Office of the **Queensland Mine Rehabilitation Commissioner**

Mine waste cover system trials - a literature review

Technical Paper 1

Queensland Government

Prepared by: Office of the Queensland Mine Rehabilitation Commissioner

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1.1	18 July 2025	OQMRC branding, copyright and accessibility information updated

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Executive Summary

The management of acid and metalliferous drainage (AMD) from mine waste has been the subject of international research and management actions given its widespread persistence and deleterious environmental impacts. Cover systems have become a critical element of AMD management. However, in Queensland, the long-term performance of cover systems in abating AMD has not been conclusively demonstrated. The Office of the Queensland Mine Rehabilitation Commissioner (OQMRC) has received anecdotal feedback of cover system failures and varying reports of cover performance from stakeholders. One critical element of cover system performance is the execution of high quality cover trials to design and test their performance and construction.

To develop a focused, practicable methodology to undertake cover trials, OQMRC has undertaken a literature review of trial methodologies (Technical Paper 1), examined case studies on cover trials and cover performance monitoring (Technical Paper 2) and developed a trial methodology for application to the Queensland environment (Technical Paper 3). The trial method recommended in Technical Paper 3 describes how to plan and implement reliable cover trials to support AMD management in Queensland in a pragmatic and cost-effective manner that avoids prescribing excessive requirements. The method applies store-and release cover design principles and is focused on the primary AMD transport mechanism of net percolation. The work draws on the globally established AMD literature addressing whole-of-mine-life AMD management and distils those critical elements for undertaking high quality trials in Queensland. Broader aspects of cover system design are also addressed within this paper if they are required to ensure a high quality trial.

The review presented in this first Technical Paper examines literature and international guidance on mine waste cover system trials. This includes the factors that should be considered when planning a field-scale trial, and activities that should be completed prior to undertaking a field-scale trial. The purpose of a cover system is to provide a stable, reliable, and sustainable engineering layer between mine wastes and the surrounding environment. Local climatic conditions impact on cover system performance and typically dictate which cover system types are suitable for a particular site. The objectives of a proposed cover design need to be stated upfront, prior to undertaking trials. Some key objectives for a cover design are to limit net percolation (NP), oxygen ingress, and salt rise to the surface.

An understanding of baseline conditions at the site is needed to support the design of a waste cover. The most important climatic variables for cover design are the potential evapotranspiration ratio, annual precipitation, and the type of climate. The features and configuration of the waste landform that a cover system is placed over strongly influences the performance of a cover system. Vegetation plays an important role in cover systems. The geochemical and geotechnical properties of the waste material and potential cover system materials play a strong role in informing the final landform and cover system design. It is important to ensure there is enough cover material with appropriate characteristics available during cover system testing. The availability, cost and haul distance from the waste source are key factors in material selection and optimisation for cover systems. Undertaking adequate/appropriate quality control and assurance (QA/QC) checks on the construction for the cover system (and landform) is identified. Trialling the proposed construction methodology to assess whether the proposed cover design can be recreated using available equipment and to identify shortfalls in the design is discussed.

Prior to the commencement of field-scale trials, site-appropriate mine waste cover designs should be developed. During the design process, modelling plays an important role in identifying and controlling risks. Detailed modelling allows multiple cover design options and scenarios to be tested prior to constructing a trial in the field. The laboratory testing of covers through experiments such as column tests of designs may also be undertaken to determine which designs should be trialled at field scale. A number of small-scale laboratory experiments that do not use columns were also identified.

Prior to undertaking a trial, objectives for the trial must be established. Most field-scale studies identified in the literature constructed trial cover systems on existing waste rock structures, while some studies were undertaken using purpose-built landforms. No clear guidance on the location of a field-scale trial was located in industry guidelines. The scale of a field-scale trial will likely be constrained by costs and the timeframe for the trial. The scale of trials reported in the literature varies. A trial period of three to five years for field-scale trials is recommended in one instance, and in another, a 5-year minimum field-scale trial, with the intention of capturing major climatic cycles. Risks such as equipment failure become more prevalent in trials that are run for longer periods. Monitoring

is critical to demonstrate the performance of a cover during a trial. Various guidance documents outline different variables that should be monitored in cover trials. A field-scale trial may fail due to the inability of a monitoring system to acquire the correct data and/or incorrect sampling procedures.

Once the trial’s sampling period has finished, data interpretation and reporting may be undertaken to allow for the assessment of the research question and objectives. The data from the trial may be used to calibrate a model and predict future success or failure of a cover system design. In the literature, there are various instances of different statistics being reported in cover system trials.

The use of appropriate controls in field-scale trials can help proponents interpret performance and test whether a treatment has an effect. Few field-scale trials were identified in the literature which incorporated control experiments, and this may be because control experiments are subject to the same challenges and limitations as replicate experiments.

1 Introduction

Acid and Metalliferous Drainage (AMD) is a potential consequence of mining activities that forms due to the natural oxidation of sulfide minerals when exposed to air (oxygen) and water (INAP 2017). AMD produces run-off and seepage with a low pH and in some cases elevated concentrations of metals and/or metalloids (Zhang et al. 2023), and this can have severe adverse and long-lasting environmental effects. For further information on AMD in mining see INAP (2017).

Several cases have been reported in Queensland of AMD being generated at mine sites then spreading to the surrounding environment and affecting native ecosystems. For example, the AMD generated from one historic gold mine in Queensland has spanned at least 80 km downstream of the mine in local rivers and to a depth of 30 cm in the riverbed and floodplains. This has adversely affected local aquatic ecosystems (Taylor et al. 2022). Soil in the area also contains copper levels that are on average 9 times the sediment trigger value in Australia (Vicente-Beckett et al. 2016). Unabated, AMD is expected to continue being generated at this mine for at least the next 500 years (Gasparon et al. 2007).

The International Network for Acid Prevention (INAP) was established to reduce liabilities associated with sulfide mine materials by enabling networking and information sharing and providing technology transfer and gap-driven research (INAP 2024). INAP has published several documents on management of AMD (INAP 2017) including the Global Acid Rock Drainage (GARD) guide (INAP 2009). The GARD guide is an internationally recognised document.

The purpose of a cover system is to provide a stable, reliable, and sustainable engineering layer between mine wastes and the surrounding environment. Cover systems form part of a wider system of interventions required to successfully manage AMD that includes, inter alia, placement of acid and non-acid forming materials and geotechnical design of structures. INAP (2017) describes six types of cover systems: simple protection, store-and-release, enhanced store-and-release, barrier type, engineered layer, and saturated soil or rock. Cover systems reduce the formation of AMD from reactive materials by limiting net percolation (NP) and/or controlling oxygen ingress (INAP 2017). The mechanism for achieving this depends on the type of cover used but can include storing water until it is removed by evaporation and transpiration. Other roles of cover systems include controlling erosion, serving as a growth medium for vegetation and ecosystems, isolating chemically reactive wastes, supporting the post-mining land use (PMLU), and to satisfy regulatory requirements (INAP 2017).

In Queensland, the *Environmental Protection Act 1994* (Qld) (EP Act), s111A states that mined land must be left in a stable condition. Regulatory settings in Queensland require application of cover systems to ‘high risk’ waste materials, classified as those that contain potentially acid forming (PAF) materials, using a prescribed ‘default’ cover system. The ‘default’ cover system comprises of a capillary layer (0.6 m), low permeability layer (0.5 m), and a top rock layer (1.5 m). For tailings storage facilities a working layer (0.5 m) must be placed below the capillary layer (DESI 2022). The Estimated Rehabilitation Cost (ERC) Guideline (DESI 2024) allows proponents to select an alternative cover design provided that the design has been tested in a field-scale trial and the results are equivalent to or better than the default design.

The ERC Guideline outlines some of the elements of a suitable field-scale trial, and further information can be found in INAP (2017) and the GARD guide (INAP 2009). The INAP framework represents the industry standard internationally for designing cover systems. This framework refers to six ‘key activities’ for cover system development. This process is presented in Figure 1. Field-scale trials constitute key activity 4 of the process described in INAP. INAP recognises that it is necessary to have completed key activities 1 – 3 prior to progressing to a field-scale trial. These planning and information gathering stages are critical to inform the design of the waste covers being tested in a field-scale trial.

The management of AMD from mine waste has been the subject of international research and management actions given its widespread persistence and deleterious environmental impacts. Cover systems have become a critical element of AMD management. However, in Queensland, the long-term performance of cover systems in abating AMD has not been conclusively demonstrated. The Office of the Queensland Mine Rehabilitation Commissioner (OQMRC) has received anecdotal feedback of cover system failures and varying reports of cover performance from stakeholders. One critical element of cover system performance is the execution of high quality cover trials to design and test their performance and construction.

To develop a focussed, practicable methodology to undertake cover trials, OQMRC has undertaken a literature review of trial methodologies (Technical Paper 1), examined case studies on cover trials and cover performance monitoring (Technical Paper 2) and developed a trial methodology for application to the Queensland environment (Technical Paper 3). The trial method recommended in Technical Paper 3 describes how to plan and implement reliable cover trials to support AMD management in Queensland in a pragmatic and cost-effective manner that avoids prescribing excessive requirements. The method applies store-and release cover design principles and is focused on the primary AMD transport mechanism of net percolation. The work draws on the globally established AMD literature addressing whole-of-mine-life AMD management and distils those critical elements for undertaking high quality trials in Queensland. Broader aspects of cover system design are also addressed within this paper if they are required to ensure a high-quality trial.

The review presented in this first Technical Paper examines literature and authoritative international guidance on mine waste cover system trials. This review includes the factors that should be considered when planning a field-scale trial, and activities that should be completed prior to and during a field-scale trial including establishing objectives of the cover design, collecting baseline information, developing cover alternatives, and monitoring.

Figure 1. Key activities for cover system development (adapted from INAP 2017)

2 Cover design objectives

The objectives of a proposed cover design need to be stated upfront, prior to undertaking trials (DESI 2023). Some key objectives for a cover design are to limit:

- net percolation (NP)
- oxygen ingress
- salt rise (Australian Government 2016a; DESI 2024).

Technical Paper 2 found that controlling NP was the key objective for some cover designs. Various NP objectives were mentioned in the literature, such as 5% (INAP 2017), <5% for wetter climates (INAP 2017), 10% (Defferrard and Rohde 2019) and <1% (Kalonji-Kabambi et al. 2021). Although NP is an important metric, other objectives, including water quality and oxygen concentrations within cover systems were also found in the literature (Chtaini et al. 2001).

There may also be other peripheral closure objectives that inform a cover design. For example, encapsulated waste material should also achieve geotechnical and erosional stability (including wind and water erosion) (DESI 2024; MEND 2004; Australian Government 2016a) and the final landform surface may also need to sustain vegetation or host a PMLU (Australian Government 2016a, 2016b).

Quantitative benchmarks may be identified for each objective to evaluate whether a cover design is likely to be appropriate. A design specification may include a benchmark for a critical parameter such as NP (L) < $\mathcal{X}$% annual precipitation (mm) and/or NP < $\mathcal{X}$ mL/m^2/annum (INAP 2017).

INAP (2017) describes an approach to determine cover system design objectives. They stress that there may be a mix of analytical and qualitative objectives; and that objectives must consider site-specific constraints. It is expected that a clear objective is stated and in later sections, the INAP framework (Section 7.3) focuses on the specific objective that a cover system will minimise the release of acidic and metal/metalloid seepage to the environment from the mine waste structure. This may be achieved by controlling net percolation to prevent transport of soluble acidity and, to a lesser degree, dissolved oxygen (INAP 2017, Section 7.3).

3 Baseline information

An understanding of baseline conditions at the site supports the design of a waste cover. The GARD guide highlights the requirements of developing designs for cover systems, which includes collecting baseline information on site conditions including climate, land, and water conditions, detailed characterisation of all materials (both waste and potential cover materials), and some non-technical considerations. These considerations are discussed in more detail below.

3.1 Climate

Local climatic conditions, particularly precipitation and the temperature, impact on cover system performance and typically dictate which cover system types are suitable for a particular site (INAP 2017; MEND 2012; Ayres 2021). The intensity of rainfall is one of the main factors that dictates the extent to which surface water is redistributed prior to infiltration and discharge from the cover system (INAP 2017).

The most important climatic variables for cover design are the potential evapotranspiration (defined as 'the sum of evaporation and plant transpiration that would occur assuming sufficient water is available' by INAP 2017:9) ratio, annual precipitation, and the type of climate. The Koppen-Geiger classification for climate is used because it has strong ties to landscape signals such as vegetation and soil development, which are relevant in the context of mine rehabilitation, and because it incorporates seasonal variations in weather. This is important in cover system design because some seasons may experience high levels of precipitation that is masked when only annual precipitation is considered (INAP 2017). At least 50 and preferably 100 years of daily climate records should be used during modelling for cover system design (O'Kane and Ayres 2012). The effects of climate change should also be considered and INAP (2017) recommend that a 'reasonable' climate change scenario is tested to assess the ability of a cover system design to respond to expected future climatic conditions (Lieber et al. 2022; Botula et al. 2024).

In Queensland store-and-release covers (shown in Figure 2) are considered the most suitable type of cover for most mining provinces due to the climate and based on INAP (2017) (for further information see Technical Paper 3). However, some cases were identified where other types of cover systems were used in Queensland such as a water shedding system (e.g. TEC Coal Pty Ltd 2023).

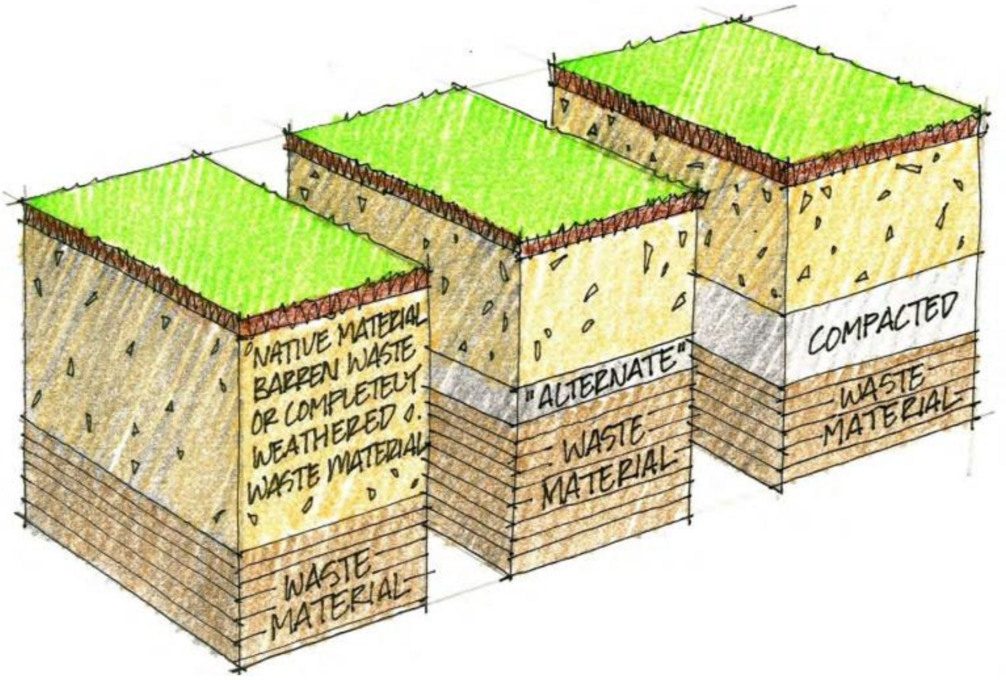

Figure 2. Store-and-release cover systems: (a) basic store-and-release cover system, (b) and (c) enhanced store-and-release cover systems showing additional lower hydraulic conductivity layers below the storage layer (INAP 2009)

3.2 Land and water

The features and configuration of the waste landform that a cover system is placed over strongly influence the performance of a cover system (Sawatsky et al. 2000). Waste landforms are typically designed in a manner that is easy to construct (Sawatsky et al. 2000) but are prone to shallow slope failures and high erosion rates (Ayres et al. 2003). Unfavourable landform design could lead to a trial failing despite the cover design being adequate.

Cover systems can alter local hydrogeological settings by changing flow pathways and partitions, altering storm responses of receiving water bodies and changing recharge and discharge rates and locations (INAP 2017). Incorrect analysis of water flows through the cover system could result in incorrect predictions for acid and/or metals loadings to the receiving aquatic environment and/or additional oxidation of reactive wastes (Ayres et al. 2003). This may lead to a cover system failing during testing or the field-scale trial not capturing failure modes that result from an incomplete understanding of the hydrogeological setting.

INAP (2009) lists consideration of site-specific discharge water quality among factors that should be considered when determining the objectives of a cover system. The quality of seepage from a waste landform has historically been used to evaluate the performance of dry cover systems. A disadvantage of this approach is that it may take tens of years before a significant change in quality is measured (INAP 2009) and in the context of a trial conducted over a few years the full effect of the cover on discharge water quality may not be captured during the duration of the trial. Regardless, measuring the discharge water quality can provide valuable information on the performance of a cover during a field-scale trial.

INAP (2009) states that vegetation plays an important role in cover systems by controlling erosion, enhancing evapotranspiration (for store-and-release covers), helping to re-establish sustainable ecosystems, and helping to satisfy requirements for PMLU. Studies have shown that increasing vegetation coverage typically decreases seepage (Haagner and Van Wyk 2022) and increases evapotranspiration rates (Millar et al. 2023; Williams et al. 2006a, 2006b). However, limitations of the effect of vegetation are also recognised in the literature. Taylor et al. (2003) listed root penetration from vegetation as one of the causes of failure of a cover at Rum Jungle. The effect of vegetation on preferential flow paths in soils is also recognised (Gang et al. 2017). In some cases, the effect of vegetation depends on the climate. Baumgartl et al. (2012) concluded vegetation only has a significant effect on water extraction in climates where precipitation is sufficient and relatively uniformly distributed, and if the cover materials can sufficiently store successive rainfall events. Lastly, it is worth noting that vegetation may not become fully established during a field-scale trial. For example, the Western Australian Government recommends a minimum vegetation establishment period of at least two summers (Main Roads Western Australia 2004). Trials generally occur over relatively short periods of time so vegetation may not reach the desired level of establishment. This could affect the performance of the cover if vegetation is relied upon significantly to meet the objectives of the cover design.

MEND (2012) published information on designing cover systems for cold climates such as those in Canada. As these conditions do not reflect the Queensland climate this will not be discussed further.

3.3 Material characterisation

The geochemical and geotechnical properties of the waste material and potential cover system materials play a strong role in informing the final landform and cover system design. Proper characterisation minimises final closure work, increases the quality of the outcome and reduces the risk of failure (INAP 2017).

Geochemical testing is comprised of ‘static’ and ‘kinetic’ testing. The purpose of static testing is to understand the potential for materials to generate and neutralise AMD. The purpose of kinetic testing is to understand the rates of AMD formation and neutralisation and related processes (INAP 2009). This includes predicting long-term weathering rates and the potential for materials to release discharge that may impact the environment, to evaluate the rate of acidity/buffering generation, and to evaluate the lag time before onset of AMD generation (INAP 2009; Australian Government 2016a). INAP (2009) and Maest and Kuipers (2005) separate geochemical characterisation in ‘Phase 1’ and ‘Phase 2’. Phase 1 comprises of purely static tests and is for screening purposes while Phase 2 comprises of additional static tests and kinetic tests to provide greater detail and is generally required in more complex settings.

The types of static tests recommended varies in the literature, but all include acid-base accounting (e.g. Hughes et al. 2007; Ross and Verburg 2015; Pollard et al. 2022; Australian Government 2016a). Methods for acid-based accounting include the chromium reducible sulfur method (CRS) (Schumann et al. 2012) and the standard and modified Sobek tests (also called ‘ABA Methods’) (Lawrence and Wang 1996; White III et al. 1999). The mineralogy of the material being analysed can affect the results of acid-base accounting methods. For example, alunite-jarosite ground minerals complicate the analyses because the response of these minerals to sulfur-specific leach tests is variable and not well understood, and these minerals can be an acidity source. The sulfide content may be underestimated in these tests due to incomplete reactions of some sulfide phases (Jamieson et al. 2015). Lastly, the results of these tests may be affected by the particle size, which affects the mineral liberation characteristics (Opitz et al. 2016). Understanding the mineralogy of the waste material may assist in overcoming these limitations.

Other analyses recommended as part of static testing include elemental analysis, sulfur speciation, pH, particle size distribution (PSD), mineralogical analysis, field measurements of in-situ properties, carbon speciation, maximum potential acidity (Price 1997; Australian Government 2016a; Hughes et al. 2007). Studies were also identified in the literature that proposed new methods for static testing such as Parbhakar-Fox et al. (2018), which developed a test for heterogeneous materials (note that most analyses are designed for homogeneous materials).

Common types of kinetic tests are column leach tests, humidity cell tests (Australian Government 2016a) and free draining (funnel) tests (AMIRA 2002). Oxygen consumption and oxygen penetration tests have been developed to address some of the limitations of the column and humidity cell tests (Australian Government 2016a; Pieretti et al. 2022). INAP (2009) and Maest and Kuipers (2005) recommend repeating mineralogical, chemical, and acid generation potential analysis after kinetic testing.

Mineralogical analysis of mine wastes, particularly for sulfide and carbonate phases, is critical for predicting the acid generation behaviour of the waste but is often overlooked or incomplete during geochemical characterisation. Jamieson et al. (2015) discusses the benefits of undertaking detailed mineralogical analysis of mine wastes, including in the context of waste covers, using a case study on gold tailings in Canada. Mineralogical analysis of the tailings revealed the presence of arsenic, and column leach studies of cover scenarios revealed that the pH of the solution produced was heavily influenced by the presence of arsenic regardless of the pH (i.e. acidity) of the input solution. In this case understanding the mineralogy of the arsenic minerals present was beneficial to interpreting the results of the leach test and could be beneficial in designing a suitable cover for this waste.

Geotechnical characterisation provides information about how the texture, arrangement, and placement of material affects water and air movement, which assists in determining the best option for limiting NP, oxygen ingress, erosion while enhancing geotechnical stability and establishment of vegetation. INAP (2009, 2017) provides detail of geotechnical characterisation that should be undertaken for potential cover system materials as part of cover system designs. The key parameters to assess when characterising the material is PSD of each material type (also part of geochemical characterisation), define the water retention curve and hydraulic conductivity function, and assessing the available water storage capacity. For further detail of these considerations refer to INAP (2009, 2017).

Sample selection and preparation prior to analysis is critical and samples should be representative of all materials that could be present. Key considerations during sampling are the location, number, size, and type of samples to collect. Sample selection is discussed in detail in Price (1997).

Correct characterisation and sampling are critical for cover system design and incorrect procedures have led to failures during field-scale trials. For example, Defferrard et al. (2014) reported a cover system that failed during field-scale trials and one of their findings was that the net acid potential of their waste was more than double at autopsy than reported during the design phase. Potential reasons for this error were not discussed, but it may have been due to samples not being representative of the waste, or incorrect characterisation.

3.4 Identification of cover system materials

The identification of potential cover materials should consider the availability, cost and haul distance from the waste source, and ensuring there is sufficient cover material with appropriate characteristics available for the trial (INAP 2017). Additional findings about cover materials from the literature were that acid-neutralising materials such as dolomite and lime may be incorporated into a cover design (Rohde et al., 2016, Gonzales et al., 2014). Incorporating dispersive (or sodic) materials in the cover design can increase the risk of erosion and create challenges with establishing long-term vegetation (INAP 2017). Lastly, the PSD of cover materials provides information about their heterogeneity (INAP 2017), which is an important factor in cover system success (Meiers et al. 2009; Schneider et al. 2010). Schneider et al. (2010) underscore that cover material fineness, homogeneity and type is likely more important than cover design itself and propose that securing such material is critical for a successful cover.

As part of this review publicly available PRC plan documents were reviewed to understand material usage, but we have chosen not to name or reference individual mine sites in the following discussion. Key findings from the review of PRC plans regarding cover materials include:

- The PRC plan framework requires that inventories of potential cover materials are made to ensure sufficient material will be available to construct the final cover system (DESI 2023). In some cases, materials were included in the cover design that were not available in sufficient quantities and with no discussion on how the deficit would be filled.
- In one PRC plan, compaction was proposed to reduce oxygen diffusion in a case where insufficient cover material was available. Ayres et al. (2003) note that over-compaction of growth medium layers should be avoided as it restricts plant root development and reduces the available water holding capacity of the layer.
- One PRC plan noted that the properties of the materials can evolve over time so the short-term performance may not be representative of long-term performance. For example, INAP (2017:16) notes that wetting and drying cycles can adversely affect the performance of clay layers in cover systems.

3.5 Non-technical considerations

INAP (2017) lists undertaking adequate/appropriate quality control and assurance (QA/QC) checks on the construction for the cover system (and landform) as one of its top six lessons learned. This may include an assessment of the level of compaction of clay layers and verification of layer thicknesses (INAP 2017). Taylor et al. (2003) studied an existing cover system at Rum Jungle and found that the cover did not perform as required because it was not built to a sufficient standard. Issues regarding construction quality will likely cause discrepancies with models, with Song and Yanful (2008) outlining that their cover construction material was potentially poorly mixed, leading to difficulties in matching the actual parameters to modelled parameters and causing ‘major discrepancies’ between measured and modelled data. Several field-scale trials identified in the literature did not describe quality control checks on the cover construction (Ayres et al. 2003; Gonzales et al. 2014; Edraki et al. 2006; Defferrard et al. 2014; Williams et al. 2006a, 2006b). If not constructed properly at the trial phase, cover designs cannot properly be compared to one another, and the most effective design may not be chosen.

Cahill et al. (2022) recommend trialling the proposed construction methodology to assess whether the proposed cover design can be recreated using available equipment and to identify shortfalls in the design. Undertaking a construction trial prior to a field-scale trial could increase the likelihood of the field-scale trial being successful. This is because shortfalls in construction that could lead to the cover not performing as intended will be identified, and the construction methodology and potentially the cover design for the trial can be altered accordingly.

4 Develop cover system design options

Prior to the commencement of field-scale trials, site-appropriate mine waste cover designs should be developed. A conceptual design for a mine waste cover should identify the types of cover that are most likely to be successful for the site-specific conditions (climate, waste type, topography, etc) (O’Kane and Wels 2003; Williams 2022). The Global Cover System Design – Technical Guidance document highlights a framework for deciding on the most appropriate cover type (INAP 2017). This document outlines an approach which plans for cover system through a front-end loaded approach, i.e. one which includes extensive initial planning to minimise costs due to changes in design further down the line, including various assessments of proposed designs. Using the INAP (2017) framework the store-and-release system is identified as the most appropriate type of cover system for much of Queensland, and these systems are discussed further in Technical Paper 3.

INAP (2017) also notes that an assessment period for a cover system design is different to the design life. For example, MEND (2012) recommends a minimum design life of 100 years, but the risk assessment of the design should be conducted over a longer timeframe and on a site-specific basis. This is discussed further in MEND (2012).

A particular cover system may contain components of several cover system designs. For example, all cover systems contain an element of erosion protection (INAP 2017). Once conceptual designs are established, a more detailed approach to cover system design may be developed that includes modelling and small-scale testing of several design options. This is discussed in more detail below.

4.1 Modelling

Modelling tools can be used to predict ‘quantitative relationships between cover system properties (material type and sequence, cover thickness, slope angle, vegetation density/mix, etc) and cover performance criteria (e.g. NP, oxygen ingress, erosion, sustainable vegetation)’ (O’Kane and Wels 2003:342).

The flow chart in Figure 3 shows the relationship between conceptual and detailed design development and shows how modelling can be used in an iterative way during cover system design. Modelling plays an important role in identifying and controlling risks as the design process progresses from conceptual stages to more detailed design (Australian Government 2016a). Detailed modelling also allows multiple cover design options and scenarios to be tested prior to constructing a trial in the field (Haagner and Van Wyk 2022). The use of modelling in this way can help to avoid costly errors or delays on site.

Detailed models can be used to predict the geochemical and stability-related outcomes of a cover design. Knoche et al. (2006) were concerned with cover systems when subjected to 100-year rainfall events, demonstrating the researchers’ desire to provide future-proofed predictions regarding their cover system designs.

Modelling provides a sound basis to advance cover system designs most likely to be successful to the next stage in the cover system implementation process. Models can simulate varying scenarios of materials proposed to construct the different layers of the cover, their proposed thicknesses, degree of saturation, vegetation and climatic variables to predict elements of the hydrogeochemical balance and geotechnical stability. The modelling will be heavily parameterised by the waste rock materials characterisation which will be important in determining the potential success of designs when waste rock characteristics are variable. The modelling will inform proponents which designs are likely to be successful in meeting the design objectives and provide a basis for more detailed testing and evaluation in the laboratory and then ultimately in field-scale trials (O’Kane and Wels 2003).

Most trials reviewed here were informed by modelling (e.g. Rohde et al. 2016; Song and Yanful 2008; Schneider et al. 2010). In these studies, modelling was used to assist the selection of appropriate cover designs to trial. This was the case in Haagner and Van Wyk (2022) which predicted the effectiveness of various designs using erosion, geochemistry, seepage and hydrogeological risk models prior to field-scale trials.

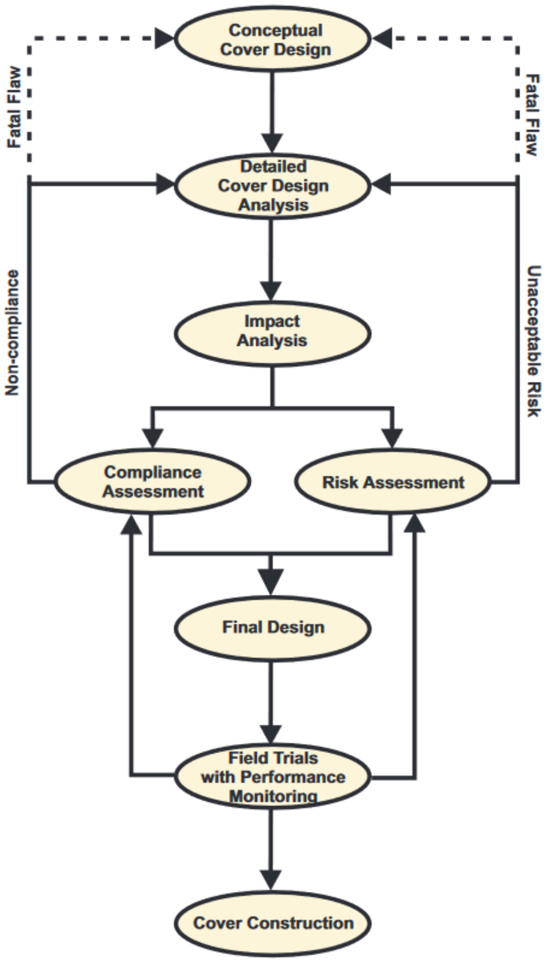

Figure 3 Flow chart of cover system design steps (from O'Kane and Wels 2003)

4.2 Small-medium scale testing

The laboratory testing of covers through experiments such as column tests of designs may also be undertaken to determine which designs should be trialled at field-scale (INAP 2017). Numerous examples where column testing was undertaken in the laboratory as part of cover system design were identified in the literature (Bussière et al. 2004; Larochelle et al. 2019; Demers et al. 2015; Pabst et al. 2017; Kalonji-Kabambi et al. 2020; Kalonji Kabambi et al. 2017; Jamson and Rohde 2019; Cosset and Aubertin 2010).

Rohde et al. (2022) trialled four designs using medium scale column tests on site. Such a trial can be used to test the outputs of modelling and assess cover performance to artificial weather events over a shorter timeframe than a field-scale trial. In Rohde et al. (2022), test columns were subjected to 11 artificial rainfall events of up to 910 mm in total wetting over five months. Dry periods of seven days were included after each artificial rainfall event to allow the cover to dry out so that soil water characterisation curves (SWCCs) and the maximum water balance (i.e. under extreme conditions) could be developed. A short experimental period circumvents continuity issues which may be problematic for long-term cover trials such as changes in management or personnel. Furthermore, column trials require little space, which may be important on operational mines. Conversely, column trials do not account for evaporative losses, the designs are not constructed using mine-site equipment (INAP 2017:102), and there may be scale-related issues such as boundary effects. Kalonji-Kabambi et al. (2020), for example, found that the concentration of sulfate in drainage from column and field-scale experiments differed. They hypothesised that this could be due to differences in the initial geochemical conditions of the waste materials in the column and the field, differences in hydrological and gas transport conditions, and differences in physical factors between the two scales. Therefore, column trials, similarly, to modelling, may be considered to present one line of evidence for a cover to be appropriate for a waste structure. More evidence may be required to determine which design should be implemented at scale, including the results of field-scale trials.

Several small-scale laboratory experiments that do not use columns were also identified in the literature. Kim (2021) developed a small-scale laboratory test to validate the water shedding performance of a capillary barrier system predicted using modelling. They concluded that the model efficiently evaluated the performance of their system and that their test could be used in place of large-scale model tests. This emphasises the value of small-scale testing in collecting data that can be used to validate models prior to undertaking field-scale trials.

Ng et al. (2015) developed an experimental cell alongside numerical models to investigate the effectiveness of 2-layer and 3-layer capillary break cover systems at minimising rainfall infiltration in humid climates. The cover system was designed for landfill applications but testing potential cover systems for mine wastes using the same approach prior to undertaking field-scale trials could be useful for assessing the performance of potential designs during high rainfall events and to support model development.

5 Plan field-scale trial

This section discusses factors that should be considered when planning a field-scale trial. An example of a field-scale trial that incorporates these elements and the baseline studies discussed previously is Haagner and Van Wyk (2022). Note that Haagner and Van Wyk (2022) tested multiple cover system design options and this may not always be feasible.

5.1 Objectives

Prior to undertaking a trial, objectives for the trial must be established. A successful trial will determine if the objectives of a cover design have been met and which cover designs, if any, should be used at full scale. The objectives of a trial differ from the objectives of a cover. INAP proposes various objectives for trials, including ascertaining whether modelling of a cover system is accurate and calibrating that model, identifying fatal flaws in the design, comparing different cover systems to each other, obtaining a gas, heat, mass and water balance for the mine waste landforms, developing or enhancing ‘understanding for key characteristics and processes that control performance’ and developing ‘confidence with all stakeholders with respect to cover system’ (INAP 2009).

In the literature, various papers clearly outline the objective of the trial or cover system. These include demonstrating cover performance objectives such as limiting seepage (i.e. NP) (Osgerby et al. 2022; O’Kane Consultants 2016; O’Kane and Waters 2003; Williams et al. 2006b), selecting a suitable cover (Adu-Wusu and Yanful 2006; Schneider et al. 2010), validating and updating models if required (Tetra Tech 2019), demonstrating the long-term performance of a cover (SRK Consulting 2020) and comparison of contaminant concentrations in seepage to legally imposed environmental objectives (Kalonji-Kabambi et al. 2020).

Note that where field-scale trials are considered experiments, they should have a research question that the trial aims to answer (Casler 2015). Research questions and objectives have been used interchangeably in this section of the review.

5.2 Location

Most field-scale studies identified in the literature constructed trial cover systems on existing waste rock structures (e.g. Defferard et al. 2016; Schneider et al. 2010; Williams et al. 2006; Tetra Tech 2019; Ayres et al. 2003; Bennett et al. 1999; Taylor et al. 2003; Mudd and Patterson 2010; Edraki et al. 2006; Rohde et al. 2016). Some studies were undertaken using purpose-built landforms (e.g. Haagner and Van Wyk 2022).

No clear guidance on the location of a field-scale trial for a cover system was located in INAP (2017), the GARD guide (INAP 2009), Australian Government (2016a), or the scientific literature that was reviewed. Osorio Wallau et al. (2021) described considerations for selecting a demonstration site for a field-scale trial in farming, and this information may be applicable to the mining sector. They list two crucial considerations for site selection: (1) suitability of the site for the proposed trial and (2) accessibility of the site. To assess the suitability of the site all potential issues that could occur on the site and their effects on the results must be considered. In the context of a mine-site cover trial, this could involve ensuring the trial is elevated out of areas prone to flooding and protected from disruption by mining operations. In terms of accessibility, factors to consider include the workload, frequency of site visits during the trial and the level of access (e.g. easy, practical, close to offices, etc.). In the context of a mine-site trial, this could include considering the ease of accessing monitoring equipment and limiting the accessibility of the site for persons not involved in the trial.

5.3 Scale

In the INAP framework, there are two types of field-scale trials – pilot and prototype. The differences between the two types are related to the scale (size in area) and purpose. Pilot field-scale trials involve a promising (or a series of) trial design(s) at a size much greater than laboratory scale and with the aim to identify fatal flaws in design as a result of continuous operation (and accompanying assessments) of the cover (INAP 2017). Prototype trials are permanent, constructed using commercial scale equipment, intended to optimise the process for full scale deployment and provide sufficient confidence to progress the design to full cover construction. An example of a prototype trial could be the construction of a cover on one section or slope of a mine waste structure. One of the objectives for prototype trials is to develop monitoring parameters, augmented by the system management approach of the cover system, and used to track cover performance as compared to predicted performance. The underlying principle here is that monitoring of constructed covers to demonstrate their performance is hindered by the time (decades at least) it will take for seepage quantity and quality to be identified from the base of the landform as well as the importance of monitoring other aspects such as precipitation, runoff and water storage change (INAP 2017:102). No studies were identified in the literature which stated whether they were undertaking a ‘prototype’ or ‘pilot’s trial. The trials that were reported are likely a combination or both types of trials.

The scale of field-scale trials reported in the literature varies. Some field plots were 1ha in size (O’Kane et al. 2000) while others were almost an order of magnitude smaller at 12 m x 12 m (Chtaini et al. 2001). A field-scale trial of three cover alternatives at Mt Isa used three 20 m x 60 m plots (Baumgartl et al. 2012) and a field-scale trial at Mount Morgan used three cells that each measured 30m x 100m (O’Kane and Waters 2003). While small plots may be less costly and allow for replicates to be constructed or more alternative designs to be trialled, they may introduce edge effects (Cuira and Simon 2013). None of the field-scale trials that were reviewed described a scientific or evidence-based approach to determining the optimal size for the trial. In practice, the scale of a field-scale trial will likely be constrained by costs and the timeframe for the trial.

5.4 Duration

INAP (2017) recommends a trial period of three to five years for field-scale trials. The Queensland Department of Environment, Science and Innovation (DESI) requires a 5-year minimum field-scale trial, with the intention of capturing major climatic cycles (DESI 2024). Geochemical lag times may undermine the validity of the conclusions drawn from field-scale trials (Price 2009; INAP 2009). This is important because depending on the size of the mine waste stockpile it can take years for changes that occur in the stockpile to be observed in the drainage (INAP 2017). Furthermore, the importance of trial length and long-term monitoring were highlighted by various documents which discussed the deterioration of covers on waste rock over time, such as measured cover failure after nine years at Rum Jungle (Bennett et al. 1999) and predicted eventual break-down of HDPE at a site in Canada (Power et al. 2018).

The literature also highlighted that events which require time to unfold should be considered when determining the duration for a trial. These include erosion, self-sustaining vegetation, and the capacity to experience repeated exposure to weather events, such as heavy rainfall and freeze-thaw cycles (Adu-Wusu and Yanful 2006; Ahn et al. 2011). During the first 3 to 5 years following the construction of a cover the materials settle and the hydraulic properties of the cover change (INAP 2017). For one field-scale trial reported in the literature, the moisture storage in the cover and NP varied each year during the 5-year monitoring period (O’Kane et al. 2000). To accurately assess the performance of a cover system the duration of a field-scale trial should be sufficient to observe these changes. The comparative review presented in Paper 2 found some risks, such as equipment failure, become more prevalent in trials that are run for longer periods.

5.5 Monitoring

INAP (2014, 2017) does not take a prescriptive approach regarding what monitoring should be undertaken as part of a field-scale trial but describes the monitoring process for the final constructed cover in detail. This information may be applicable to a field-scale trial and is included in the discussion below.

Under INAP (2017:104), monitoring of a cover system has a series of general objectives:

- Obtain a gas, heat, mass and water balance for the landform.
- Develop or enhance understanding for key characteristics and processes that control performance.
- Develop a set of field data to calibrate a numerical model (which can be used to adaptively manage cover system design moving forward within the design development time scale).
- Develop confidence with all stakeholders with respect to cover system performance.

A review of the literature found over 100 different variables to be considered when monitoring a field-scale trial of a cover (e.g. U.S. Environmental Protection Agency 1994; MEND 2004; Reid 2005; Price 2009; Australian Government 2016a, 2016b; INAP 2017; DESI 2018). Key Activity 4 in Table 8-1 of INAP (2017) states that monitoring of field-scale trials should include ‘all elements of the water balance and evolution of cover materials’ (INAP 2017:99). For the water balance, this may include capturing climate, soil-atmosphere-plant, landform load and water balance, groundwater and surface water systems (INAP 2014, 2017). Other variables that were monitored in the literature include the properties of all materials (underlying waste and all cover materials, this may involve monitoring at various depths in the cover), erosion, vegetation cover, in-situ temperature, test cell areas and oxygen (Tetra Tech 2019; Haagner and Van Wyk 2022; Meiers et al. 2009; O’Kane and Waters 2003; Gonzales et al. 2014).

To increase the likelihood of a successful trial it is important to ensure that the monitoring system acquires the correct data and that correct sampling procedures are used. There may be various reasons why such errors are made: too small a sample size, choice of unsuitable measurement variable, choice of unsuitable measurement equipment, poor construction of treatment, too short a sampling timeframe, too infrequent sampling, wrong choice of statistical procedure, and confounding variables (Reid 2005; Australian Government 2016b). The sampling frequency needs to consider climate, the objectives of monitoring, aspects of the test location, and is influenced by the type of monitoring equipment installed (INAP 2017). For example, Tetra Tech (2019) collected data at one-minute time steps where possible, excluding volumetric water content which was measured on a weekly basis and before and after rainfall events where possible. The short duration of sampling was selected based on the rapid time of run-off concentrations in the area and the frequency of prolonged high intensity rainfall events. MEND (2004) highlights the need to design monitoring systems to allow ‘feedback’ so that the sampling frequency can be changed based the observed variation in factors being monitored (i.e. if a variable changes frequently the sampling frequency may need to be increased).

Spatially, monitoring should capture the entirety of the landform from the top, down the slope to its base. This will ensure potential influences on performance from a spatial perspective are identified. INAP (2017) notes that measurements at a single location in a cover system may not be representative of the entire cover due to variability in the cover and in situ density and recommends installing multiple monitoring locations so that variability is understood and accounted for.

O’Kane Consultants (2022) describes the data capture rates from the monitoring program of a field-scale trial at Cadia Valley. They provide details of the number of each type of sensor installed and the number of each sensor that was still operating at the time of the report. Over 400 sensors were installed and 40 were no longer operating. The largest failure of sensors was water content sensors wherein 16 were installed and zero were operational at the time of reporting. Failure of monitoring equipment was a key issue identified from the case studies in Paper 2 and can lead to gaps in the data collected. To avoid this it may be important to regularly maintain, repair or replace equipment and integrate that maintenance into the sampling protocol (INAP 2017).

6 Reporting outcomes and learnings

The data from the trial may be used to calibrate a model and predict future success or failure of a cover system design (Cahill et al. 2022). Cover system trials at the Mt Whaleback mine, which were performed alongside modelling, highlighted that after the trial it is fundamental to revisit the soil-atmosphere cover design model to develop a calibrated model, to defensibly predict long-term performance (O’Kane et al. 2000). Calibrated models run alongside monitoring also provide the opportunity to show uncertainties and aspects of cover system performance which merit further research (O’Kane et al. 2000). Similarly, Ramasamy and Power (2019) discuss that field data will inform saturated flow and contaminant transport models, and that this process of data being used to calibrate models is iterative with further monitoring and adaptive management of the cover system.

‘Accurate and transparent reporting of data and continued access to datasets through the life of the project’ (Australian Government 2016b:93) was highlighted as important. In the literature, there are various references to databases recording performance of covers or AMD related monitoring data although we were unable to find any public record of these (Khalil et al. 2014; O’Kane et al. 2000).

Accurate and transparent reporting may also entail basic statistics (i.e. calculating mean, median, maximum, minimum) and comparison to model outputs, benchmarks or design objectives. In the literature, there are various instances of different statistics being reported in cover system trials. In some studies, proponents will present the range of values, such as maximum and minimum NP, or will highlight an average value (Defferrard and Rohde 2019). These values may then be compared to a benchmark. In other scenarios, more detailed data analysis is reported. An example of this is Schneider et al. (2010), who reported a detailed analysis of data for variables that may affect the heterogeneity of cover materials.

7 Risks and limitations associated with field-scale trials

INAP (2017) states that for a final cover system the greatest risk of ‘failure’ (not defined) occurs during the ‘adaptive management period’. This is defined as the period following construction and before sufficient vegetation is established during which the cover system is in its furthest state from equilibrium with the surrounding environment. During this period vegetation has not been established to stabilise the landform. Vegetation may not be established during a cover system trial and operators should be aware of the heightened risk of ‘failure’ this presents.

Papers were identified in the literature that discuss the potential for certain waste rocks to spontaneously combust (Tian et al. 2024) and this should be considered during a cover system trial.

Other risks that may present during a cover trial are the potential for AMD being generated and the risk that the trial is unsuccessful. These risks are not discussed in the literature.

As experiments, field-scale trials must clearly state their research question(s), develop a robust protocol for answering the question(s), undertake the experiment, analyse the data appropriately and interpret the results (Casler 2015). Paper 2 found that it was difficult in some cases studies to identify the goal or objective of reported field-scale trials, and this makes it difficult to determine if a trial is successful.

Replication plays an important role in experimental design because it allows for analysis and control of experimental errors and increases the precision and inference of an experiment. In some scenarios there is perceived value in testing scenarios on a very large scale, but little perceived value in testing replicates (Casler 2015). Casler (2015) discusses this in the context of on-farm experiments whereby seed supplies are often highly limiting and extremely valuable, but the scenario is directly applicable to field-scale testing of cover systems. Blocking and mother-daughter experiments are proposed as solutions for this scenario, but the author notes that there are situations where the experimental units are so expensive that there are trade-offs in the experimental design. Few examples of cover field-trials which included replicates were identified in the literature (e.g. Schneider et al. 2010) and this may be due to the high costs associated with field-scale trials and/or a preference by the proponents to trial different cover designs/scenarios.

The use of appropriate controls in field-scale trials can help proponents interpret performance and test whether a treatment has an effect (Reid 2005; Australian Government 2016b). Few field-scale trials were identified in the literature which incorporated control experiments (Ayres et al. 2003; O’Kane et al. 2006) and this may be because control experiments are subject to the same challenges and limitations as replicate experiments. A suitable control cover for a field-scale trial in Queensland may be the ‘default’ cover system recommended in the ERC Guideline (DESI 2024). In this case the ‘default’ cover is expected to perform well, and the purpose of the trial may be to compare the performance of an alternative cover design with the ‘default’ design. It should be noted there is little data in the public domain comparing the ‘default’ cover with alternative cover designs, and as such there is not overwhelming evidence to suggest that the ‘default’ cover performs better than other cover designs.

In addition to the use of controls, controlling for effects other than those of primary interest will also be important, achieved through the control of confounding variables. Briefly, variables which will affect the construction and effectiveness of a cover must be controlled for in the trial and be as similar as possible between the compared treatments. For example, the quality and quantity of the waste material in the different field plots should be the same, as should be the approximate location and timing of the experiment, to account for potential meteorological differences, and the same monitoring equipment should be used and calibrated across the different treatments (Reid 2005; Casler 2015; INAP 2017; DESI 2024).

Inconsistencies are reported in the literature and guidance documents regarding the timeframe for a field-scale trial (INAP 2014, 2017; DESI 2018 Appendix C). Capturing significant weather events is a common criterion in defining the duration of a field-scale trial (DESI 2024), however this is not within the operator's control (Rohde et al. 2016), and it may not be feasible to continue a field-scale trial until this criterion is met. One study in the literature emulated heavy rainfall in the laboratory to accelerate a cover's exposure to extreme weather events (Kalonji-Kabambi et al. 2021). The author noted that the metal and sulfate concentrate in the drainage waters differed between testing scales during the beginning of the tests then became more uniform over time. They attributed this to differences in the initial geochemical conditions of the waste material, and potentially also differences in the hydrological and gas-transport conditions and physical conditions between the different scales (Kalonji-Kabambi et al. 2021). Therefore, while small-scale simulations may be useful for simulating rainfall conditions they should not be relied on solely for predicting cover performance.

Taylor et al. (2003) and Mudd and Patterson (2010) trialled several cover design options at Rum Jungle with the goal of defining the cause of deterioration of the covers. The covers were said to have worked for the first 10 years after installation but failed after that. The cause of failure was increased permeability from shrinkage cracks in the clay-rich layer combined with illuviation of coarse materials into the cracks, root penetration, and termites. In this case undertaking a 3–5-year trial would not be sufficient to see the failure of the proposed cover systems. While undertaking field-scale trials of cover systems is essential, it does not eliminate the risk of a cover system failing longer-term. This presents a long-term risk of cover systems in that they must be managed long-term, including after the mine operator has left a site. As the focus of this review is on conducting a trial for a cover system, long-term risks of cover systems will not be discussed further in this review.

In Technical Paper 2 the design and operation of monitoring systems were found to be critical to ensure that failure modes can be identified and addressed, but consistent monitoring was found to be a challenge. During one field-scale trial the data capture rate of monitoring equipment over the period of one year was 67% (O'Kane et al. 2006). Several challenges were identified such as instruments failing to log data and battery failures, and this may result in a trial being unsuccessful due to the relevant data not being collected.

8 Conclusion

This review is the first Technical Paper in a series of three technical papers regarding cover system field-scale trials. This body of work was developed to address feedback received by the OQMRC regarding cover system failures and performance, and the execution of high-quality cover system trials. The outcome of these three technical papers is the development of a simple, practicable methodology to undertake cover trials.

In the current Technical Paper literature was reviewed to provide an insight into factors that should be considered when planning a field-scale trial, and the necessary preliminary steps leading up to a field-scale trial. This includes establishing objectives of the cover design, collecting baseline information, and developing cover alternatives.

Key findings from this review include:

- Developing a thorough understanding of the site where a cover is located is crucial to ensure the correct cover system type and designs are chosen.
- Correct characterisation and sampling of waste materials and potential cover materials is critical to understand their acid generation and neutralisation potentials and geotechnical properties. This will inform cover design.
- Modelling plays an important role during cover system design and may be an iterative process. Small/medium scale testing can provide an intermediate step between modelling and a field-scale trial. It can also be a useful tool to investigate aspects of cover performance

that are not practical to test during a field-scale trial, such as different timeframes, comparing multiple cover designs and undertaking a robust experimental design.

- Several examples of incorrect construction of covers for field-scale trials were identified in the literature. Undertaking quality control checks during construction and potentially trialling the construction methodology may be necessary.

Limiting NP was a common objective for field-scale trials identified in the literature. In some cases, no clear objective of the trial was identified, and it was difficult to determine whether the trial was successful. Often, capturing significant weather events was a key factor in determining the duration of a trial, but several cases were identified in the literature where the desired weather events were not captured during the trial. To determine whether the objective of the trial has been met monitoring of key variables, such as NP, is necessary. However, monitoring was identified as a challenge during field-scale trials.

An outcome of this review was the identification of numerous field-scale trials for cover systems that could be investigated further. Technical Paper 2 continues from this work by undertaking a comparative review of field-scale trials for cover systems in Queensland and locations with a similar climate to Queensland, with the aim of benchmarking current practices for field-scale trials.

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