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Mine Waste Cover System Design — Linking Predicted Performance to Groundwater and Surface Water Impacts

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ABSTRACT

Current best management practice requires the placement of a cover onto most types of mine waste including tailings, waste rock and/or spent heap leach rock at closure of the mine. The objectives of a cover system may vary from site to site but generally include

1. dust and erosion control;
2. chemical stabilisation of acid-forming mine waste (through control of oxygen ingress)
3. contaminant release control (through control of infiltration); and/or
4. provision of a growth medium for establishment of sustainable vegetation.

In our experience, there has been a general tendency by stakeholders to develop performance criteria for cover systems, which are tied directly to these specific design objectives. In many cases, this practice has led to the development of single, often very conservative, numerical values of cover performance criteria such as 'net percolation', 'rate of oxygen ingress' and/or 'plant density/mixture'. In our opinion, there is a need to develop cover performance criteria on a case-by-case basis and with due consideration of the short-term and long-term impacts on the receiving environment at a particular site.

This paper puts forward a methodology for developing site-specific performance criteria for a cover system designed to isolate acid-forming mine waste and to control acid rock drainage. The proposed methodology links the predicted performance of a cover system to groundwater and surface water impacts. This way, the appropriate level of control (of oxygen ingress and/or net percolation) required by the cover system can be determined. A case study is presented that illustrates the application of the methodology proposed in this paper.

INTRODUCTION

At many mine sites, the design and construction of a cover system for closure of a mine waste storage facility represents the single biggest issue, not only with respect to environmental impact and cost but also public and regulatory scrutiny. It is therefore in the best interest of the mining companies and regulators alike to follow a rigorous procedure for cover design, which results in the selection of a cost-effective cover system, which at the same time protects the environment.

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Figure 1 shows the steps required in designing a cover system, which meets 'impact-oriented' performance criteria. Briefly, the process includes five steps. First, a conceptual cover design is selected based on site-specific considerations such as type of waste, size and geometry of the storage facility, climate, etc. Next, a detailed cover design analysis should be carried out which explores different cover design options and relates cover design parameters (eg cover thickness) to cover performance (eg net percolation to the underlying waste). The third step consists of an impact assessment, which is aimed at quantifying the relationship of cover design parameters (such as cover thickness)

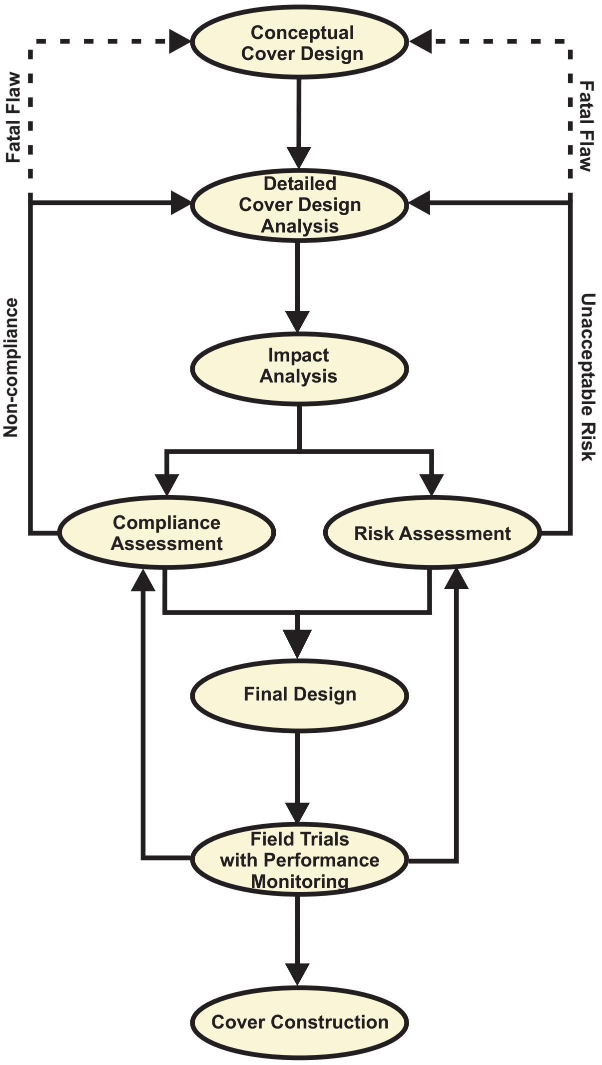

FIG 1 - Flow chart of cover system design steps.

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to environmental impacts (eg groundwater quality). In the fourth step, the impacts are evaluated against regulatory standards. Depending on the jurisdiction and applicable laws, this step may simply imply a comparison of predicted impacts (eg metal concentration in groundwater) against numerical standards, or may involve a complex risk assessment. If the predicted impacts comply with all standards, or pose no unacceptable risk, than the final design can proceed. If, however, the impacts (or estimated risks) are unacceptable, then the preliminary cover design will require modification(s). A 'fatal flaw' in the design is triggered if simple modifications to the cover design are not adequate, and as a result a different conceptual design is required. This feedback loop between impact assessment and cover design is crucial for developing a cover system that is protective of the environment while not being overly conservative.

The following sections discuss in more detail the various steps of cover system design illustrated in Figure 1. The final section of this paper presents a case study that will illustrate the practical application of this methodology.

CONCEPTUAL COVER DESIGN

The first step of cover system design involves an assessment of the type of cover most likely to be successful for the site-specific conditions (climate, waste type, topography, etc). Four basic types of cover systems are generally distinguished; although the materials utilised to construct these basic cover system designs are site-specific:

- a water cover,
- a 'conventional low hydraulic conductivity' cover,
- a capillary barrier cover, and
- a store-and-release cover.

In a water cover, the mine waste is submerged under water, typically by flooding the tailings impoundment or relocating the tailings/waste rock to an alternative storage basin (such as an open pit). The water cover significantly reduces the potential for air to move into the tailings; hence providing protection against future oxidation of the mine waste (eg Davé *et al*, 1997). A water cover is oftentimes the 'cover system of choice' in humid environments, and in particular for tailings (MEND, 2001). However, there may be problems with physical stability of the storage facility (many tailings dams were not designed to be flooded), as well as seepage, water quality, and land use issues.

A conventional infiltration-limiting cover system typically consists of a low hydraulic conductivity layer (clay or geosynthetic membrane), in combination with a number of other layers. This type of cover system requires protective soil layers to minimise deterioration of the low hydraulic conductivity layer due to desiccation, frost action, erosion, animal burrowing and/or plant rooting (Caldwell and Reith, 1993). Typically, a complex cover system of several layers and considerable depth (1.2 to 1.5 m thick) results. If the low hydraulic conductivity layer must also serve as an oxygen barrier then additional constraints apply, eg clay layers must remain tension-saturated (eg Morris and Stormont, 1997).

A capillary barrier effect is created when a fine-textured material layer is placed over of a coarse-textured material layer. The capillary barrier is created when the underlying coarse material is drained (ie is unsaturated), thus possessing a hydraulic conductivity much lower that that of the overlying fine-textured material. The result is a low hydraulic conductivity layer that prevents downward movement of soil moisture from the upper fine-textured layer. This phenomenon ceases when the fine-textured material layer is close to full saturation and the negative pore-water condition at the interface of the two materials is less than the negative pore-water condition at which the hydraulic conductivity function of the two materials cross. In many cases this condition is generally near zero pressure due to the coarse-textured nature of the underlying material. At this point, the net percolation to the underlying waste will be a function of the saturated hydraulic conductivity of the fine-textured material, which in general is at least one-order of magnitude greater than 'typical' compacted barrier layer materials. The capillary barrier cover system significantly reduces net percolation into the underlying mine waste as long as the entire cover profile remains unsaturated (eg Aubertin *et al*, 1997). However, it does not prevent the ingress of oxygen to the underlying waste unless provisions are made to maintain the soil moisture content of the overlying fine-textured layer near saturation.

A store-and-release cover (also referred to as a 'water storage cover', or an 'evapotranspiration cover') consists of one or several layers, which are designed to maximise root penetration and soil moisture storage (O'Kane *et al*, 2000; Wels *et al*, 2000). This type of cover relies on the moisture retention and storage characteristics of the cover material to 'store' infiltration for subsequent removal by evapotranspiration. The storage cover has to be designed in such a way that all incoming infiltration during the dormant season can be stored within the root zone. Note that the root zone is not limited to the cover layer but may extend into the upper layers of the mine waste. In this case, the cover material would primarily serve as a medium for initiating plant growth and to avoid wind and water erosion of the underlying waste material.

It is important to recognise that the selection of a cover system design is site-specific. A cover system that functions as designed at one site may not perform well at another site. Key variables that need to be evaluated during this initial selection process include climate (in particular evaporation and precipitation), type and volume of mine waste, size and geometry of the waste storage facility, and available cover materials. Initial back-of-the-envelope calculations may suffice to rule out one or several of the cover types. The remaining cover system design option(s) may be carried forward into the next phase for detailed cover system design analysis. The different cover options that are carried through the entire cover system design process (Figure 1) depend on the outcome of the initial assessment and the regulatory framework. If only one option is carried forward (usually the one deemed most cost-effective based on the initial analysis and engineering judgment), and the compliance/risk assessment indicates a fatal flaw, then another cover option must be selected and carried through the entire cover design process (Figure 1).

DETAILED COVER DESIGN ANALYSIS

During the detailed cover design phase, numerical analyses are carried out to develop quantitative relationships between cover system properties (material type and sequence, cover thickness, slope angle, vegetation density/mix, etc) and cover performance criteria (eg net percolation, oxygen ingress, erosion, sustainable vegetation).

These quantitative relationships are generally developed by constructing numerical models, which simulate cover performance (eg an unsaturated/saturated flow model to simulate net percolation through a cover). The cover system properties are then systematically varied within a plausible range and the corresponding cover performance is computed. The scope and extent of such sensitivity analyses will depend on the complexity of the cover design, the range of materials and material properties available for cover construction, and site-specific climatic conditions.

Figure 2 is a conceptual 'tornado' sensitivity plot, which illustrates the change in net percolation for a compacted barrier layer cover system as a function of cover thickness, vegetation (root zone depth and transpiration rate), potential evaporation rate (on the basis of which pan coefficient is used to reduce pan evaporation data), and cover material hydraulic conductivity. A

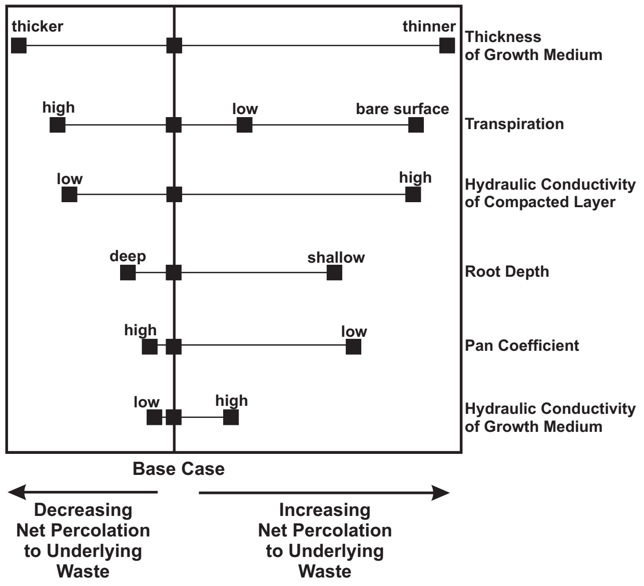

FIG 2 - Conceptual tornado sensitivity plot illustrating the change in net percolation as a function of cover system properties.

'base case' simulation is used that represents the 'most reasonable' input parameters, and then additional simulations are completed by varying the input parameters. The parameters to be varied and the extent to which each is varied is based on the range of physical laboratory test results for material properties and the potential changes to *in situ* conditions and material properties due to biological, physical, and chemical factors.

The tornado sensitivity plot allows for the determination of the key parameters controlling performance of the cover system, which for the case shown in Figure 2 would be the thickness of the growth medium, the hydraulic conductivity of the compacted layer, vegetation parameters, and potential evaporation. In addition, specific scatter plots relating one cover design parameter to one cover performance criterion may also be developed. For example, predicted net percolation can be plotted as a function of the saturated hydraulic conductivity of the compacted layer.

The cover performance criteria for which a sensitivity analysis is usually performed include net percolation, surface run-off, sediment loss, oxygen ingress, vegetation density, vegetation diversity, or some other site-specific criteria. Additional site-specific cover design parameters to be evaluated may include slope angle, slope length, level of compaction effort, compaction moulding water content, percentage bentonite added to modify the properties of a layer of the cover system, etc. The quantitative relationships between cover design parameters and cover performance criteria provide a framework for evaluating the range of environmental impacts for different cover scenarios, and ultimately, to select the most cost-effective cover design (see below).

An important aspect in cover performance modelling is the selection of a relevant time frame and environmental conditions for simulating cover performance. Those conditions should be selected with a view towards potential environmental impacts. For example, if acute toxicity to fish is likely to be the dominant environmental impact, then the determination of cover performance under extreme conditions (eg the 'wettest year' or the 'driest year') may be required. However, if groundwater quality standards and/or bioaccumulation of metals in fish are the key environmental impacts, then the determination of a long-term 'average' performance of the cover system may be more appropriate.

In this context, it should be pointed out that the net percolation predicted from the mean or median rainfall record for a given site may not be representative of the long-term 'average' performance of a cover system. A statistical analysis of the net percolation predicted for each individual year of the climate record can be used to determine the 'average' net percolation over the time frame of the climate record. The latter methodology accounts for the impact of antecedent moisture conditions, as well as the occurrence and intensity of daily rainfall on the long-term 'average' cover performance.

IMPACT ANALYSIS

The impact analysis quantifies the relationship between cover performance criteria and environmental impacts. The specific environmental impacts to be evaluated depend on the objective(s) of the proposed cover system design and local regulations. The environmental impacts most commonly evaluated during cover system design include:

- impacts on surface water quality,
- impacts on groundwater quality,
- impacts on air quality,
- impacts on vegetation, and
- impacts on wildlife.

The methodology presented in this paper requires the development of an 'impact matrix' prior to conducting any quantitative impact analysis, which summarises the potential links between common cover performance criteria and types of impact. Table 1 shows an example of an impact matrix for the hypothetical case of a cover system design for an acid-generating uranium tailings impoundment. The matrix differentiates

TABLE 1

Impact matrix for hypothetical cover design.

Cover performance criteria	**Environmental impacts**				
	Surface water quality	**Groundwater quality**	**Air quality**	**Vegetation**	**Wildlife**
Net percolation	S	S			
O_2 ingress	S	S			w
Radon emission			S		
Soil loss	w	S	w		
Plant density	w			S	
Plant diversity				S	S

Notes:
S = strong link; w = weak link

between 'strong' links (S) and 'weak' links (w). Clearly, the impact matrix will vary from case to case. For example, the link between radon emissions and air quality may be of critical importance in a cover system design for radioactive tailings (eg Strachan and Raabe, 1998), whereas links between oxygen ingress and surface and groundwater quality are often critical in cover system designs for sulfidic mine wastes. The development of a qualitative impact matrix such as the example shown in Table 1 provides the framework for developing a quantitative impact analysis. It establishes the dominant links, which will need to be evaluated in greater detail.

Specific indicators should be selected for each type of impact, in order to quantify the 'magnitude' of the impact. The selection of specific indicators is often subjective and can significantly influence the outcome of the impact analysis and ultimately the cover design. For example, water quality impacts to a local stream may be evaluated using peak concentrations or long-term average loads. Furthermore, concentrations (or loads) may be estimated for only one selected contaminant or for a set of contaminants. An iterative process between the impact analysis and the compliance/risk assessment (see below) may be required to identify the impact indicator(s) most critical for the cover system design (Figure 1).

A numerical analysis should be carried out to establish the relationship between predicted impacts and cover system performance criteria once the impact matrix has been developed and a set of impact indicators has been selected. The type of numerical analysis required for this step can vary greatly from simple empirical and analytical models to more complex numerical models. Examples of commonly used models for impact analysis include:

- run-off and erosion models to estimate soil loss and surface water quality impacts (eg Flanagan and Livingston, 1995; Willgoose and Riley, 1993);
- geochemical speciation and reaction models to evaluate geochemical controls in mine waste and along the flow path (eg Wels *et al*, 2000; Mayer *et al*, 2000);
- airflow and ARD production models to assess ARD production in waste storage facilities (eg Lefebvre *et al*, 2001; Wels, Lefebvre and Robertson, 2003, these proceedings);
- groundwater flow and transport models to assess the fate of contaminants in a receiving aquifer or nearby stream fed by groundwater (eg Wels *et al*, 2000; Uwiera and Reeves, 2000); and
- ecological models to assess plant community development and wildlife impacts (eg McLendon *et al*, 2002).

The main objective of the impact analysis is to quantify the relationship between cover system performance criteria and environmental impacts. To illustrate the process, consider the hypothetical case of a cover system design for an acid-generating waste rock pile. For this hypothetical case, surface water quality is identified as the key environmental impact and peak dissolved metal concentration (eg Al) is selected as the impact indicator (eg to assess acute toxicity to fish in the stream). Figure 3 shows the types of relationships between surface water quality (eg dissolved Al) and selected cover system performance criteria that may be obtained for this scenario using impact analysis.

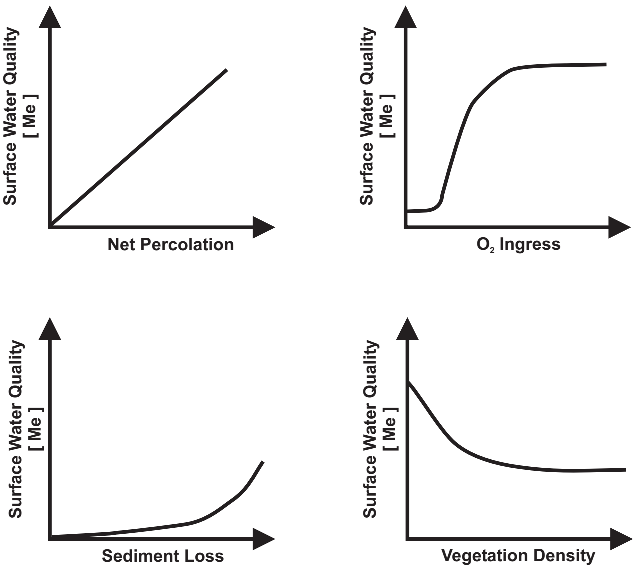

FIG 3 - Relationships between surface water quality (concentration of dissolved Al) and cover system performance criteria.

Oxygen ingress and net percolation are typically the two most important cover system performance criteria influencing surface and groundwater quality for acid generating waste rock. The rate of oxygen ingress (through the cover) controls the long-term rate of oxidation of the acid-generating waste, and therefore often the source strength of any seepage leaving the waste storage facility. Net percolation (or 'cover flux') determines the rate (volumetric flow) of seepage leaving the waste storage facility. A quantification of the impacts of those two cover system performance criteria on surface water quality requires an integrated analysis of the geochemical reactions and the flow and transport processes occurring in the waste and along the flow path. A case study of such an integrated impact analysis, using a geochemical model, a seepage model and a groundwater flow and transport model, is provided in the final section of this paper.

Soil loss and vegetation density also have an impact on surface water quality, albeit typically of lower magnitude than net percolation and oxygen ingress. Soil loss (due to erosion of the cover material) can result in elevated levels of suspended sediments in nearby surface waters. However, this may not result in a significant increase in dissolved metal concentrations unless erosion and soil loss are so severe that the mine waste itself is eroded. Soil loss, however, may also influence the long-term performance of the cover system. For example, significant erosion of cover material over time can potentially increase net percolation (and/or oxygen ingress), thus negatively impacting on surface water quality. Vegetation density (on the cover surface) may also have an indirect (positive) impact on surface water quality by reducing erosion and/or net percolation.

The above example illustrates in a relatively simplistic manner the interdependence of the various cover system performance criteria and how they interact to impact on the environment. This interdependence complicates the impact analysis because numerous sensitivity analyses must be completed. For example, the impact of net percolation on surface water quality (shown in Figure 3) strictly speaking applies only to one scenario where all other criteria (oxygen ingress, soil loss, vegetation density) are held constant. This complexity is a deterrent for a rigorous impact analysis and often leads to the analysis of only a few selected 'cover scenarios' where all cover system performance criteria are assumed to be known and set constant. However, in our opinion, this practice should be discouraged because it may not lead to the most cost-effective cover design. In many cases, sensitivity analyses required for the development of 'type curves' (such as those shown in Figure 3) represent only a small fraction of the overall cost of impact analysis. Yet such type curves may assist the engineer in optimising the cover system design in such a way that cover system construction and liability costs are significantly reduced, resulting in an overall reduction in the project costs.

COMPLIANCE AND/OR RISK ASSESSMENT

The next step in the process of cover design entails a comparison of predicted impacts against applicable environmental standards (Figure 1). The nature and extent of this assessment can vary significantly depending on the complexity of the site and the regulatory framework. At a minimum, the predicted impacts must be compared against numerical standards (eg maximum concentration in groundwater, surface water, or an annual load into a stream). The use of numerical guidelines for regulating mining activities (including design for closure) is still common practice in many parts of the United States (eg the use of state standards for evaluating impact to surface water and groundwater). Such an assessment of compliance is relatively straightforward. However, this approach has been subject to increasing criticism because numerical guidelines ('standards') often do not adequately address site-specific conditions (eg increased mineralisation in a mining district). In addition, the use of fixed numerical standards such as metal concentrations in streams or groundwater invariably requires the determination of a compliance point, (ie the location at which such a determination is made). Yet, the selection of a compliance point is often somewhat arbitrary (eg the property boundary) and may not be linked to the specific location of an environmental impact.

In recent years risk assessment has become increasingly popular as an alternative method for assessing environmental impacts at mine sites (eg Linkov *et al*, 2002). The mining impacts such as contaminant levels in groundwater or streams are evaluated during a risk assessment in terms of risk to biological receptors (eg USEPA, 1997). It is common to distinguish between human health risk assessment (HHRA) and an ecological risk assessment (ERA), depending on whether the receptors are humans or other organisms such as fish, invertebrates, etc. A range of site-specific conditions is also taken into account during the risk assessment (eg land use, aquatic communities, background water quality, etc) in order to determine the human or ecological risk caused by the environmental stress. This approach yields site-specific 'threshold' or 'trigger' values to be used for decision-making (eg cover design). Such an approach is preferable over the use of fixed numerical standards because it recognises the special conditions often encountered at mine sites (eg natural mineralisation). The problem of fixed numerical standards is now widely recognised and many countries are now moving towards risk-based compliance criteria (eg ANZECC, 2000).

FINAL DESIGN

The results of compliance or risk analysis are used to finalise the cover design (Figure 1). If a detailed impact analysis has been completed using a series of 'cause and effect' curves (as shown in Figure 3), then the applicable standard (from numerical guidelines) or 'trigger' values (from a risk analysis) can be used to select the level of required cover system performance. In reviewing the results of the cover design sensitivity analysis (Figure 2), the specifications of the cover system needed to meet all applicable standards (fixed or risk-based) can be selected. If the impact analysis was only carried out for selected cover scenarios, then any of the cover scenarios, which are shown to meet the standard(s) or perform better than the trigger value(s), could be used for the final design.

If the assessment indicates that none of the proposed cover system designs are likely to result in compliance or acceptable risk, the proposed cover design must be modified and the assessment process must be repeated (Figure 1). If the required modifications to the cover design are deemed too expensive or not achievable then this would constitute a 'fatal flaw' and the conceptual cover system design must be re-evaluated.

The use of the proposed cover design methodology (Figure 1) relies heavily on numerical modelling, which is subject to a certain level of uncertainty. It is therefore good practice to perform field trials, in which the performance of selected cover options can be monitored under actual field conditions (Ayres *et al*, 2002; Wels *et al*, 2000; O'Kane and Waters, 2003, these proceedings). The results of field trials can then be used to further optimise the final design (Figure 1).

CASE STUDY

A case study of a cover design for an acid-generating waste rock storage facility is presented to illustrate the methodology discussed above and shown in Figure 1. The site is located in a subtropical monsoon climate. Mean annual rainfall is approximately 1450 mm with about 90 per cent occurring during the five month wet season. Annual potential evaporation at this site is approximately 2500 mm.

At closure of the mine, a detailed site characterisation was carried out to identify existing mining impacts and to provide a basis for the development of a closure plan. It was determined that the local aquifer system had been significantly impacted by sulfide oxidation products from the tailings storage facilities and a waste rock pile. The closure plan called for relocation of the tailings into the open pit (under water) to prevent future oxidation and ARD from this source. The waste rock storage facility, the only remaining potential long-term source of ARD, was to be rehabilitated *in situ* using a dry cover.

Approximately 25 to 30 per cent of the primary rock in the waste storage facility either contains high sulfide material, or has been impacted by acidic drainage resulting from the presence of the sulfide material. Localised acidic seeps, as well as circum-neutral seeps with elevated metal concentrations, are emanating from the waste storage facility. The primary objective of the cover design was to reduce the future contaminant load from this waste rock pile to 'acceptable' levels.

At this site, a detailed impact analysis was required to determine what would constitute an 'acceptable' level of control. A 'very high quality' cover, typically required to maintain 'pristine' groundwater conditions, was not necessarily required for this site, because of the significant existing impacts to the local groundwater system (groundwater was not suitable for human consumption). Instead, the cover was to be designed in such a way that it would protect the ecology of a nearby stream.

Conceptual cover design

The conceptual cover system design for the waste rock storage facility is a dry cover system. The conceptual design takes advantage of the high potential evaporation conditions at the site, as well as the good quality cover materials available near the waste rock storage facility. The conceptual cover system design includes a layer of compacted clay placed directly on the waste rock surface reshaped to the final contours of the desired landform and overlain with a growth medium layer. The compacted clay layer represents a barrier layer to control net percolation during extreme rainfall conditions, while also maintaining tension-saturated conditions to control oxygen diffusion. The overlying growth medium serves three purposes:

1. prevent desiccation of the clay layer;
2. additional control of net percolation by serving as a moisture store and release cover layer; and
3. a growth medium for revegetation.

Initial investigations of borrow pits on site identified two types of fine-grained materials for use as potential cover material:

1. 'stable' clays, and
2. 'active' clays.

The 'stable' clay features superior geotechnical properties (less potential for swelling, shrinkage, and potential for chemical alteration of the clay crystal structure) whereas the 'active' clay features superior hydraulic properties (higher moisture retention capacity and lower hydraulic conductivity).

Detailed numerical modelling was carried out to evaluate both the geotechnical and hydraulic performance of the proposed conceptual cover. For the purposes of the paper and this case study, only the results of the hydraulic modelling and their implications in terms of environmental impact to a nearby stream are presented.

Detailed cover design analysis

Detailed soil-atmosphere cover design modelling was completed using the site-specific climate data, as well as material properties and conditions determined in the field and laboratory. The main focus of the soil-atmosphere modelling was to determine net percolation and oxygen ingress as a function of clay type and thickness of the growth medium.

Figure 4 shows the predicted annual net percolation assuming either a compacted layer of 'stable' clay (50 cm), or a compacted layer of 'active' clay (50 cm) for a range of return periods. In either scenario, a 2 m thick growth medium of stable clay was assumed to overly the compacted layer to prevent desiccation. Figure 4 illustrates the significant difference in predicted performance as a result of using either the active clay or the stable clay for the compacted layer of the cover system. For example, for a return period of two years, the predicted net percolation (infiltration through the cover) is approximately 15 mm and 300 mm for the active clay and stable clay cover systems, respectively. These net percolation rates represent one per cent and 20 per cent of mean annual rainfall (MAR), respectively.

Note that the predicted rates of net percolation increase significantly for greater return periods, regardless of which clay type is chosen. These results illustrate the variability in cover performance due to the climatic conditions, which vary from year to year. For this case study, long-term average rates of net percolation were considered more relevant than those for extreme conditions (eg 1:100 wet year) because any year-to-year variations in waste rock seepage and contaminant load would be 'buffered' in the groundwater system before it reaches the local stream. Hence, additional cover design analyses focussed on the 'average' cover performance, which represents the average predicted performance utilising 50 years of climate data.

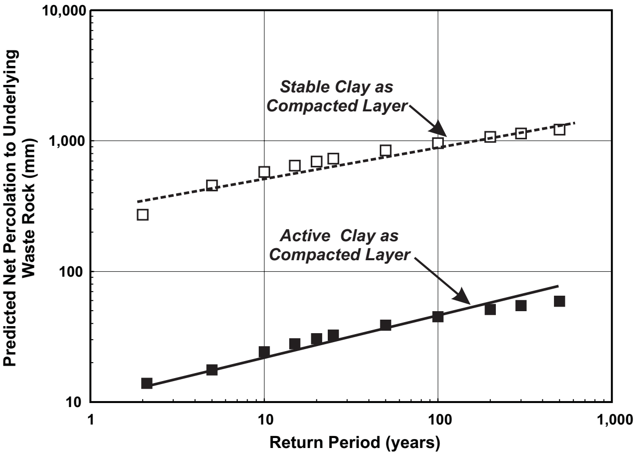

FIG 4 - Predicted annual net percolation for a compacted layer of 'active' clay and 'stable' clay for a range of return periods.

Figure 5 shows the average net percolation (expressed as percentage of MAR) as a function of the thickness of the overlying growth medium (non-compacted stable clay) assuming that either the stable clay or the active clay is utilised for the compacted layer. In both scenarios, the predicted average rate of net percolation decreases with an increase in the thickness of the growth medium. This decrease in net percolation is due to the fact that a thicker growth medium has a higher storage capacity. The thicker layer is also able to protect the underlying compacted clay layer from wetting-drying cycles. Such wetting-drying cycles are known to increase the effective hydraulic conductivity of the compacted clay layer over time, thus increasing net percolation over and above that which is shown in Figure 4.

Figure 6 shows the predicted annual ingress ('mass flux') of oxygen as a function of the thickness of the growth medium for the case of a compacted active clay layer cover system. The oxygen ingress is primarily controlled by the degree of saturation of the compacted clay layer. A thicker growth medium reduces the amount of drying in the compacted layer, thus reducing the annual oxygen ingress. The model predicts an exponential decrease in oxygen ingress with an increase in growth medium thickness.

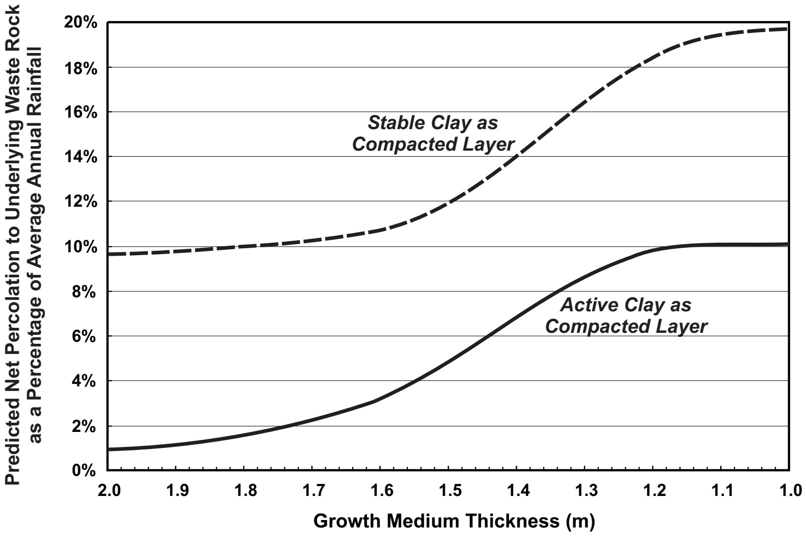

FIG 5 - Average net percolation (percentage of mean annual rainfall) as a function of the thickness of the overlying growth medium.

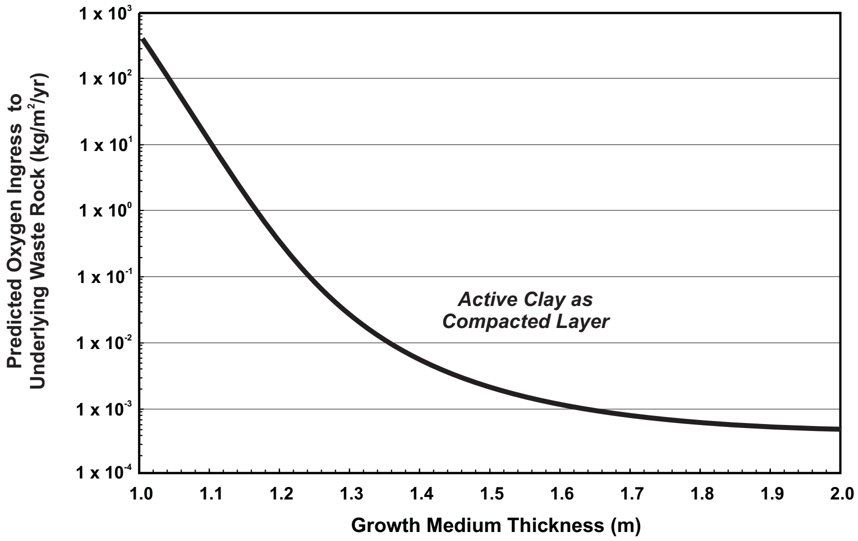

FIG 6 - Predicted annual oxygen ingress as a function of growth medium thickness ('active' clay compacted layer).

The large increase in oxygen for reduced thickness of the growth medium would lead to further oxidation of the underlying sulfidic material, thus potentially increasing the contaminant load emanating from the waste rock pile via seepage.

Impact analysis

An initial review of site conditions indicated that zinc would be the key contaminant of concern at this site for the following reasons:

1. zinc occurs in highly elevated concentrations in waste rock seepage (up to 400 mg/L);
2. zinc is relatively mobile in the circum-neutral groundwater; and
3. zinc is potentially toxic to aquatic organisms (ANZECC, 2000).

The nearest (ephemeral) stream of ecological significance that might be impacted by waste rock seepage is located approximately 1000 m down gradient of the waste rock storage facility. For the purpose of this impact analysis, it was assumed that zinc could only reach the stream via groundwater flow. Hence, the impact analysis focused on the prediction of zinc concentrations reaching the stream via groundwater flow. The impact analysis employed geochemical models, a seepage model, as well as a groundwater flow and transport model to predict the timing and magnitude of zinc concentrations discharging into the creek for different cover scenarios.

A detailed assessment of the geochemistry of the waste rock material was carried out including geochemical testing and modelling. It was concluded that, even though a significant amount of carbonate material (and therefore neutralisation capacity) exists in the waste rock, localised areas of significant ARD potential exist. The current composition of pore water in the WRD was estimated to be slightly acidic (pH ~6.6) with elevated sulfate (4000 mg/L) and average zinc concentrations of about 10 mg/L.

Static acid-base accounting test results further indicated that as much as 25 to 30 per cent of the waste rock dump could potentially become acid generating, provided oxygen entry was not limited in the future. Geochemical modelling suggested this increased rate of oxidation would reduce the pH in pore-water to about 5.8, with a commensurate increase in zinc of up to 100 mg/L (ie a concentration ten times higher than predicted for current conditions).

The detailed cover design analysis had suggested that the proposed low hydraulic conductivity cover (using 2 m of growth medium and a compacted, active clay layer) would reduce oxygen ingress by about 99 per cent, thus representing an effective oxygen barrier (Figure 6). In other words, the rate of sulfide oxidation within the WRD may significantly decrease after cover placement compared to current conditions. Note, however, that a reduction in the rate of oxidation may not result in a significant improvement in seepage water quality for a very long time owing to the poor quality pore water already present in the mass of waste rock. Seepage modelling carried out for the waste rock pile indicated that the volume of pore-water (with poor water quality) currently stored in the WRD is significant relative to the amount of (clean) rain water entering the WRD through a low hydraulic conductivity cover system. The modelling results suggested that it would take many decades to 'flush' all contaminants currently present within the pore-water of the waste rock storage facility, even if no further release of contaminants (due to oxidation, desorption and/or dissolution reactions) occurred.

Based on these analyses, a total of four cover scenarios with differing seepage rates, initial (current) zinc concentrations and 'future' zinc concentrations were selected for further impact analysis (see Table 2).

- **Scenario One:** waste rock storage facility removed (no cover required);
- **Scenario Two:** a 'high quality' cover (eg 2 m growth medium over 0.5 m compacted, active clay);
- **Scenario Three:** a 'lower quality' cover (eg 1 m growth medium over 0.5 m compacted, active clay);
- **Scenario Four:** a 'low quality' cover (eg 1 m growth medium over 0.5 m compacted, stable clay)

Scenario 1 was not a realistic option but was included for reference purposes only.

A groundwater flow and solute transport model was developed for the site to predict the timing and magnitude of peak zinc concentrations in shallow groundwater discharging to the nearest stream. The groundwater flow model was calibrated using groundwater level and stream flow monitoring data. The model input parameters for zinc transport (porosity and dispersivity of the aquifer and retardation factor for zinc) were developed based on (limited) field observations.

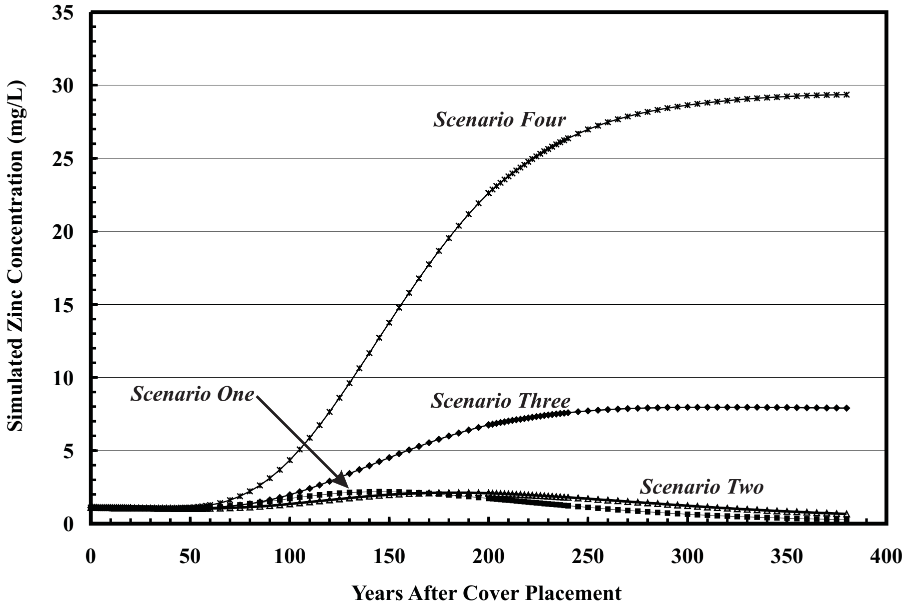

FIG 7 - Predicted zinc concentrations in shallow groundwater for four cover scenarios.

TABLE 2

Cover scenarios evaluated during impact analysis.

Scenario	WRD seepage rate	WRD seepage quality (mg/L)	
		Initial Zn	Future Zn
1	0% of MAP (ie no WRD)	10	0
2	1% of MAP	10	10
3	10% of MAP	10	50
4	20% of MAP	10	100

Figure 7 shows the predicted zinc concentrations in the shallow groundwater for the four scenarios in vicinity of the stream. The predicted times for a 'breakthrough' of peak zinc concentrations at the stream range from ~150 years for Scenario One, to ~400 years for Scenario Four. Note that even in Scenario One (waste rock storage facility removed) zinc concentrations are predicted to increase slightly before finally declining due to 'flushing' of zinc currently stored in the local aquifer system.

As expected, the highest zinc concentrations in groundwater discharging to the stream were predicted for Scenario Four, which represents the scenario with the highest zinc load from the waste rock dump to the aquifer system. Note that the predicted peak zinc concentrations in shallow groundwater discharging into the stream are similar for Scenarios One and Two (Figure 7), implying that the zinc load released from a high quality cover is small relative to the zinc currently stored in the aquifer system.

Compliance and risk assessment

The predicted zinc concentrations in the stream base flow for all four scenarios are well above the applicable 'low-risk' trigger value of zinc (0.008 mg/L for protection of 95 per cent of species; ANZECC, 2000). Hence, a biological study was initiated to evaluate the chronic and acute toxicity of local aquatic organisms to zinc. This study is currently still in progress. Once completed, this study will provide a framework for selecting the appropriate cover scenario required to protect the aquatic ecosystem at this site.

SUMMARY

The methodology put forth in this paper calls for developing site-specific performance criteria for a cover system designed to isolate acid-forming mine waste and to control acid rock drainage. The methodology allows for determination of the appropriate level of control (of oxygen ingress and/or net percolation) required by the cover system by linking the predicted performance of a cover system to groundwater and surface water impacts. A case study has been presented to illustrate this approach.

The methodology presented in this paper (Figure 1) advocates the use of a series of steps including, conceptual cover design, detailed cover design, impact analyses, compliance/risk assessment prior to final design and field trials. The detail and depth to which those analyses are carried forward depends on the site-specific conditions and the regulatory framework. Ideally, detailed sensitivity analyses should be carried out for a range of cover options (both during the phase of cover design and impact analysis) to determine the most cost-effective cover design. If this is not feasible, an impact and compliance/risk analysis should at least be carried out for one (or several) selected cover scenarios.

The cover design process traditionally proceeds from top to bottom as shown in Figure 1. However, cover design does not necessarily have to proceed in this order. In fact, there may be advantages to perform an impact analysis and/or a compliance/risk assessment before any detailed cover design analysis has been carried out. In this 'top-down' approach an overall framework for cover design is developed that may bring focus to the detailed cover design analysis.

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