Mine Closure 2026 – AB Fourie, G Boggs, J Heyes & M Tibbett (eds)

doi:10.36487/ACG_repo/2615_84

Contaminated site assessment strategies to address mine closure planning challenges

Dana Windle [a,*], Tamie Weaver [a], Dora Kovacsy [a]

[a] *Environmental Resources Management Australia Pty Ltd, Australia*

Abstract

Strategies for contaminated site assessment and remediation have been developed to address mine closure planning challenges, based on direct experience at multiple Australian mines.

The typical approach to contaminated site assessment at mines references a contaminated sites register and focuses on small or operational areas (such as workshops, refuelling, landfills, airports and historical spills). Challenges arise when applying contaminated site guidance – the National Environment Protection (Assessment of Site Contamination) Measure (ASC NEPM) and the Per- and Poly-fluoroalkyl Substances National Environmental Management Plan (PFAS NEMP) – to mines, for example due to their typically large size (potentially unachievable sampling densities) and remote nature (including limited formal waste disposal locations). Mineralised conditions and Traditional Owner land use also present challenges applying standard assessment criteria that do not account for elevated background concentrations (mineralisation) or site-specific exposure pathways. While contaminated site assessment and remediation is typically a closure cost provision, it is often based on limited information, undertaken later in closure planning, and costs are frequently underestimated.

Strategies to address these mine-specific challenges that reflect Australia's ASC NEPM/PFAS NEMP framework and local regulations include undertaking aspects of contaminated site assessment well before closure, e.g. risk assessment that includes Traditional Owner land uses. Leveraging existing and new data through dashboards and visualisations helps to improve decision-making and stakeholder communications and assists with deriving background concentrations to inform site-specific, risk-based criteria. Development of mine-wide conceptual site models (CSMs), remedial objectives and strategies assists in prioritising assessment of spatial or contaminant-based domains that consider historical activities, current conditions or potential future land uses. Finally, assessing individual PFAS (per- and poly-fluoroalkyl substances) sources while considering mine-scale processes that may distribute PFAS more widely is key.

These strategies support closure through improved and more complete remediation planning, allowing areas to be cleared or remediated before closure, and potentially identifying practices to change or implement that may reduce future contamination. These approaches better inform liabilities and costs associated with managing contaminated sites, facilitating more timely and cost-effective mine closure.

Keywords: *contaminated land, site assessment, remediation planning, mine closure*

1 Introduction

In the authors' experience, the approach to contaminated site assessment and remediation at large Australian mines is often very different to the approach taken at smaller sites with 'traditional' contaminants although all contaminated site assessments undertaken should be consistent with national guidance applicable in Australia.

[*] Corresponding author. Email address: dana.windle@erm.com

1.1 Traditional contaminated sites

Contaminated site assessment in Australia is undertaken with reference to the National Environment Protection (Assessment of Site Contamination) Measure (ASC NEPM) published by the National Environment Protection Council (NEPC 1999) and also, more recently, the Per- and Poly-fluoroalkyl Substances National Environmental Management Plan (PFAS NEMP) published by the Heads of EPA Australia and New Zealand (HEPA 2025). The-ASC NEPM was first published in 1999 and revised most recently in 2013. The purpose of ASC NEPM is to provide a nationally consistent approach to contaminated site assessment, ultimately in order to protect human health and the environment. The ASC NEPM outlines a staged approach, from Preliminary Site Investigation (PSI), through to Detailed Site Investigation (DSI), risk assessment and then remediation (if required).

A PSI is primarily a desktop-based assessment that involves review of site history and land uses to identify activities and areas of potential contamination (sources) in the context of the general site setting and characteristics. Identified sources/source areas are then further assessed on site through a DSI which includes collection of environmental samples of soil, groundwater, surface water, sediment and/or soil vapour, as required. Multiple stages of DSI, potentially including offsite assessment, may then be undertaken to characterise the nature and extent of contamination.

Results from a DSI, or multiple stages of DSI, are used to undertake a Tier 1 risk assessment, typically comparing environmental sample concentrations to published default assessment criteria for the applicable onsite and surrounding land or water uses. If exceedances of the default assessment criteria are identified, further risk assessment and establishment of site-specific criteria may be undertaken or required.

The ASC NEPM provides default assessment criteria for soil and/or soil vapour for human health under a range of land uses, i.e. residential (low or high density), commercial/industrial, and public open space. However, there are no default human health assessment criteria for soils in an agricultural land use setting. Default ecological assessment criteria for soil are provided for areas of ecological significance, urban residential areas and public open space, and commercial/industrial land uses but, similarly, ecological criteria are not available for agricultural soils.

There are, however, national guidelines that outline default assessment criteria for sediment, surface water and groundwater use for a range of exposure pathways. Examples include the National Health and Medical Research Council (NHMRC) guidelines which present assessment criteria for human health exposure via drinking water and/or recreational activities (Australian Drinking Water Guidelines and Guidelines for Managing Risks in Recreational Water; NHMRC 2011, 2008), and assessment criteria for protection of ecological, irrigation or stockwatering environmental values from the Australian and New Zealand Governments (ANZG 2018) and Australian and New Zealand Environment Conservation Council (ANZECC 2000).

Ultimately, remediation may be required to reduce or manage the risk associated with contamination or to otherwise clean up the site; however, the ASC NEMP does not provide guidance on remediation of contaminated sites. Although the National Remediation Framework (NRF) has recently been developed by the Cooperative Research Centre for Contamination Assessment and Remediation of the Environment (CRC CARE 2019), with contributions from multiple state departments, this remediation framework has not been formally endorsed nationally and also does not include guidance on remediation of PFAS or abandoned mining sites.

Throughout the entire contaminated site assessment process, the ASC NEPM encourages assessment and remediation with reference to a conceptual site model (CSM) that outlines the sources, transport and exposure pathways, and the receptors (human health and ecological) of the identified contamination. Importantly, a CSM should evolve over time as more information is gained through progressive assessment. Examples of potentially contaminating site activities referenced in the ASC NEPM include underground structures, fuel or chemical storage, handling and use, waste generation and disposal, spills and incidents (including fires), and imported fill material. However, the ASC NEPM focuses on ‘traditional’ contaminants such as petroleum hydrocarbons, chlorinated hydrocarbons, other organic contaminants (such as polychlorinated biphenyls (PCBs), polycyclic aromatic hydrocarbons (PAHs), phenols), organochlorine and other pesticides, herbicides, metals/metalloids, inorganics (cyanide, nutrients) and asbestos rather than metals, acidity and salinity that are more typically associated with mining.

With the emergence of the PFAS family of contaminants since the ASC NEPM was published, and reflecting the unusual chemical properties of PFAS that result in their different behaviour in the environment, the PFAS NEMP has been published to specifically guide assessment for PFAS in Australia. The PFAS NEMP was first published in 2018 and revised in 2020 and 2025 and provides a nationally endorsed approach for contaminated site assessment for PFAS in addition to the ASC NEPM. In the environment, PFAS do not readily degrade and are often highly leachable and mobile.

1.2 Approaches at mine sites

A typical approach at most mine sites involves development of and reference to a contaminated sites register. This may be prepared and updated as part of mining operations, or may not be compiled until closure begins to be considered.

Contaminated sites registers often focus on small, localised operational or potential source areas across the larger mine site, although larger-scale mining operations and sources may also be identified. Examples of smaller contaminated sites that are typically identified on mine contaminated sites registers, and which may be subsequently assessed following the ASC NEMP and/or PFAS NEMP process, include workshops, bulk fuel or chemical storage and use, refuelling areas, landfills and waste disposal locations, airports, historical spills, explosives storage and handling, fire-fighting training areas, power generation, bioremediation areas, wash-down areas, sewage and waste water treatment and discharge areas. Larger-scale sources typical of mining operations that can be listed in contaminated sites registers include tailings storage facilities (TSFs), stockpiles and waste rock dumps, and irrigation and waste water discharge areas.

Each operational area or source is usually considered a separate contaminated site, which may be individually assessed and/or risk ranked, and assessment is often undertaken in the immediate vicinity of the contaminated site, without consideration of the wider CSM for the mine and its operations.

2 Challenges at mine sites

The authors' combined experience with site assessment and remediation across Australia has led to identification of common challenges specific to mine sites.

2.1 Confidential information sharing

Our collective experience includes all mining stages (feasibility, construction, operation, rehabilitation and closure), a range of mining targets (including base metals, mineral sands, uranium, bauxite, iron ore, manganese and coal), and has been gained across a range of jurisdictions: Victoria, New South Wales, Queensland, Northern Territory and Western Australia. Due to confidentiality considerations, the examples presented in this paper are not from specific sites, but aggregate learnings from multiple mine sites.

Although environmental reporting for many mines is provided publicly (e.g. annual reporting requirements under mine licensing and environmental approvals), details on contaminated site assessment are not always readily available; the authors were unable to find a publicly available contaminated site register for an individual mine to reference in this paper. Although some mines are listed on publicly available contaminated site registers (e.g. Queensland Government Contaminated Land Register or Western Australia Contaminated Sites Database), these registrations typically apply to a whole parcel of land or mining lease and often do not include detail on individual contaminated sites within the mine. For contaminated land generally, there is often a reluctance to discuss or share challenges and issues, meaning that a body of knowledge is not readily available for shared learning and improvement and, instead, depends on direct experience. For example, of the more than 1,000 papers available from previous Mine Closure conference proceedings, only 5 have the term 'contaminated', 'contaminant' or 'contamination' as a keyword and 14 have these terms in the paper title.

Further, a key component of a PSI is often review of available data and information for nearby sites and similar operations, such as through publicly available audit reports. Due to the remote nature of many sites or lack of auditor involvement at a mine-wide scale, leveraging data and findings from nearby mines can also be a challenge.

2.2 Multiple small sources within a large footprint and bespoke operations

Other challenges arise in assessing contaminated sites at mines due to the multiple smaller contaminated sites, bespoke nature of each mining operation, and overall large footprint.

For example, at some mines there may be multiple separate locations, at once or through time, where petroleum hydrocarbons have been stored or distributed (such as diesel refuelling areas), with each requiring localised assessment of the potential to be a contaminant source when considered with the local geology, which may vary significantly across the mine site. In other cases, multiple smaller contaminated sites may be co-located, such as in processing areas. This can result in multiple sources of different contaminants in one area, and associated interaction of different contaminants in soil, or overlapping groundwater plumes. One example might be low pH conditions in groundwater caused by release of acid from a storage tank, which subsequently inhibits natural biological attenuation of nearby petroleum hydrocarbons also released into groundwater.

In addition, acid and metalliferous drainage and/or acid sulphate soils may represent unique and particularly large source areas or volumes for management at many mine sites. For contaminant sources with large areas or volumes (such as materials handling areas, waste rock dumps, overburden dumps or TSFs), assessment consistent with reference to the ASC NEPM or other local regulations means that sampling densities are not realistically achievable. The ASC NEPM provides guidance on minimum stockpile sampling, but only stockpiles up to 200 m^3 in volume. For larger stockpiles or areas, characterisation with respect to contaminated land guidance would possibly require thousands of samples, with associated unrealistically large effort and cost.

2.3 Long and complex site history

Other challenges arise due to the often long and complex history of a mine, potentially including multiple owner companies, a frequently changing workforce, and potentially many operational changes, which together can lead to loss of historical information and site knowledge.

Company and staff changes can mean that site history and records are lost or incomplete. In the case of more traditional contaminated land, and as advised in the ASC NEPM for the PSI stage, verbal history from long-serving employees can be invaluable in understanding historical operations and potentially contaminating activities. Information on historical and undocumented spills or incidents such as fires are often only available anecdotally and therefore may not be available for mines with shorter-term employees and a changing workforce. At all types of sites, longer-term records are invaluable in the assessment of contaminated sites, but these are often difficult to access or lost, particularly those that were hard copy only.

On site, mine progression often means that the current conditions and layouts do not reflect the historical conditions. Due to large bulk material movements and earthworks, contaminated material can be moved or lost, as contaminated areas are excavated and relocated, or buried. There are multiple examples where landfills and subsurface or buried infrastructure have been forgotten over time and uncovered accidentally during contamination assessment or other works at a site. Such changes and movement of landmarks can make identification of target investigation locations difficult for both planning stages and field teams.

Further, changes in regulations and industry standards over the long operating period of a mine can mean that historical assessments are not consistent with current expectations. One frequent example is development of previous PSIs consistent with the ASC NEPM. However, in many cases such PSIs were undertaken prior to emergence of PFAS as a family of chemicals of concern (around 2018), and therefore sources and transport pathways specific to PFAS may not be identified. For example, fire-fighting training grounds or foam deluge systems on petroleum fuel storage tanks would not have been considered as potential source areas.

Development and ongoing refinement of a CSM is critical to all stages of contaminated site assessment. However, development of a CSM can be challenging for large sites and may require regular updates to maintain currency and relevance, particularly due to ongoing changes to mining areas. In the authors' experience, it is also common for CSMs to be focused on individual contaminated sites or a specific purpose (such as groundwater model development), rather than a site-wide approach for contaminated site assessment. An example might be source–pathway–receptor assessment for a refuelling area with respect to a nearby creek or mining workers. While this considers the local risk from an individual source, it may not identify cumulative risks and does not allow risk ranking within the wider mine site context. Contaminants that do not degrade and/or those that bioaccumulate, such as PFAS or selected metals, can often only be assessed in the context of a mine-wide CSM.

2.4 Risk assessment and mineralisation

The CSM and associated risk assessment may also change over time, such as during transition from operations through rehabilitation to closure. For example, it is common for risk to human health or ecological receptors to be identified as low during operations, when exposure is essentially in a commercial/industrial setting, and while exposure to mining workers or ecological species can be readily managed. However, the risk profile can change significantly during closure and particularly with a change to land use. For example, dust with elevated concentrations of heavy metals generated from road traffic may be easily managed during operations via water application, but this could represent a risk at closure to nearby communities or plant uptake. Risks from water quality in and discharging from operational water features may be easily managed through water treatment or active management approaches (including groundwater pumping/dewatering) while a mine is operational, but this may not be possible during closure or under more passive management scenarios.

Complicating risk assessment in the mining context is the lack of readily available assessment criteria in soils for post-mining land uses such grazing and/or Traditional Owner cultural use. Exposure pathways such as ingestion of bush tucker or bioaccumulation in plants and grazing animals are not included in the ASC NEPM. As a result, it is common for site-specific assessment, often involving specialist risk assessors and also engagement with Traditional Owners, to be required to inform site assessment and remediation. This may be a lengthy process and outcomes are often not available at early stages of (and to inform) contaminated land assessment.

Naturally mineralised conditions that are characteristic of mine sites can cause further challenges applying standard criteria for both organic and inorganic contaminants in soil, surface water and groundwater. Although the ASC NEPM allows for consideration of ambient background concentrations of some inorganics in soils, this is for ecological receptors only and not human health. At coal mines for example, concentrations of total hydrocarbons can be naturally elevated and require consideration when applying assessment criteria for standard petroleum hydrocarbon analysis in soil. For waters where natural conditions exceed the default guideline values (such as in mineralised settings), use of background data to derive site-specific trigger values (typically 80^{th} percentile) is inherent in the national guidelines (ANZG 2018). For groundwater, the typical approach of using an upgradient monitoring bore or information from a nearby site to derive background concentrations cannot be readily applied to many mines. It is often difficult to identify location(s) representative of 'background' outside the influence of mining, either spatially (upgradient) or temporally (before mining). Background may also vary across the site, with depth, or with geology/hydrogeology.

2.5 Timing, costs and remediation options

In some cases, closure planning fails to consider contaminated site assessment, and in others contaminated site assessment can be delayed until later in planning stages, with other closure aspects given preference. As a result, contamination is often first considered as mines approach rehabilitation, when resources (time, equipment and personnel) are more limited.

As contamination is often not considered during operations, contaminated soils (including waste rock that may be perceived as operationally low grade or uncontaminated) can be widely spread or blithely used as a resource, resulting in more extensive distribution of the contaminated material. A lack of closure planning and forethought can also result in contaminated material being placed in inappropriate areas. Examples include use of poor-quality or inappropriate capping material which can allow contaminant exposure at the ground surface, or opportunistic placement of tailings into mined pits which are close to surface receptors or site boundaries. Site assessment during rehabilitation phase also reduces the time and therefore options available for remediation of contaminated sites. For example, passive or longer-term treatment options such as monitored natural attenuation of hydrocarbons or wetland treatments may not be viable as closure deadlines approach, and it is not uncommon to see quick (and sometimes more expensive) remediation options adopted by default. An example of this is a mine that is contemplating adoption of reverse osmosis treatment for leachate generated from onsite landfills at a nominal cost of AUD 1 million annually as the current disposal options will no longer be available due to their imminent closure. It is likely pre-planning and design could have prevented this requirement by elimination of leachate generation or allowing time to seek alternate and lower cost options.

Remediation options can also be limited due to the typically remote nature of mine sites and other factors. There may be technical or logistical challenges with implementing specialised remediation technologies on site, and higher costs for mobilisation of specialist contractors. Due to these time and cost constraints, it is therefore typical for remediation at mine sites to be focused on ‘dig and dump’ (excavation and burial) of any identified contaminated soils. There are also typically limited formal waste disposal options (e.g. appropriately lined landfills) near mine sites, and so onsite burial is often favoured. Other challenges can arise with onsite waste disposal, i.e. waste may not be contained in appropriately designed or lined waste cells or may require long-term environmental monitoring (typically in the order of decades) that is not compatible with the closure timeframes. For example, clay-rich or inert material for landfill construction may not be available on site or nearby, meaning that other (potentially less robust) materials are used, with likely poorer environmental outcomes such as more extensive leachate plumes.

Overall, while contaminated site assessment and remediation is typically a cost provision for mine closure, it can often be based on limited information and not fully considered early on in closure planning. As a result, costs (both financial and environmental) and timeframes are often underestimated.

3 Strategies

Through their combined experience at Australian mines, the authors have identified the following strategies to address the identified mine-specific challenges during contaminated site assessment and remediation.

3.1 Early assessment, engagement and consideration of contaminated land

There seems to be a general reluctance in some operational mines to assess contaminated land, potentially due to the perception that the site condition will change by the time closure is realised, and also potentially with a view to minimising operational costs. However, early assessment and consideration of contaminated land or contaminant sources allow decisions to be made during operations, through rehabilitation and into closure, that can minimise contamination and remediation, with associated cost savings.

Early contaminated site assessment can identify operational improvements that minimise further contamination. For example, more-thorough assessment of a known release of petroleum hydrocarbons to groundwater would likely allow earlier identification of the potential for additional and ongoing leaks from underground storage tanks. For at least one mine site, this delay has led to a greater extent of contamination than if the contamination had been assessed more fully when first identified. In this example, diesel has continued to leak from storage tanks for 3 decades after the initial leak was identified due to irregular and inappropriately designed and implemented monitoring that resulted in the ongoing leak not being identified. Contamination and the associated remediation effort could have been reduced or avoided if clean-up and targeted monitoring had been implemented effectively at the time of the initial leak, with large associated cost reductions (potentially in the order of millions of dollars).

As well as during operations, undertaking aspects of contaminated site assessment at the early stages of closure planning and well before closure allows robust costs to be developed and cost liabilities to be further refined, but can also reduce costs. Planning can mean that remediation works can be undertaken while there are sufficient resources on site, making full use of a knowledgeable workforce and potential personnel or equipment downtime, rather than requiring special mobilisations. Early assessment also widens the remediation options able to be applied and may allow application of longer-term or less energy intensive remediation technologies to reduce contaminant mass and reliance on 'dig and dump'; this approach is also more consistent with the waste hierarchy in the ASC NEPM. For example, use of onsite bioremediation for hydrocarbons may allow contaminated soils to be retained or replaced in situ following treatment, rather than requiring their disposal as a waste material.

Early assessment of potentially contaminated sites should also include early engagement with stakeholders, community, and Traditional Owners, including to inform site-specific risk assessment for future Traditional Owner or other land uses not covered in the ASC NEPM. This approach is inherent in the ASC NEPM, which advocates for early-stage community engagement that continues through the site assessment process, and also has regard for sites of cultural or spiritual significance. Early engagement can help set expectations and reach agreement on a final site condition, use or landform, which then defines and drives the extent of site assessment and remediation in specific areas and how landforms may be backfilled or constructed for closure. The agreed final landforms can then also be considered in site-specific risk assessment, e.g. acceptable water quality to allow potential direct contact by humans (swimming) or catching and eating fish within pit lakes.

3.2 Consolidating and leveraging existing and historical data

Effective and efficient management of environmental data presents challenges across many industries including mining, particularly as approaches to management change. Multiple databases or servers may have been developed and used over time, or applied to different data (e.g. soils, water levels, water quality), or by different operational teams (e.g. environment, water, mining, exploration). Historical data or data collected by other parties (consultants, stakeholders, etc.) or for specific projects is often 'buried' in individual un-editable reports and not integrated within current operational databases. There is then a high likelihood that this data are lost, which represents both a loss of knowledge and a waste of effort and money.

Consolidation of existing data, including documents in portable digital format (pdf), spreadsheets and older or alternate databases, into a collated, complete and single format that is readily able to be updated is a key first step in leveraging existing data, maximising the value of data collected, reducing rework, and providing an indication of site conditions over time.

A first approach to consolidating data could be undertaking a bore census, which involves collation of all available bore construction information as well as geologic borelogs. Key bore construction information includes bore location (eastings/northings), elevation (ground level and top of casing), screen interval and geology, as well as other details on the drilling and development methodologies, aquifer testing, observations and bore condition. The information consolidated within a bore census can then be easily interrogated and used to develop CSMs, build 3D models of geology, and design monitoring bore networks. Another example of developing a complete database would be consolidation of soil and groundwater field and analytical data, including groundwater elevations, field parameters and laboratory analytical data. Once this is information is consolidated, it can be much more readily compared, integrated and used for contaminated site decision-making.

There are multiple database tools available depending on the data to be consolidated and where the site sits within its life cycle. The selection of a database needs to consider whether the data will comprise point data and/or continuous data, and whether it will also include photos and attachments. A further consideration is the ultimate use of the data and its presentation. Once established, it is critical that the database is then maintained as current and complete, recognising the processes and resources required for this task.

3.3 Visualising and communicating data

Once existing and historical data have been consolidated into a single and electronic format, the data can then be readily presented in visualisations and dashboards to assist in decision-making and communication. There are multiple ways to visualise and communicate data, depending on the data and the required outcomes, with some examples outlined below. Typically, dashboards and visualisations have been used to communicate and share data or results with external stakeholders. However, there is also immense value in using this approach for internal communications, including providing improved and more efficient field/site to office communications.

3.3.1 3D visualisations

3D visualisation of geology/hydrogeology is common in mining, including the use of tools such as Leapfrog, Vulcan and MineScape. Typically, these 3D models and visualisations are focused on and show greater resolution for resource and target geology. However, development of 3D visualisations for large or complex sites is also recommended in the ASC NEPM for CSM refinement for contaminated sites generally.

Leveraging consolidated geology/hydrogeology information (including a bore census), often with reference to existing mining models and with enhancements to focus on shallow or non-target geologies, is a key way to visualise and communicate subsurface contamination and the mine-wide CSM. Visualisations can be enhanced and support interpretation by presenting information such as groundwater elevations, bore screens, and soil or groundwater analytical results. For example, at several sites the outcomes of bore census and consolidated groundwater databases of analytical data have been combined with 3D operational mine resource models to present cross-sections through proposed mine features, including pit lakes, to explain potential source–pathway–receptor linkages as part of closure planning. This approach has helped to identify and communicate potential water quality risks from proposed final landforms such as pit lakes and waste rock and overburden dumps. An example of this type of visualisation is provided in Figure 1.

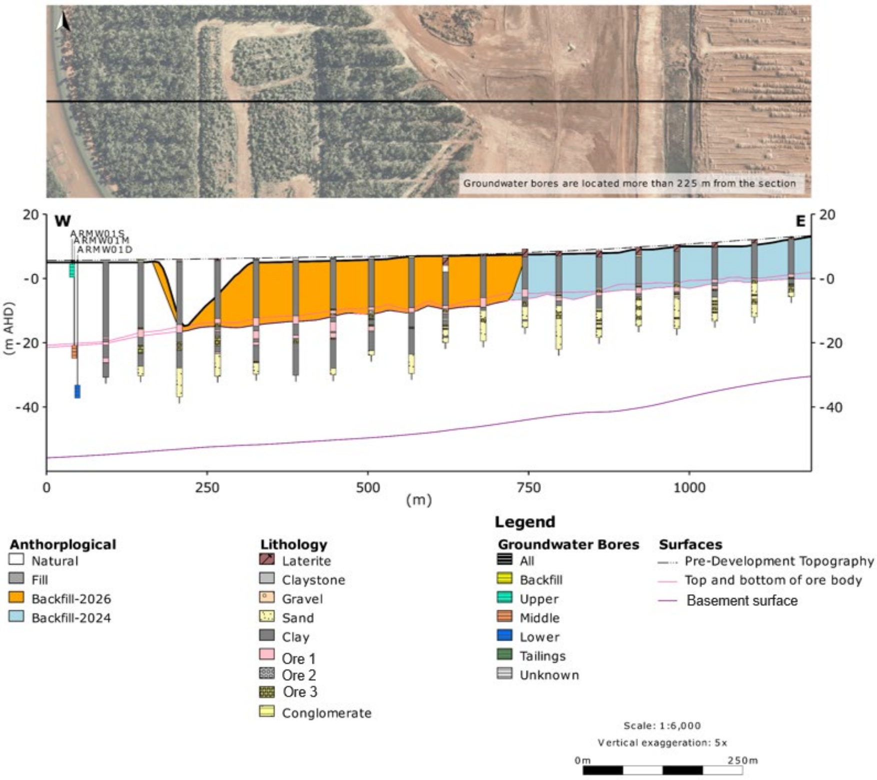

Figure 1 Example cross-section generated based on bore census and mine resource model

3.3.2 Geographic information system web maps

Geographic information system (GIS) web maps allow visual overlay of spatial data, combining historical and current mapping, aerial photos and consolidated database information (such as bore locations, groundwater elevations and soil/groundwater quality data). This type of visualisation can be used in all stages of contaminated site assessment, from PSI through to remediation.

A GIS web map could be generated as part of a PSI, allowing the various sources of information to be consolidated. Overlay of historical and current georeferenced maps, plans and aerial photos can be used to identify areas, infrastructure and sources of potential contamination, and also to identify potential receptors. This information can then be overlain with previous investigation locations and results to further assess or define potential source areas, for example, historical soil sampling in a former fire training area. A GIS web map generated during and as an outcome of a PSI can then also be used to allow transparent planning and justification for subsequent DSIs, including development of Sampling and Analysis Quality Plans.

Onsite implementation of a DSI can also leverage the same GIS web map, improve safety and support decision-making and communication between the site- and office-based teams. For example, maps of subsurface services (power, water, sewer, etc.) can be included in the web map, allowing adjustment of onsite locations in real time to avoid intersecting services during intrusive works, while still targeting the source area or meeting the objectives of the investigation location. Real-time geolocation is also particularly beneficial when targeting former infrastructure where above-ground landmarks may no longer be present due to changes at the site.

Observations made on site, including photos and notes, can be geolocated and uploaded to the GIS web map, making note-taking and communication more precise and efficient. This has been particularly beneficial when executing longer field programs, particularly when onsite work is conducted on a rostered basis, by reducing handover time and the chance of tasks being missed or repeated. Real-time updates also allow tracking of progress against schedules and budgets by the office-based team.

As well as supporting high-quality onsite DSI works, combining the sampling results and outcomes from field programs into tools like a GIS web map can support efficient data interrogation, DSI reporting, update of the CSM and milestone reporting. The web maps can also be shared live with external stakeholders to aid in communication and visualisation, also providing data transparency with respect to project outcomes.

3.3.3 Dashboards

Dashboards that integrate with collated databases are a further way to visualise, interrogate and communicate data and the CSM. Examples include PowerBI and other bespoke solutions (such as R and Python code) which enable data to be presented in graphs and maps automatically from databases. Presentation of data in this format allows rapid screening against different assessment criteria, comparison of concentrations between sampling locations, identification of data outliers and statistical or visual identification of data trends. This has proven particularly effective in a mine closure project where groundwater data from hundreds of groundwater monitoring bores over several decades were presented as a dashboard, illustrating spatial distribution of concentrations, exceedances of assessment criteria for contaminants of concern, and contaminant trends over time in a single and accessible platform. Through this platform and associated statistical assessment, selection and justification of background concentrations were able to be made that accounted for natural background mineralisation and considered the mine-wide CSM. This allowed for the development of site-specific criteria for application to groundwater from specific hydrogeological units during rehabilitation and closure. The dashboards were able to be easily shared with external stakeholders, with this transparent approach facilitating communication and understanding while also allowing data interrogation. An example of this type of visualisation is provided in Figure 2.

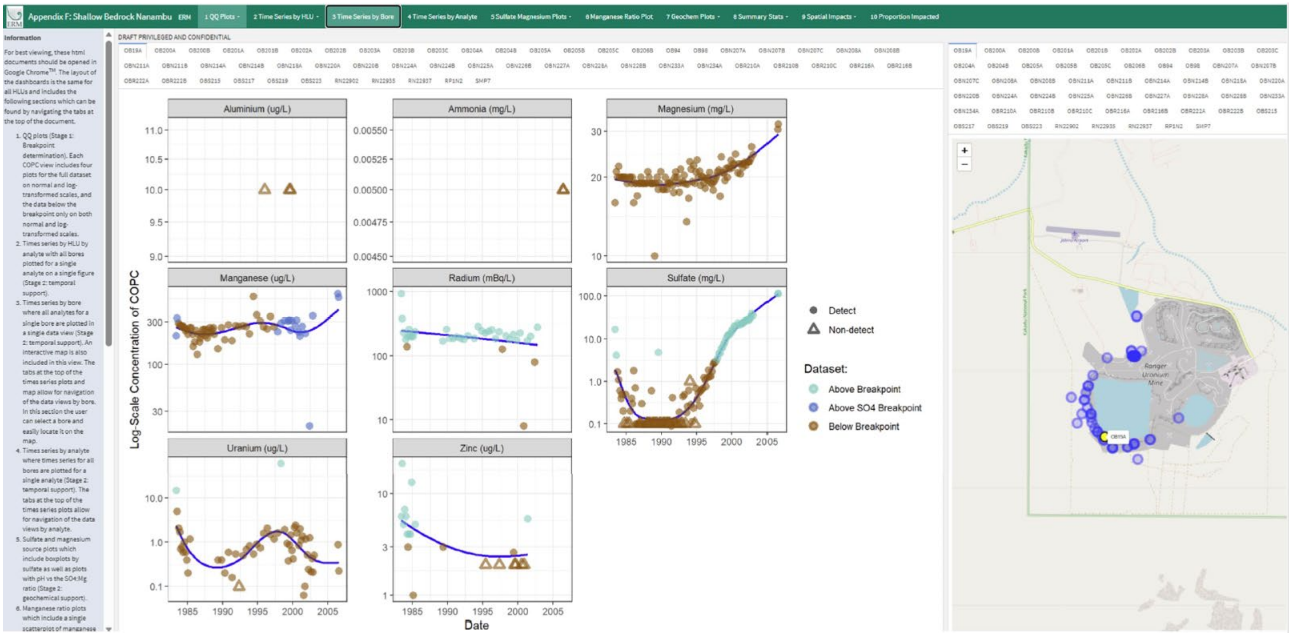

Figure 2 Example dashboard showing maps and graphs

3.4 Domain approach

Industry best practice is to divide large contaminated sites into assessment domains, often based on historical or current potential contamination or activities. Definition of domains may also include consideration of future land uses, highlighting the importance of considering the future land use early in the site assessment process. The domain approach is consistent with the ASC NEPM that advocates for sites to be divided into assessment areas and/or exposure areas.

The domain approach is also typically adopted for mine sites, with example domains being TSFs, stockpiles, processing areas, grazing areas and irrigation areas. Domains do not need to be co-located or the same size and shape. For example, a long and narrow domain may be defined for a rail line, conveyor or pipeline, a very large domain for strip mining operations, or a very small domain for multiple individual refuelling areas with potential hydrocarbon contamination.

This approach can work well in many cases by supporting risk ranking/prioritisation and allowing staged site assessment. However, in other cases and particularly when in the early stages of contaminated site assessment, a strict domain approach can be too inflexible or may set the expectation of the same approach and sampling density being applied across all areas of a specific domain. The GIS web map approach outlined above is one strategy to provide flexibility in site assessment and reporting, for example, allowing the domain extent to be adjusted as site assessment progresses.

A further consideration that is less common at mine sites, but is becoming more apparent, is the potential value of aligning domains with current and future title or lot boundaries, rather than mining licence boundaries. This particularly becomes a consideration for close out of contaminated site assessment, such as through the involvement of an environmental auditor where, typically, titles rather than mine licence boundaries are considered. In Western Australia for example, land is classified on the contaminated sites register based on title boundaries as ‘contaminated – remediation required (CRR)’, ‘contaminated – restricted use’ (C-RU) or ‘remediation for restricted use’ (RRU).

3.5 Mine-wide conceptual site model and perspective

Although detailed assessment of individual contaminated sites and development of a local CSM may be important to understand local-scale risk, as discussed earlier, it is equally important to develop a mine-wide CSM that is robust and undergoes regular updates. A mine-wide CSM can support risk ranking and allow development of site-wide criteria and objectives (such as developed through dashboard interrogation), enabling a consistent approach and potentially reducing effort managing individual sources or contaminated sites across a mine. Consideration of each individual contaminated site within the mine-wide context may allow grouping of similar contaminated sites with associated realisation of remediation efficiencies. Similarly, developing a flow chart or process that guides site assessment effort or decision-making, or preparing an overall remedial strategy for an individual contaminant, may also reduce effort and save time and money. For example, petroleum hydrocarbon contaminated soil at multiple locations could be excavated to a defined distance and depth based on analytical soil data, with all excavated soils then placed together for collective onsite bioremediation and re-use.

A mine-wide perspective is particularly important for PFAS due to their unique behaviour in the environment, i.e. they do not readily degrade, can bioaccumulate and are often highly leachable and mobile. Consistent with the PFAS NEMP (HEPA 2025), contaminated site assessment at mines typically focuses initially on primary sources of PFAS, such as fire-fighting activities or fire incidents, fire training facilities, airports, fire-fighting foam storage, foam deluge systems and power generation facilities. However, secondary sources of PFAS such as landfills, waste water treatment plants, biosolids and waste water irrigation can be equally, if not more, important to understand. Understanding surface water (e.g. dust suppression, irrigation, soakaways and operational water movements), groundwater (e.g. groundwater extraction, dewatering and injection) and material movements over the history of mining operations is key to identifying secondary sources of PFAS, with the scale (spatial and temporal) on which these processes occur typically being unique to mines. Consequently, secondary sources of PFAS may be remote from the primary or other secondary sources, and this further supports the need for a mine-wide CSM for both PFAS and other contaminants of potential concern.

For PFAS, the low-level ecological water criteria (less than 1 mg/L) and potential for bioaccumulation, are a particular challenge, with exceedances of criteria often triggering site-specific assessment and/or biota sampling to assess risk to ecological receptors. Such assessments can be supported by a mine-wide CSM which considers water and material movements in addition to results of PSIs and DSIs. As indicated above, undertaking assessments for PFAS early in closure planning can also support operational changes that reduce the spread of PFAS contamination away from the primary and secondary source areas. For example, if a particular water storage is identified as containing PFAS, it could be separated from the wider operational water movements to prevent spread of contamination.

4 Benefits

In the authors' experience, adoption of the strategies outlined above, as applicable for contaminated land assessment at each mine site, provides a range of benefits throughout the ASC NEPM process.

At PSI stage, multiple types of existing data and site history can be leveraged to their full value, resulting in development of more robust DSI scopes that are better targeted towards higher risk areas. On site and during reporting stages, DSI and field sampling campaigns can also be more efficient and flexible, reducing errors, rework and maximising available resources on site.

Early identification of contaminated or potentially contaminated sites can enable operational changes to be made, reducing the nature and extent of further contamination, with associated reduction in future remediation requirements. Early identification of contamination and associated remediation planning also expands the range of remediation options available, potentially allowing lower cost and more passive options to be realised, and allowing areas to be cleared or remediated before closure. This also reduces timeframes and costs of environmental monitoring during closure.

Early development of and reference to a mine-wide CSM and risk-based, site-specific criteria can better account for mineralised conditions and support final land use planning. Prevention of contamination, through improved operation practices, can allow additional value to be realised for future site users and potentially provide better outcomes for stakeholders, community or Traditional Owners.

Overall, the strategies outlined better inform liabilities and costs associated with identifying managing and remediating contaminated sites. Cost savings can be realised during operations, rehabilitation and into closure, including through reducing future contamination and the need for additional remediation. Ultimately, these strategies facilitate more complete site assessment remediation planning, and therefore timely and cost-effective mine closure.

5 Conclusion

Strategies for contaminated site assessment and remediation have been developed to address mine closure planning challenges, based on direct experience at multiple Australian mines. Key challenges that are common to many mine sites relate to assessment of multiple sources at sites that are large and typified by long and complex histories. Further challenges arise due to typically mineralisation conditions, including for risk assessment and remediation, and particularly due to the remote nature of many mine sites, which limits remediation options. Strategies to address these challenges involve early assessment, engagement and consideration of contaminated land in operations and closure planning. The value of consolidating and leveraging existing data to support decision-making and stakeholder communication cannot be underestimated. While different strategies and combinations of strategies will apply at individual mine sites, a robust mine-wide CSM and perspective should be developed and updated through the entire contaminated site assessment and remediation process for every mine. Benefits in adopting these strategies include time and cost improvements for site assessment and remediation during operations, rehabilitation and closure.

References

ANZECC 2000, *Australian and New Zealand Guidelines for Fresh and Marine Water Quality*, National Water Management Strategy.
ANZG 2018, *Australian and New Zealand Guidelines for Fresh & Marine Water Quality.*
CRC CARE 2019, *National Remediation Framework.*
HEPA 2025, *PFAS National Environmental Management Plan 3.0,* National Chemicals Working Group.
NEPC 1999, *National Environment Protection (Assessment of Site Contamination) Measure (ASC NEPM),* revised May 2013.
NHMRC 2011, *Australian Drinking Water Guidelines 6,* revised June 2025.
NHMRC 2008, *Guidelines for Managing Risks in Recreational Water*, Australian Government.