure would allow full access to the contamination, and the approach for hydrocarbon remediation is generally stockpiling the soil for bioremediation (on-site), which is achievable within a 6 to 12-month timeframe. Unsurprisingly, given the focus on conventional contaminants, and PFAS categorisation as an emerging contaminant class, there is limited to no information on the extent of PFAS contamination that may exist on mine sites, nor is there any data on the volume of PFAS used on sites. However, if PFAS contamination liabilities are identified, the design, trialing and implementation of a remedial strategy may take several years and considerable engagement with regulators and other stakeholders to achieve a suitable outcome, given the uncertainty as to the nature and magnitude of PFAS site remediation compared to well established remediation of other contaminants (Newell et al. 2020). Therefore, postponing contaminated site investigations to assess PFAS liabilities may have real impacts on progressive rehabilitation costs and schedules.

Furthermore, regulators have generally not driven mining companies to assess, report on or remediate identified contamination that is within the boundaries of operational mining leases unless it is at risk of migrating off-site and impacting nearby sensitive receptors. However, given the solubility and mobility of PFAS, the risk of off-site migration should not be underestimated.

Overall, the practice of delaying investigations and the associated understanding of environmental liabilities and CSM may result in insufficient time and/or funds to appropriately manage contamination-related liabilities to suit the intended final land use.

5 Implications for successful mine closure

To understand the risks associated with PFAS and successful site closure, three key aspects need to be considered in concert:

1. Site contamination: PFAS concentrations (nature and extent of impact) and site characteristics (sources, hydrogeology, soil types, etc.).
2. Legal: Financial assurance and regulatory compliance.
3. Social: Community/stakeholder expectations.

In terms of the first aspect, by proactively conducting an inventory of potential PFAS sources, followed by a staged approach to environmental sampling, there may be an opportunity to use this knowledge to ensure the PFAS remains localised. This may involve implementing measures to prevent the spread of localised sources of PFAS (for example, those associated with firefighting training areas) and they may be as simple as diverting run-off around a contaminated area, or preventing the use of impacted water for dust suppression. Conversely, if PFAS liabilities are not characterised, and operational activities (such as transfer of water between dams, or use of impacted water for dust suppression) continue, the result may be a diffuse and extensive contamination footprint, which presents much more of a challenge to address.

Given that PFAS contamination at mine sites may be comingled with other co-contaminants such as hydrocarbons, a detailed review of remedial options and pilot trials may be required in order to tailor a solution to the site-specific problem. A combination of technologies may need to be employed. Selection of remedial technologies to meet desired targets is dependent on availability of treatment technologies (some may not be economically viable for remote locations), an understanding of PFAS fate and transport, a well -prepared CSM, and defined (and achievable) treatment targets.

Management of PFAS contamination on mine sites can also be more complicated than other industrial sites, due to the act of mining itself, which often results in alteration of hydrogeological conditions. If open cut pits or voids act as sinks for groundwater, and groundwater has been impacted by PFAS, this may result in accumulation of PFAS over time, which would require detailed assessment in order to understand whether remediation is required in order to achieve relinquishment.

In terms of the second and third aspects, the emergence of the PFAS contaminant class has seen regulatory and community expectations change, with the mining sector slower to respond than other industries. This is likely due to a number of reasons, including a lack of regulatory drivers to do so and limited awareness, within both the public and the mining sector, of the risks PFAS poses at this time. Such changing expectations can (and, in the case of PFAS, most likely will) lead to changes in closure execution in terms of contaminated land investigation; and such changes will inevitably incur closure costs that were not originally considered.

Investigating contaminated land close to closure is a material risk for mine operators, and often insufficient attention is given to the cost of contaminated land investigation and remediation during the development and operational phases of a mining project. The liability in terms of contaminated land is often under-represented, giving an inaccurate reflection to management and stakeholders of the actual amount to be expended when operations cease. This is particularly true for PFAS where an initial localised contamination could enter the water source for the site (e.g. an aquifer) and be spread across the site through the contaminated water being used as dust suppression, irrigation (on rehabilitation areas) and process water. In this way, over years of operation, a small-scale contamination problem could become a large-scale, site-wide contamination problem requiring extensive investigation and remediation.

Despite making some provisions for contaminated land investigations as a part of closure, there is rarely a sufficient understanding of the extent, nature and management approach to PFAS contamination. PFAS liabilities often result in a new, potentially significant, cost item that is not adequately captured in current financial provisioning schemes (planned and/or unplanned), nor internal closure cost calculators.

The assessment and understanding of PFAS liabilities should be considered at an early stage, not only to limit the spread of potentially localised sources, but also to ensure appropriate funds are provisioned to manage longer-term monitoring and/or remediation costs. If PFAS sources and pathways are understood early on, measures to mitigate and/or prevent the spread of PFAS contamination can be implemented and remediation, if needed, can begin whilst both the contamination is more contained and the mine is still profitable.

6 Proposed framework for considering PFAS contamination in closure planning

By proactively identifying, assessing, and managing site contamination issues over the life of the mine, from exploration to lease relinquishment, opportunities to reduce liability and avoid unnecessary creation of liability can be identified. A lack of integration during operation may lead to short-term profitability decisions being made that increase liability upon closure; note that the right key performance indicators for both mine planners and the environmental teams during operations will drive the right behaviour on the ground and set up for a successful closure. Therefore, it is recommended that a) progressive contaminated land assessment practices (based on best practice guidance and any relevant local or national legislation) are adopted at the corporate level, to ensure consistency across sites under their ownership; and b) these practices should include a series of rehabilitation milestones related to contaminated land that are applied throughout operation.

A framework to deal with FPFAS contamination on mine sites has been proposed. However, first and foremost, education and awareness within the industry is critical to ensure mine operators are able to appropriately consider and assess the risk of PFAS contamination at their site. By proactively developing an understanding of PFAS contamination liabilities at mine sites and simultaneously driving a behavioural shift around the way sites think about contaminated land remediation, it may be possible to implement operational changes that limit the spread of PFAS, which would in turn reduce the time and cost of remediation at closure. The proposed framework consists of five main steps:

1. Define the intended PMLU (e.g. grazing, native grassland, commercial/industrial use) and the associated environmental values. These will inform the target criteria for assessment of environmental media; although it should also be noted that, within Australia, the protection of aquatic ecosystems will be the primary risk driver, regardless of the PMLU, given the low guideline value for PFOS (0.00023µg/L for 99% species protection).

2. Conduct a staged approach to understanding potential liabilities associated with PFAS contamination. The stages of assessment may comprise the following:

    a. An inventory of all historical and current AFFF (being the primary source of PFAS) use at the mine site, including review of the type(s), volumes, storage, incidents and accidents. If activities such as metal plating, landfilling or wastewater treatment also take place at the site, these should also be considered as potential sources of PFAS.

    b. Based on the findings of the inventory, preliminary sampling targeting the primary source zones should be conducted, following PFAS-specific sampling protocols (for example, as outlined in Australia and New Zealand's PFAS National Environmental Management Plan (NEMP) (HEPA 2020)). This may include sampling existing monitoring bores (if in relevant locations), water and sediment from surface water bodies or drainage lines, and shallow soil in areas of use or loss. The preliminary site investigation should also seek to understand the site setting and environmental conditions, as well as human and environmental receptors, in order to develop a preliminary CSM.

    c. Site prioritisation, based on the preliminary results, to identify which source zones across the site have a risk of causing harm to the environment and/or human health, either on-site or off-site.

   d. Detailed site investigations should aim to fill spatial or temporal gaps identified in the preliminary site investigation. In order to address temporal gaps (including an understanding of potential seasonal variability), PFAS sampling could be added to existing compliance sampling regimes (quarterly, or biannually), noting the requirement for specific sampling protocols. In order to gather sufficient data to understand the extent of PFAS and potential risks to receptors, more than one round of detailed site investigation and/or multiple monitoring rounds may be required. The CSM should be refined following review of each new data set. If the data indicates there are potentially complete source-pathway-receptor linkages associated with off-site receptors, engagement with stakeholders and local communities may be required.

   e. Site-specific risk assessment may be warranted given that assessment criteria have been developed for very few PFAS species. Based on the detailed site investigation(s), a site-specific risk assessment can further assess any source-pathway-receptor linkages that have been identified (in the CSM) as being potentially complete. The risk assessment will inform the need (if any) for management or remediation.

   The CSM should be regularly reviewed and updated, to incorporate changes in site operations, new incidents or contaminant release events, additional knowledge (such as revised hydrogeological modelling) or the identification of new receptors. This will support the early identification of any liabilities that may need to be factored into closure planning.

3. Review whether the intended PMLUs are appropriate and achievable in areas with identified site contamination. This should include a risk assessment around the type and level of contamination present across the site and whether there are feasible remediation and/or disposal options. Remediation is required to a suitable-for-use level, which will need to be determined based on regulations, guidelines and community consultation. Therefore, reconsideration of adopted PMLUs may be appropriate in some portions of the site.

4. Perform cost benefit analysis or similar of mitigation, treatment and/or disposal options available given desired end-use, available technology and stakeholder input to select the preferred option.

5. Develop practical rehabilitation milestones and their criteria based on the preferred option for management or remediation. Both mine planning and closure planning aspects must be taken into consideration at this step. This could include factors such as aligning with existing progressive rehabilitation schedules (to combine equipment use, etc.), or the construction of any treatment plants or remediation systems.

The critical themes that underpin this framework are:

- Contamination should be addressed on a site by site basis, particularly in relation to PFA.
- The framework should be revisited semi-regularly to ensure up to date information, early warning of risks, and consistency with the latest PMLU and mine planning.
- Contaminated land should be managed progressively from the outset to avoid significant liabilities upon closure.

7 Conclusion

Contaminated land is often not considered in detail at mine sites until operations are close to closure, which is a traditionally accepted approach when considering conventional contaminants, such as hydrocarbons or metals. However, where there is potential for PFAS contamination, significantly more time and resources are likely to be required to appropriately assess and manage contamination risks. Where remediation is required, a combination of technologies may need to be employed to address PFAS (and any co-contaminants), requiring pilot testing to tailor the approach to site-specific conditions. By proactively identifying sources of PFAS contamination, there may be opportunities to mitigate the spread of localised sources using operational controls, such as diverting run-off around these areas, or avoiding use of contaminated water for dust suppression. These early actions could prevent large-scale mobilisation of PFAS, which may present technical, temporal and budgetary challenges that could affect final closure and relinquishment.

It is important to incorporate PFAS management within a series of progressive rehabilitation milestones throughout the lifecycle of the mine, rather than delaying until operations are planned to cease. The framework provided in this paper can be used to assist decision-making around PFAS management on-site and the development of rehabilitation criteria for successful mine closure.

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