Thirty Years of Applied Unsaturated Soil Mechanics in the Mining Industry

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Abstract: Mining companies in the western, free-market, tradition are generally in business to turn 'natural' capital into financial capital by extracting resources in a way that generates consistent economic returns while managing risk and meeting regulatory and legal obligations throughout the asset lifecycle. Resource extraction requires creation of landforms, such as tailings storage facilities (TSFs) and mine rock stockpiles (MRSs), to manage material that is not economic for ore recovery. Two foundational 'imbalances' are created when material that was below surface, is extracted and placed on the surface within a TSF or an MRS: a thermodynamic imbalance and a gravitational imbalance. The thermodynamic imbalance results from material that was in a reducing environment for the most part, such as sulphide minerals (e.g. pyrite) that formed at depth in the absence of oxygen, is placed into an oxidizing environment, such as in a TSF or MRS. The gravitational imbalance results from meteoric water, as well as groundwater and run-on interact with the mine landform by landing on or infiltrating into it. In the context of these two imbalances, the system (the landform) continuously works from a state of higher potential energy to lower potential energy, which can lead to metal leaching and acid rock drainage (ML/ARD), also known as acid and metalliferous drainage (AMD). These landforms are unsaturated systems, as are cover systems placed on them to manage ML/ARD risk through control of water inflow and/or oxygen ingress to the underlying reactive materials. This paper presents a conceptual model approach as a tool to understand, and thus mitigate, ML/ARD risk for design, construction, and performance of TSF and MRS landforms. The model can be applied and updated throughout the mine lifecycle, ideally beginning during project development when key strategic decisions are made. The conceptual model is incorporated into a repeatable and formal decision-making process that allows for transparent reduction of uncertainty and increase in effectiveness of engineering controls.

Introduction

Metal leaching and acid rock drainage (ML/ARD) or acid and metalliferous drainage (AMD) results from water flowing through reactive material(s) that have been extracted or exposed during mining. The global cost of managing ML/ARD is in the range of hundreds of billions of dollars. INAP[1] states that ML/ARD is one of the most serious and potentially enduring environmental problems for the mining industry, which if left unmitigated can result in significant long term water quality impacts. In the western United States alone, it is estimated that it would cost ~USD$30 to $70 billion to clean up the over 15,000 hard rock mines with ML/ARD problems[2]. Canada's MEND program (Mine Environment

Neutral Drainage) estimates there is upwards of C$5 billion total liability to address ML/ARD risk in Canada[3].

Across a broad range of commodities, MRSs typically contribute 60 to 80% of the total acidity load at mine sites with a further 20 to 30% associated with TSFs constructed using run-of-mine rock[4]. Mine rock used to construct TSF starter dykes, dams, and buttresses is often the source of ML/ARD from a TSF, particularly during construction and operation. Other landforms such as heap leach pads, open pit high walls, and underground mine voids can also contribute to acidity load at a mine site.

Landforms

In the mining industry, landforms include: TSFs, MRSs, ore stockpiles, low-grade ore (LGO) stockpiles, heap leach facilities (HLFs), open pits, back-filled pits, and underground workings [5]. This paper, consistent with the Landform Design Institute (LDI)[1], considers that a mine landform 'exists' well before shovel hits ground. In other words, landform design[2] begins during strategic planning for a mining project and therefore must be considered as part of a project description (PD) and/or preliminary economic assessment (PEA).

Considering spatial scale, as defined by LDI[6], and illustrated in Figure 1, a mine landform is on the approximately km x km scale. The regional scale represents multiple mines in a valley or region, whereas the lease (or landscape) scale represents a single lease or property (say on a 10km x 10km scale) consisting of multiple landforms. A lease, or mine site, can consist of a number of domains, typically organized on a surface water sub-catchment basis (note, not shown in Figure 1). Domains can have a number of landforms, and landform elements, within a singular domain. Landform elements are specifically designed physical subcomponents of a mine landform, ranging from the 10m x 10m scale to multiple hectares, and therefore include cover systems, wetlands, hummocks, berms, etc. As per LDI[6], microtopography are small additions to the landform, or the landform's elements, which are typically 'field-fit' for enhancing flora and fauna, and consist of roughening, and mounds / swales, amongst many things.

Landform design is inclusive of cover system design, and vice versa; one cannot be designed, constructed or its performance evaluated, conceptually or otherwise, in isolation of the other. Hence, the following sections include discussion on conceptualization of cover system and landform performance.

Cover Systems

A cover system is a technology in the mining industry, which falls within the broad range of applied sciences aimed at preventing and/or mitigating potential risk arising from mining activity. More specifically, cover systems are exactly that; systems, because their performance, including performance expectation, is intimately linked to the underlying material and hydrologic conditions (i.e., the landform itself), as well as vegetation and site-specific climate conditions. Hence, while cover systems are frequently labelled as 'caps', 'liners', or 'covers', a cover system is much more than the cover material

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[1] https://landformdesign.com/.

[2] Landform Design: is the interdisciplinary process of shaping and engineering mine-disturbed landscapes to create stable, sustainable, and functional landforms that support post-mining land use objectives and environmental performance over the long term.

itself. An incorrect thought process, and thus design approach, will often result if a cover system is thought of as the cover material only, because the tendency is then to design each layer in isolation of other factors that influence cover system performance.

Cover systems are the building blocks for achieving agreed-upon land uses and support, as a general purpose, surface reclamation of a mine landform, while also providing a stable, reliable, and sustainable interface between the landform and the environment. Purposefully, within the mining industry, this interface is planned as being one that develops into either an aquatic ('water cover') or terrestrial ecosystem ('dry cover'); either may also include a riparian zone. The latter, 'dry covers' is the focus herein. More simply, cover systems support reclamation of the surface of landforms created from mining activity, and typically are expected to limit net percolation, and/or control oxygen ingress into the landform during operations and in closure, as a means of managing ML/ARD risk.

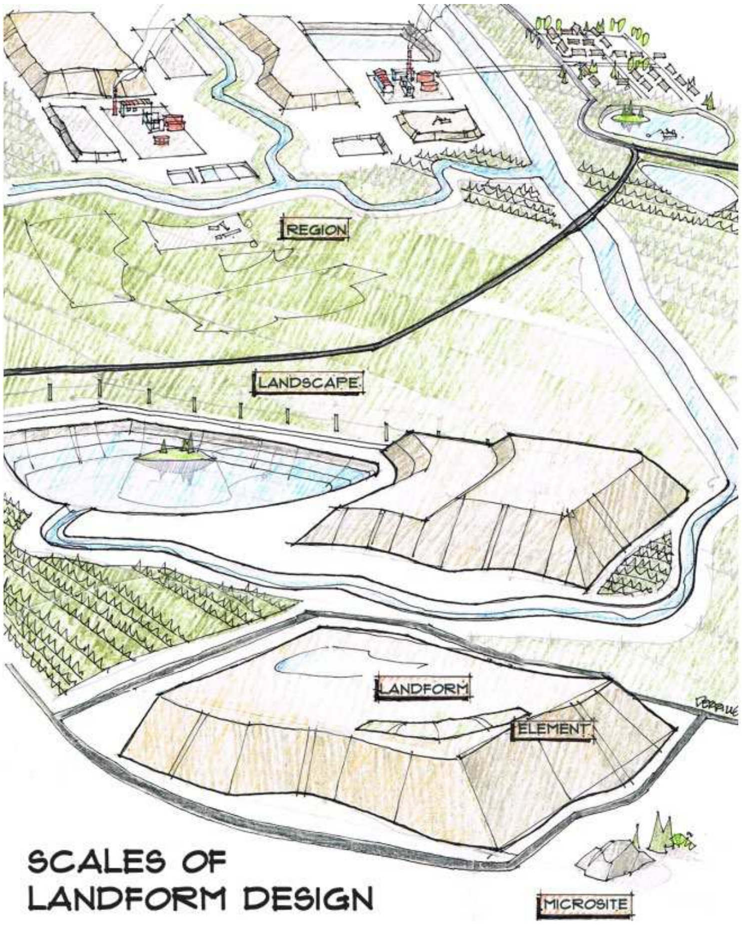

Figure 1: Spatial scale for landform design[6], illustration by D. Shuttleworth.

The Need for Robust Conceptualization for Mine Landforms and Cover Systems

At some point in time, when a mining company has decided that resources in the ground can no longer be extracted while providing the requisite return on investment (ROI), mine operations cease, and mine landforms, such as MRSs and TSFs, must be closed. ICMM[7] describes integrated mine closure as a dynamic, iterative process that incorporates environmental, social, and economic considerations from the outset of mine development. Progressive closure and reclamation, closely aligned with integrated mine closure, is widely regarded as best practice in the mining industry. It involves systematic rehabilitation of disturbed land during mining operations, rather than deferring all activities until after closure. Despite clear guidance, progressive closure is often lacking in practice, especially when dependent on operational fleet, as this is in conflict with financial priorities (i.e., cash flow from production vs cost to progressively execute rehabilitation programs). This is less of a technical issue, or a 'values' issue, and more a reflection of poor alignment between mine planning outcomes (ore delivery) and closure planning outcomes (longer term liability and risk). The root cause is typically a failure by mine closure practitioners to demonstrate the value of progressive closure to mine planners and business decision-makers, early in project development.

The poor alignment results in most conceptual, pre-feasibility, feasibility, and detailed mine closure design activities being undertaken late in the operational stage, towards the end of the production phase of the asset's lifecycle. Consequently, planning for closure often becomes an exercise in tactically, likely even transactionally, optimizing the ability of the landforms on the site to meet closure objectives and post-mining land use expectations without the benefit of integrated and progressive mine closure. In most instances, it is at this time in the asset's lifecycle that unforeseen liabilities are 'discovered'. These unrecognized and poorly funded liabilities typically manifest as, amongst many: i) water quality issues requiring long-term collection, conveyance, storage, and treatment, and/or ii) a requirement to move large volumes of material over long distances when executing closure works, to achieve required closure outcomes.

The relative ability to influence cost by mining stage is depicted in Figure 2, which illustrates the importance of an integrated mine closure approach. However, this author's experience is that early in project development, during the planning phase, which includes the concept study, preliminary study, and feasibility study stages, there is often a rush to choose a singular design for a project component. Common mistakes include: i) the design team 'transferring a successful design' from a previous project, rather than applying / transferring the design approach of the successful design, or ii) assuming 'what good looks like' in the absence of consultation with all stakeholders and rightsholders. Then, because this 'first design', is typically viewed as 'the design' moving forward; it becomes very challenging to materially change the initial design as a result of the 'project development meat grinder'.

Hence, there is a need to develop a conceptual model for performance of the different landforms at this early first phase of mine development. This conceptual model of performance, which is foundational and must be developed reliably in light of site-specific empirical constraints, must be developed before any numerical modelling occurs. In the context of this paper, a conceptual model is a tool used to identify and outline key processes happening in a real-world system that the user is interested in quantifying. Building a conceptual model is therefore the first step in building numerical, mathematical, or reactive transport models[8],[9], as it is necessary to understand processes important to a particular system, and their site-specific controls, before diving into the calculations. At this conceptual model stage, which is the model stage at the PD and PEA stage, i.e., the planning phase of an asset's lifecycle, as shown in Figure 2, a focus on accuracy is far more important, as compared to a focus on precision. This is the point in time where the relative ability to influence costs is at its maximum. Unfortunately, as described above, this is not the approach typically applied.

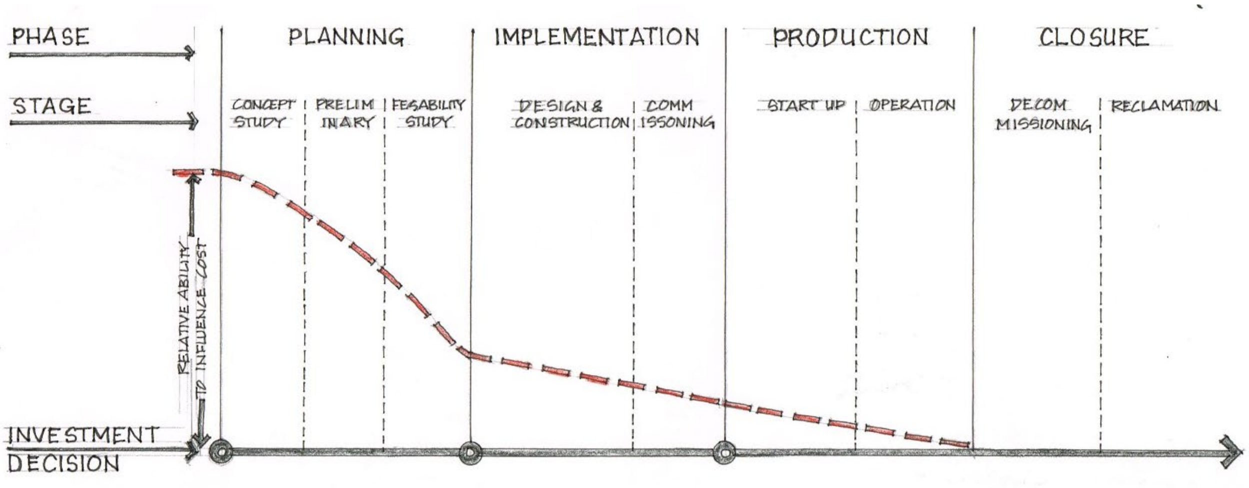

Figure 2: Relative ability to influence cost as a function of mining stage(adapted from Lee[10] and Hustrulid & Kuchta[11], illustration by D. Shuttleworth.

Concepualizing Cover System Performance

The MEND 'Cold Regions Cover System Design Technical Guidance Document'[12], and the INAP 'Global Cover System Design – Technical Guidance Document'[13] provide an approach to conceptualize cover system performance, and therefore design. In the case of the INAP document[13], a decision-making tool is presented advocating the use of a hierarchical framework structured from the basis of 'engineering ease'[3] in which to develop a conceptual cover system design. This is depicted in Figure 3, where climate is the first 'filter' to look through, because it is the facet of cover system design for which we have no control over. Next is hydrogeologic setting, which can be 'engineered', such as foundations, ditches, trenches, cutoff walls, and pumping wells, albeit challenging to engineer.

Our capacity to 'engineer' materials and vegetation to influence cover system performance is substantially greater as compared to engineering ease with changing hydrogeologic conditions. For example, finer-textured materials retain more water than coarser-textured materials, which will increase a cover system's capacity for plant available water and thus reduce net percolation. Layering a finer-textured material over a coarser-textured material will enhance plant available water and reduce net percolation in comparison to a single layer of the finer-textured material alone.

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[3] Engineering Ease: typically refers to the relative simplicity, efficiency, and practicality with which an engineering solution can be designed, constructed, operated, or maintained, often describing how straightforward a design is from a technical execution perspective. In the context of Figure 3 however, it is in reference to an increasing ability to engineer the hierarchical components of the cover system conceptual model.

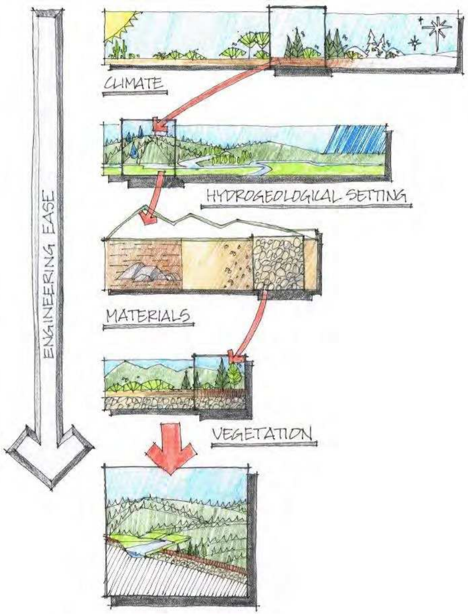

Figure 3: Conceptual cover system design framework portraying four filters for climate, hydrogeology, materials, and vegetation[13], illustration by D. Shuttleworth.

In the context of Figure 3, this robust site-specific conceptualization of cover system performance can be applied during the planning phase of the mine project, while also allowing for numerical modelling, when required in later phases (and stages), to be focussed on refining and enhancing the conceptual model and comparing alternate cover system designs. Very often, numerical modelling to support cover system design is 'started too early' (i.e., in the context of Figure 3, during the planning phase). There is a focus on undertaking deterministic numerical modelling before a full understanding of what is required from the cover system, which confounds a designer's capacity to assess uncertainty, and put appropriate controls in place. Regardless of the phase of the mine, rarely is there comprehensive data for all numerical modelling inputs. However, with a robust conceptual model, assumptions and limitations in numerical modelling can be communicated in a simple manner, by using the conceptual model of cover system performance as the communication tool, as well as for communicating results of sensitivity analyses.

Types of Cover Systems

Put simply, there are six (6) basic types of cover systems: i) simple-protection type cover systems, ii) store-and-release type cover systems, iii) enhanced store-and-release type cover systems, where the enhancement is a result of the presence of an underlying lower permeability layer, a capillary break layer, or a seasonally frozen layer, iv) barrier-type cover systems, that include an underlying layer that has a field saturated hydraulic conductivity (k_{fs}) of 1 x 10^{-7} cm/s or less, such as a compacted clay layer (CCL), a compacted sand-bentonite layer, or a permanently frozen layer (permafrost aggradation), v) engineered layer type cover systems, which include geomembranes with a k_{fs} 1 x 10^{-7} cm/s or less, and vi) saturated soil or rock type cover systems. The reader is directed to MEND[12] and INAP[13] for further details on cover system types.

Recognizing that the preceding list classifies, or labels, cover system types, which can at first glance appear to be an opportunity to enhance communication of design intent, it is foundational to focus on cover system functionality, when describing a cover system, rather than design intent. A particular cover system may fall into more than one cover system type. For example, in respect of net percolation[4] (illustrated in Figure 4), all cover systems have some capacity to store-and-release water, as well as shed water, regardless of cover system type (note that net percolation is different than net surface infiltration[5]). All cover systems also provide a degree of erosion protection, and a cover system with a geomembrane may also serve as a store-and-release cover system during seasonally drier climate conditions. Hence, a cover system should be evaluated on a continuum of functional performance values because differing mechanisms will be dominant depending on site-specific controls and on site-specific conditions.

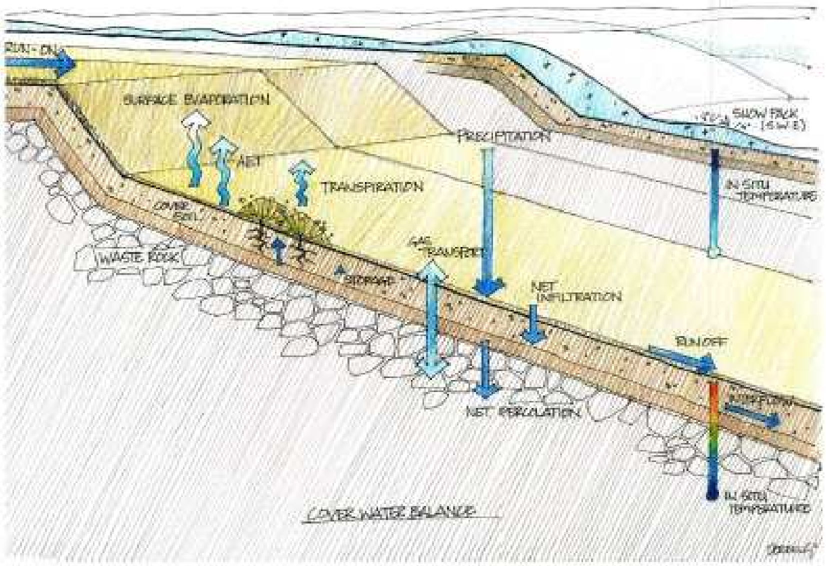

Figure 4: Conceptual schematic of a cover system water balance[12], illustration by D. Shuttleworth.

Cover system performance is not binary; rather, cover system performance is best communicated as a probability of exceedance, in comparison to design criteria, such that the probability of cover system performance can be communicated in the context of consequence effect. In this manner the benefits from risk mitigation determined from the presence of one cover system, or another, can be evaluated against cost.

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[4] 'Net Percolation', is in reference to water reporting into the mine landform following placement of a cover system. It is the result of meteoric water (*i.e.*, rainfall and/or snowmelt) infiltrating into the cover system surface, which will either be intercepted by vegetation, runoff, or infiltrate into the surface. Water that infiltrates will be stored in the 'active zone' and may then subsequently exfiltrate back to the surface and evaporate, or be removed by transpiration. A percentage of the infiltrating meteoric water will migrate beyond the active zone as a result of gravity overcoming the influence of atmospheric forcing (*i.e.*, evaporation), may report as interflow (water moving laterally within the cover system due to a hydraulic discontinuity), with the result being net percolation to the underlying mine landform.

[5] Net Surface Infiltration', is in reference to water reporting into the mine landform for 'bare surface' conditions (i.e., no cover system).

Application of this conceptualization of cover system performance allows for focus on using numerical modelling for sensitivity analysis when it is required, and understanding probability of meeting design criteria, rather than simply focussing on a binary prediction, such as ‘average performance’, to make decisions on cover system design. For example, in Figure 5, the net percolation criteria for a project is 40mm, which in the context of a 100-year climate database with an average annual precipitation of 800mm (PPT data not shown in Figure 5), equates to a net percolation criterion of 5% of average annual precipitation. In the case of the predicted net percolation data resulting from continuous 100-year soil-plant-atmosphere cover system numerical model simulations, a barrier ‘type’ cover system (shown in Figure 5 as cover system No.1) would have an ~95% probability of being less than the 5% net percolation criterion for any given year of the 100-yr climate data base. For the same climate database, an enhanced store-and-release ‘type’ cover system (cover system No.2 in Figure 5) would have an ~80% probability of being less than the 5% net percolation criterion for any given year of the 100-yr climate database. Cover system No.3, shown in Figure 5, which is a store-and-release ‘type’ cover system, would have an ~50% probability of being less than the 5% net percolation criterion for any given year of the 100-yr climate database.

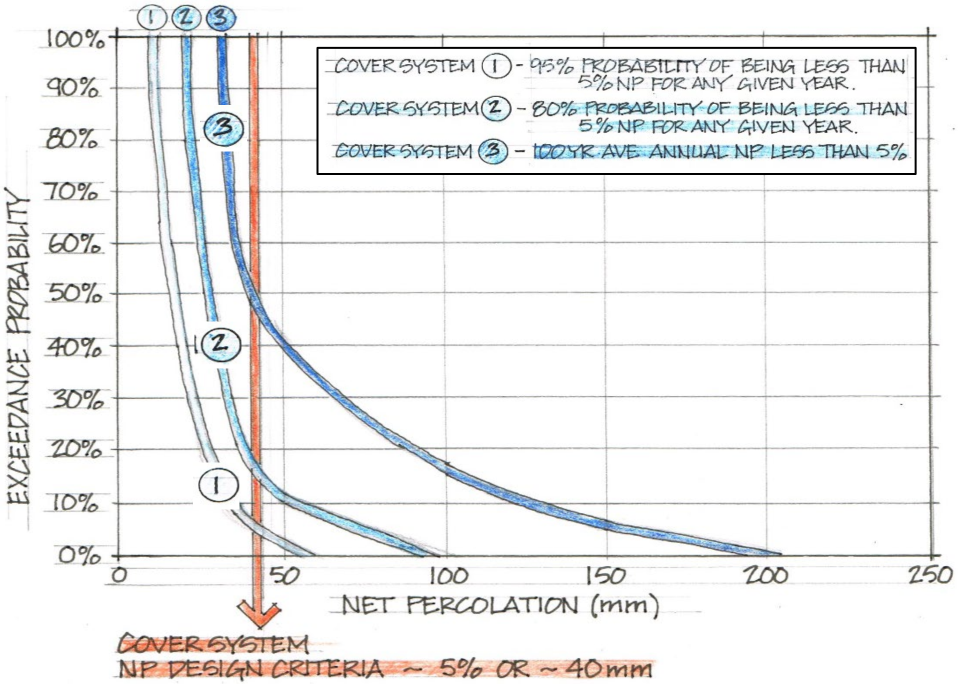

Figure 5: Cover systems function on a continuum, illustration by D. Shuttleworth.

It is likely that the predicted annual average net percolation rate for cover system No.1 would be easily distinguished from No.2 and No.3. However, if comparing the average annual net percolation rate for cover systems No.2 and No.3, the two rates would very likely be quite similar. Hence, a probability of exceedance approach allows the designer to communicate the benefit of consequence effect differences (e.g., seepage rates from the base / toe of the landform and resultant water quality, or changes in phreatic surface elevation for a TSF) in terms of cost and performance benefit between the two cover systems as a function of probability, rather than using a binary ‘pass / fail’ approach.

The same probability exceedance curves for different cover systems can be developed for oxygen ingress, plant available water, and erosion.

The Binning Concept

Binning, which is a generalization for rounding, is also referred to as discretization, or bucketing. It is a well-known data pre-processing technique, where a set of data that fall into a particular interval, are replaced by a value, or description, representative of the interval.

The Köppen-Geiger climate classification system characterizes precipitation (PPT) and temperature on a seasonal and annual basis. Both parameters are integral to understanding key physical processes that control a cover system's water balance and consequently, influence plant water availability, net percolation, oxygen ingress, and erosion for a mine landform. The influence of orographic effects and climate change can also be incorporated into a site's Köppen-Geiger climate classification to inform on performance.

The modified Köppen-Geiger system[14] divides climate into five major climate types, which makes the system a good example for application of the binning concept. The five main groups are Tropical (A), Arid (B), Temperate (C), Continental (D), and Polar (E). To address the dynamic nature of intra-annual climate variability (seasonality), subtypes exist for both PPT and temperature, which further sub-divide tropical, arid, and temperate regions. The amount and timing of water availability are controlled by regional climate. The primary parameters of PPT and temperature are not static, varying on a seasonal, annual, and decadal basis. With a fulsome understanding of the dominant climate at a site, including the highs, lows, and cycles of annual, seasonal and decadal variation inherent in all climates, a cover system designer can begin to 'bin' cover system performance on the basis of an appropriate site-specific Köppen-Geiger classification. Note that the influence of orographic effects and climate change can be applied to determine of these conditions alters a site's Köppen-Geiger classification.

Understandably, there is a tremendous potential range for cover system performance for a landform on any given mine site, given the extent of location, climatic setting, ore type, etc. Binning allows a cover system designer to focus on the importance of accuracy, versus precision. For a cover system conceptual model developed during the planning phase (see Figure 2), it is foundational to determine 'what bin', or value, a measured facet of cover system functionality is situated within. In this context and phase of a mine project, how close the measurement is to the accepted value (the accuracy) is more important than how close the measurements are to each other (the precision).

Any mine landform can be located and characterized by its major climate type and sub-type, on the basis of seasonality of temperature and PPT. Using INAP's Global Cover System Design guidance[13] a mine landform situated in the Elk Valley in southeastern BC can be used as a relevant example for application of the binning concept. For this example, the landform experiences a Köppen-Geiger climate classification in the Dfb 'bin' based on regional and seasonal temperature, as well as precipitation conditions. This 'bin' helps the designer identify the level of control on net percolation or oxygen ingress that is most applicable at the site for the landform and different cover system types. Net percolation rates for a cover system on a mine landform are binned into Very Low (VL), Low (L), Moderate (M), High (H), and Very High (VH) rates. INAP[13] uses the Köppen-Geiger climate classification system to bin climate based on regional conditions first, followed by seasonal temperature and precipitation conditions, before using the nature of the geologic system and geochemical characteristics to inform on cover system needs. INAP[13] then provides the range of the interval for net percolation (or oxygen ingress, not shown below), depending on texture of the near surface mine landform material and the cover system type (layering, texture, thickness, vegetation, etc.). The following 'bins' of net percolation performance expectations and the corresponding cover system type are determined as per INAP[13] for this the Dfb site.

- *Very Low (VL):*
  There is a high probability that net percolation will be <5% of average annual precipitation for any given year.
  Cover system type: Barrier Layer - compacted clay layer; CCL, with k_{fs} of 1×10^{-7} cm/s, or less; sand-bentonite or geomembrane layer, if CCL not available.
- *Low (L):*
  There is a high probability that net percolation will be 5% to 15% of average annual precipitation for any given year.
  Cover system type: Enhanced Store-and-Release - with lower hydraulic conductivity layer.
- *Moderate (M):*
  There is a high probability that net percolation will be 15% to 25% of average annual precipitation for any given year.
  Cover system type: Enhanced Store-and-Release - with capillary break.
- *High (H):*
  There is a high probability that net percolation will be 25% to 50% of average annual precipitation for any given year.
  Cover system type: Store-and-Release.
- *Very High (H):*
  There is a high probability that net percolation will be >50% of average annual precipitation for any given year.
  Cover system type: Erosion Protection – Vegetation.

Landform features, such as slope angle, slope length, and vegetation conditions (i.e., plant available water requirements), are then incorporated into the cover system conceptualization of performance.

The value is not only in assigning a 'bin' but also in understanding what the climate information is telling a designer about how a cover system will function annually and seasonally. INAP[13] also provides binning ranges, from Very Low to Very High, for oxygen ingress. The same conceptualization can be used for plant available water use, and cover system erosion.

Concepualizing Mine Landform Performance

In the context of ML/ARD, an appropriate conceptual model (tool) for mine landform performance should include key inputs necessary to estimate metals release from TSFs and MRSs in a simple, yet robust manner. The conceptual model should communicate inputs, ideally phrased as questions, to capture important features of TSFs and MRSs by using the same 'binning' or categorization approach described earlier, to capture the variability in parameters important for metal release from tailings and mine rock at the landform scale. Four high-level 'bins' are represented schematically in Figure 6 and organized in a hierarchy of 'engineering ease' as shown earlier for conceptualizing cover system performance (see Figure 3).

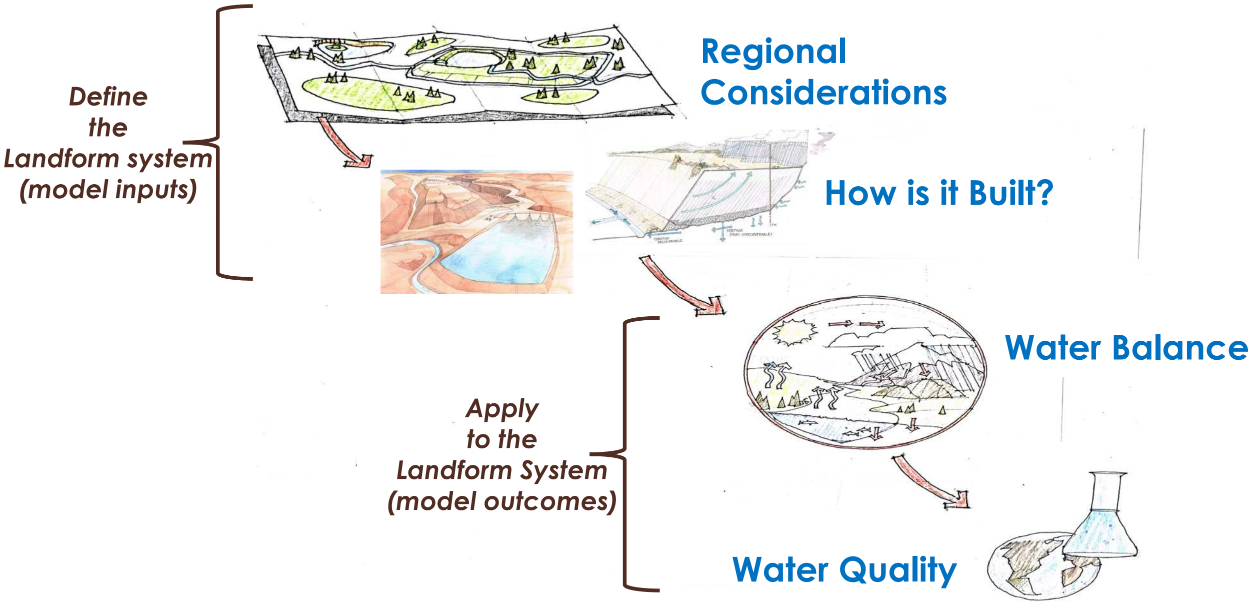

Figure 6: Summary of the conceptual model, or tool, for mine rock stockpiles and tailings storage facilities[15], illustrations by D. Shuttleworth.

The conceptual model tool's inputs are first determined by defining the TSF or MRS system, i.e., regional considerations and how/where the landform is constructed. Regional considerations include the 'sub-bins' of climate conditions, geologic systems, and hydrogeologic conditions, noting that the geologic system defines geochemical characteristics. Generally, these are conditions inherent to the location of the mine and cannot be engineered, or perhaps very challenging in the context of hydrogeologic conditions. The 'how it's built' overarching bin considers tailings deposition and TSF construction method(s) or MRS construction method(s) as sub-bins, whether conventional or with a focus on source control (see further discussion as per [16] and [17]). These are engineering design choices that are selected by the landform designer and influenced by regional considerations. Inputs are then used to evaluate model outcomes for water balance and water quality. The water balance will include the sub-bins of: i) groundwater and surface water interaction, i.e., recoverable-unrecoverable seepage ratio(s), coupled surface-atmosphere water balance(s), and landform-based water balance(s), and ii) operations versus closure water balance. The resulting water quality, controlled by risk of ML/ARD, oxidation depth, exposed surface area (for a TSF), and construction method (for an MRS), are sub-binned in terms of acidity and metals release from the different landforms considering flow pathways and hydrologic retention time defined by the landform design and water balance.

Note that for both types of landforms, MRSs or TSFs, but in particular TSFs, the conceptual model's fourth overarching bin, water quality, is very easily replaced by geotechnical stability, with the connection to the preceding water balance overarching bin and sub-bins determining the landform's pore-water regime on the basis of the water balance.

Following the framework above, the conceptual model depicted in Figure 6 has the appropriate level of site-specific focus, while still being at a high-level, and can be applied in the time frame typical of PD and PEA development (i.e., during the planning phase as per Figure 2). Perhaps equally as important, the conceptual model tool forces the designer to focus on accuracy, rather than focus on being precise. Precision comes later in project development during pre-feasibility, feasibility, and detailed design. This conceptual model approach also provides a strong framework and starting point for pre-feasibility and feasibility studies, which will include numerical modelling.

Understanding and Managing Oxygen during and after Landform Construction

Oxygen is the first oxidant of concern for managing ML/ARD risk, noting that iron will also donate electrons to serve as an oxidant at lower pH ranges. Oxygen can move into and through mine rock and tailings by (1) advection and/or (2) diffusion, as shown in Figure 7. In tailings, oxygen ingress is typically limited to diffusion, because the smaller grain size of tailings material limits advective airflow into a facility. Mine rock stockpiles typically have larger and wider distribution of grain sizes (ranging from car-sized boulders to silt and clay size fractions, depending on the geologic system), which allows both advective and diffusive flux of oxygen to enter the stockpile. This advective flux is partially the reason why such significant acidity and metal is released from MRSs. Hence, for conventionally constructed MRSs, re-supply of oxygen is relatively uninhibited to greater depths, both laterally and vertically, giving a greater mass of 'reactive' material (i.e., material containing sulphide minerals) access to oxygen relative to tailings. In short, with conventional MRS construction methods, there is essentially an unlimited re-supply of oxygen for ongoing sulphide oxidation because of the landform's inherent high internal air flow capacity and the geometry of a MRS (i.e., the difference in height from toe to crest, which forms an inherent gradient for airflow). In contrast, sulphide oxidation in tailings is controlled by diffusion of oxygen from the surface (oxygen transport to a slowly advancing oxidation front); hence, acidity generation is a surface dominated mechanism for TSFs. Water will also transport metals through both advective and diffusive processes; however, in the case of metals moving through a typical mine landform, it is assumed that advective flux is much more effective at transporting metals through unsaturated materials.

Linkages to Conceptual Cover System Performance

Mine landforms with tailings or mine rock not only differ in respect of the manner in which gas is transported into and within the landform, but also in respect to cover system constructability and water transport and/or storage. Tailings material is typically much finer-textured than mine rock, and while placed at much higher water content than mine rock, tailings also have much higher water retention capacity than typical mine rock. Hence, cover system construction on tailings can be challenged by the need to create sufficient bearing capacity, as well as settlement due to tailings consolidation, following cover system placement. Cover system construction on tailings with low bearing capacity is always more challenging than anticipated (e.g., will typically cost more than anticipated as a result of needing more material to create a 'working platform' on which to construct the cover system). In contrast, mine rock is generally coarser-textured, and thus is often well drained. Cover system construction on mine rock stockpiles can be challenged by steep and long slopes, which is a vastly different condition than a typical mine landform containing tailings.

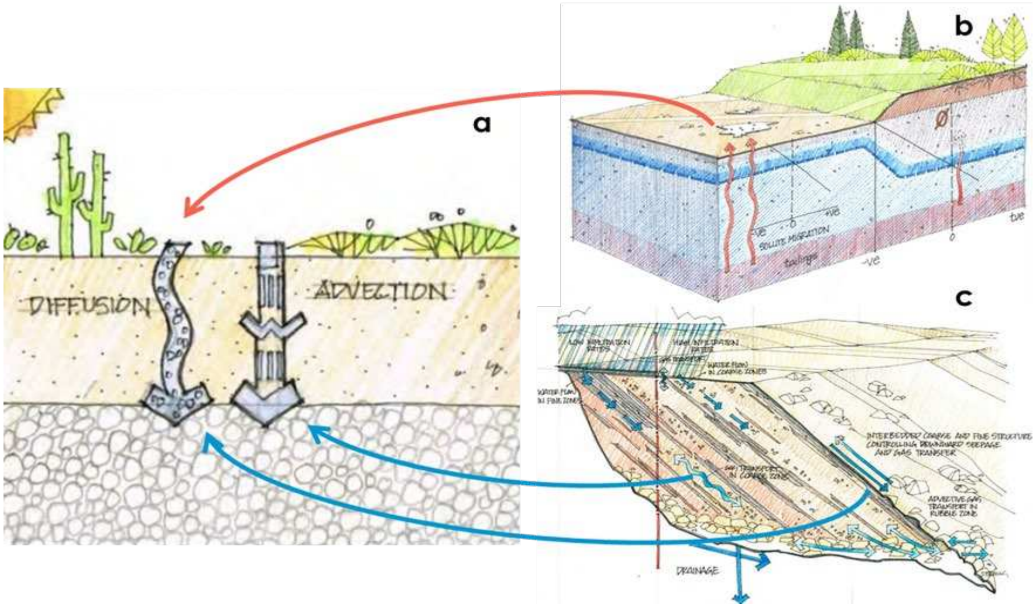

Figure 7: Diffusive gas flow is dominant in tailings, versus in mine rock stockpiles where advective gas transport dominates, noting that diffusive gas flow also occurs in mine rock stockpiles (sources: a[13], b[13], and c[12]), illustrations by D. Shuttleworth.

The differing texture of tailings and mine rock also influences cover system performance as a result of the hydraulic conditions within these materials. Coarser-textured mine rock will typically be drained (i.e., gravity driven seepage; vertical hydraulic gradient equal to 1), so cover system performance will be 'de-coupled' hydraulically to any phreatic surface in a MRS. In contrast, tailings, as a result of being finer-textured, and typically placed at relatively low solids content, will often have a phreatic surface that is near to the surface of the landform, or at least a pore-water pressure regime near surface that retains water to a much higher extent than mine rock. Hence, even if the tailings are drained, they are often hydraulically 'coupled' to the cover system and thus can influence the cover system's water balance. Meaning, during conditions where evaporative demand is in excess of available water within a tailings landform cover system, water from within the tailings mass (i.e., tailings pore-water) will be 'drawn up' into the cover system in response to this demand. This can result in an inadvertent supply of more water for plant water use (inadvertent in the context of the designer's intent), which may adversely impact intended plant species and groupings, and thus land use expectations. Further, if the tailings pore-water contains salinity, or other adverse constituents, there is probability of adversely impacting the rooting zone in a cover system through advective and diffusive transport of the constituents from the tailings, into the cover system. While this can still occur with mine rock material, the probability is substantially higher for tailings given the finer-textured nature of tailings materials and typically higher water content conditions.

In some cases, where closure of a TSF does focus on application of a so called 'dry cover', the landform often includes need for a surface water management pond on the landform, if only ephemeral. In these situations, there will be a high probability of tailings pore-water adversely impacting surface water in ponds, and thus 'overflow' of the pond, as well as surface runoff from the terrestrial component of the top of the landform.

A Focus on Source Control for Mine Rock Stockpile Construction

INAP[4], Sawyer et al.[16] and INAP[17] clearly illustrate the opportunity to decrease reliance on a cover system to manage net percolation and oxygen ingress by constructing MRSs that limit internal air flow capacity, thus reducing probability of re-supply of oxygen deep into the landform. This results in a more engineered landform, with reduced uncertainty when predicting performance, as a result of controls put in place during landform construction. In addition, this in turn reduces reliance on collection, conveyance, storage, and treatment of effluent from the mine landform during operations, closure, and post-closure.

Conceptualizing performance in respect of airflow for an MRS constructed using conventional construction practices (high tip heads, resulting in segregation during placement, etc.) is shown in Figure 8. This is compared to conceptualizing performance for an MRS constructed with a focus on limiting sulphide oxidation within the MRS during and following construction, as shown in Figure 9, by limiting vertical airflow capacity as a result of shorter lifts, and placement of horizontal engineered layers of run-of-mine (ROM) finer-textured material. For both conceptualizations shown in Figures 8 and 9, ambient air temperature is lower than internal MRS temperature. Hence, because warmer air is more buoyant (less dense) than cooler air, and the pore-air pressure gradient causes advective gas movement (i.e., convection). Thus, in the case of Figure 8 for the conventional construction MRS, deep re-supply of oxygen into the MRS occurs allowing for consistent on-going sulphide oxidation. The gradient is a function of the height of the MRS landform; hence, as a result of the toe to crest elevation difference the airflow reaches laterally deep into the MRS. The opposite would occur when ambient temperature is warmer than inside the MRS; internal pore-gas would be less dense, and thus less buoyant, causing advective oxygen ingress as a result of convection from the top of the MRS (or a lift of the MRS during construction).

In both conditions, whether as shown in Figure 8 or Figure 9, diffusion of oxygen across the mine rock material surface remains as a mechanism supplying oxygen into the MRS for sulphide oxidation, albeit at limited depth.

In Figure 9, an MRS constructed with a focus on source control limits the lateral extent of oxygen ingress as a result of placement of an engineered layer of relatively finer-textured ROM material on each lift, as well as a reduction in lift height between the layers, which results in less segregation of material during placement. Note that ‘finer-textured’ ROM material is not ‘clayey’ material; rather, it is characterized as material, which is well-graded and has more than 40% of the material passing the #4 sieve (4.75mm). This material has water retention characteristics such that when it is drained, there is sufficient water content to reduce air permeability and thus reduce landform internal airflow capacity.

There are a number of opportunities to enhance limitation of oxygen re-supply through reduction of lateral air supply across the outer batter slope(s) of an MRS during and following MRS construction, thus limiting reliance on a cover system placed post-construction. These are shown in Figure 10; their application, or combination thereof, are dependent on site-specific conditions. Ideally, cover system expectations can be simplified to managing diffusive gas flux, if required, to the near surface mine rock within the MRS, limiting net percolation to manage draindown[6], if required, while meeting plant water use requirements and serving to manage erosion on the landform.

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[6] Draindown: the additional water that drains due to gravity from a porous material if the supply of water at the top of the material is reduced. For example, take a 20 litre bucket and fill it with dry beach sand. Drill holes in the base of the bucket that allow water, but not sand, to drain from the

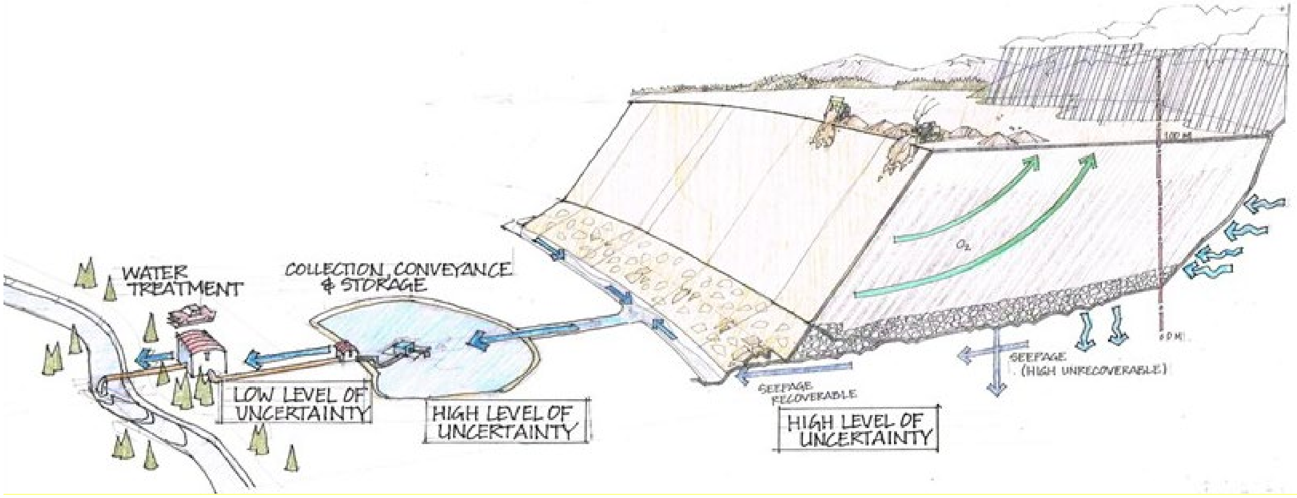

Figure 8: Conventional MRS construction, with water collection, conveyance, storage, and treatment[16] and [17], illustration by D. Shuttleworth.

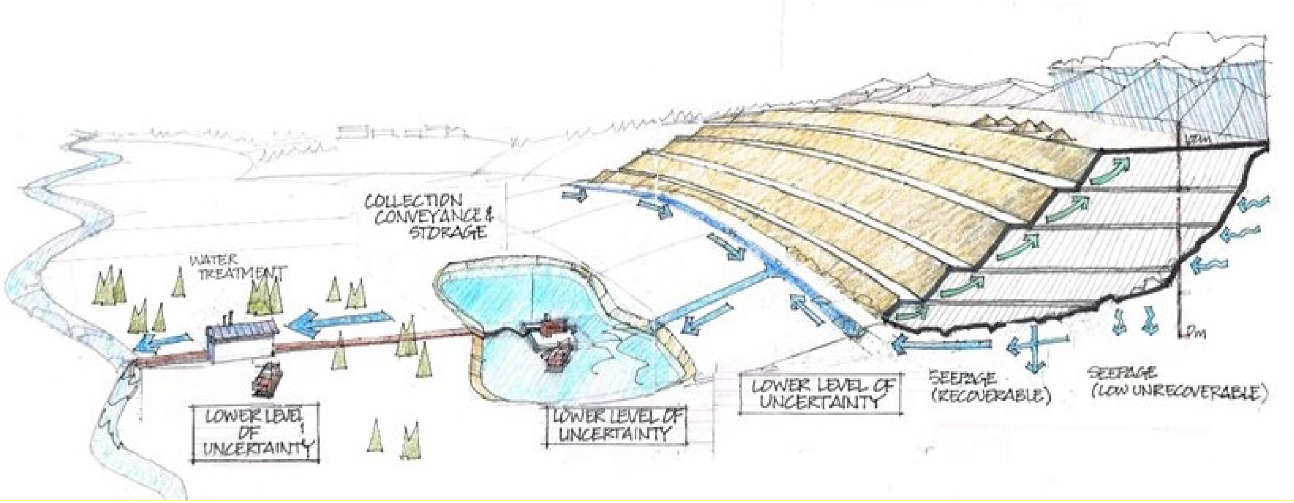

Figure 9: MRS construction with a focus on source control, with water collection, conveyance, treatment[16] and [17], illustration by D. Shuttleworth.

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bucket. Apply a relatively higher rate of water to the top of the bucket. Initially, the water will fill up storage capacity within pore-spaces of the dry sand, eventually, water will start to leak out the holes; and will continuously leak as you supply water to the top of the bucket. The leakage rate will be the same as the rate of water supplied to the top of the bucket, provided water is not spilling out over the edges of the bucket. When the water supply at the top of the bucket is reduced, the leakage rate at the bottom does not immediately equate to the reduced application rate at the top; rather, it remains high and then gradually decreases as water in the sand drains down. If the application rate is reduced substantively, or even made zero, the sand will take some time to draindown due to gravity. The water retention characteristics of the sand and the height of the sand will also influence draindown rates and timing (*i.e.*, draindown rates are a function of the volume of pore-space and how finer-, or coarser-, textured the beach sand is).

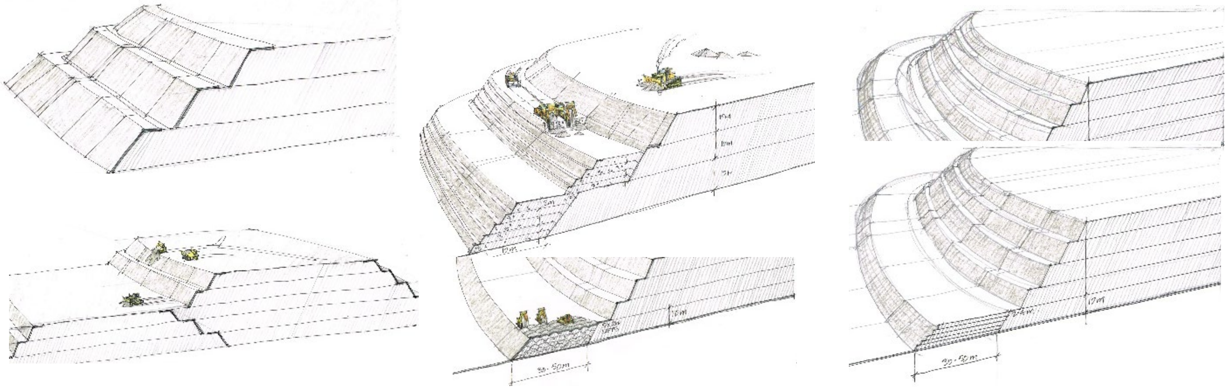

Figure 10: Examples of mine rock placement for MRS construction with a focus on source control to manage lateral airflow capacity within an MRS, illustrations by D. Shuttleworth.

Decision Making early in the Project, during the Planning Phase

During a mine project's planning phase, as shown in Figure 2, it is common for the project to be challenged with a higher level of uncertainty, as well as poorly defined control(s), when developing designs. In these situations, it is important for mine landform designers to consider that decision making using a scenario planning perspective is most appropriate, where scenario planning is defined as per[18], and shown in Figure 11. The tendency is to 'jump' to alternatives and inclusion of controls to address uncertainty in the inevitable 'chase' to develop a 'conservative' design. Unfortunately, later in project phases, these conservative controls are often difficult to rationalize as the design is optimized; they are often 'hidden' from decision makers. Hence, the purpose of developing scenarios at the early planning phase of the mine project is not to focus on a singular future condition, but rather, to process and evaluate multiple opportunities, and learn from each of them. Hence, scenario planning is not the same as strategic planning. The latter focusses on a narrow range of issues and concentrates on developing a plan for a predictable future. In contrast, scenario planning includes multiple plausible future conditions, attempts to prepare for many different future conditions, and rather than focussing on 'a plan', focus is on 'the process'.

"Large infrastructure with a life-span of decades results in few opportunities for learning and may easily lead to 'lock-in' situations, and in these situations adaptive management is mainly limited to the operational level"[19]. This statement is directly applicable to construction of an MRS in the mining industry. The tendency in current practice is to increase the level of control for a design by moving towards an adaptive management approach[17], where a greater degree of risk is taken, with the intention of learning from and correcting throughout design and construction. It is tempting to assume that there is a high level of control while MRSs are being constructed, that trials can be performed, and monitoring data utilized. The reality is that for such large-scale infrastructure with decadal lifespans, there is little opportunity for design changes in latter phases of project planning, even less opportunity once a permit is received and further limited, if even possible, once construction has begun and water collection infrastructure is in place[17].

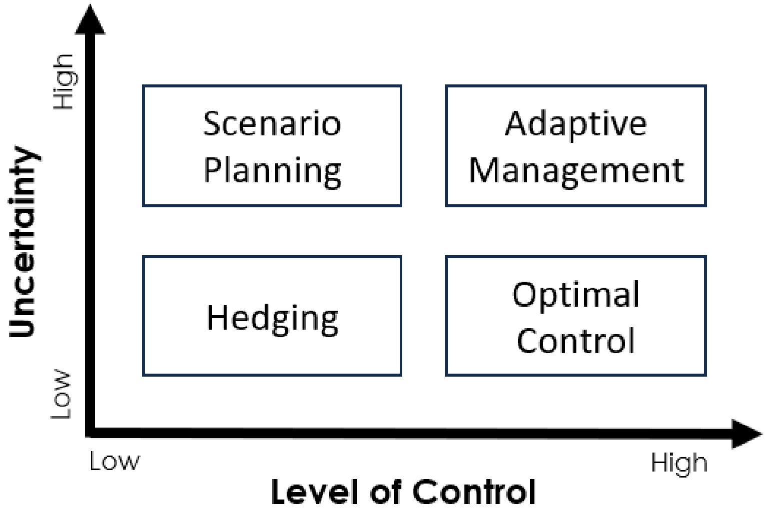

Figure 11: Level of control vs uncertainty[18].

As a result, adaptive management for conventional MRS construction typically occurs outside the footprint of the MRS, because of the high uncertainty in predicting water flow and water quality emanating from an MRS constructed with conventional methods. Hence, while it is reasonable to assume that there is relatively low uncertainty in water treatment technology (i.e., conventional water treatment is typically viewed as 'proven technology'), as shown in Figure 9, there remains relatively high uncertainty in collection, conveyance, and storage of water for subsequent treatment. These challenges are articulated transparently when discussing the 25 years of managing closure[20], and in particular the extent of infrastructure enhancement for water collection, conveyance and storage of contact water for subsequent treatment over that time period.

The opportunity that arises from designing and constructing an MRS with a focus on source control, as shown in Figure 9, is that prediction of seepage water flow and water quality has much lower uncertainty, thus making design and implementation of collection, conveyance, and storage of water of lower uncertainty. In simplest terms, the ability to predict seepage flow and quality for an MRS is much higher with an engineered MRS landform. Further, because oxygen re-supply is limited, and thus sulphide oxidation is limited, water quality of unrecoverable seepage will be substantially different i.e., better, than for an MRS constructed with conventional methods where re-supply of oxygen for sulphide oxidation is largely unlimited. Sulphide oxidation is reduced thus increasing the time for any available alkalinity within the MRS to react with pore-water, while also increasing contact and decreasing pore-water velocity. Even further, this may provide the opportunity to reduce the required recoverable-unrecoverable seepage ratio. Ideally this will also allow for a site to transition from active water treatment technology to semi-passive water treatment technology given that flow rates, and water quality of recoverable seepage, is vastly improved as compared to conventional MRS constructed seepage characteristics.

Referring to Figure 11, the focus for adaptive management is then within an MRS landform itself that is constructed with a focus on source control. One example of this, among many, would be enhancing the design of the horizontal engineering layers as ongoing performance monitoring during MRS construction may indicate the layer is not quite limiting airflow to the extent required, or decreasing lift height, and so on. In other words, elimination of the 'lock-in' situations[19].

Oxygen Ingress into Tailings Storage Facilities

Oxygen ingress into TSFs is mechanistically different compared to MRSs, due to the finer-textured tailings material, which is discussed further here.

A study was conducted by sampling and testing across the Joutel TSF in northern Quebec[21] measuring various parameters, including thickness of oxidized, hardpan, and transition zones in the tailings profile. The authors do not explicitly state oxidation depth(s) for this site, situated in a Dfc Köppen–Geiger climate classification (subarctic climate, boreal). However, they emphasize the presence of a hardpan layer close to the surface, which influences the oxidation process by limiting vertical water infiltration and affects the depth of oxidation in the tailings. An additional publication[22] explicitly identifies a hardpan horizon forming at depths of approximately 0.1m to 0.3m below the surface. The researchers state this layer results from precipitation of secondary minerals such as ferric oxyhydroxides and gypsum, acts as a barrier reducing porosity and permeability, thereby influencing the depth and progression of oxidation within the tailings profile.

Another study was conducted characterizing geochemical, mineralogical, and microbiological aspects of the Joutel TSF[23]. In this study, the researchers found sulphide oxidation reactions had proceeded to depths ranging from 0.2m to 1m below the tailings surface. Pyrrhotite rich tailings showed more extensive alteration compared to pyrite and arsenopyrite rich tailings. This study also reports that the most abundant sulphur-oxidizing bacteria were located 0.2m to 0.4m below the surface, coinciding with the absence of oxide coatings and a sharp decline in oxygen concentration, indicating active microbial-mediated oxidation at these depths.

The Joutel TSF studies illustrate that the depth of oxidation in the tailings varies, with oxidation fronts typically extending from approximately 0.1m to 1m below the surface over the approximately 25 to 30 years since tailings deposition ceased.

The Bell Mine was a porphyry copper-gold mine located close to Granisle, British Columbia, situated in a Dfc Köppen–Geiger climate classification. Mining at the site began in 1970, with milling starting in 1972; the site operated until 1992. A study reports that the tailings are potential acid generating (PAG) on the basis of a 1991 ML/ARD assessment, that the sulphide depletion rate was predicted to be 0.7m per year, and the acid front would advance 2m over a 10 year period[24]. Based on field data collected and analyzed some 20 years later, the authors state: i) *"the sulphide depletion rate was much slower than predicted"*, ii) *"observed neutralization potential depletion was much slower than predicted"*, and iii) *"the observed acid front was advancing much slower than predicted"*. Generally, all field measurements by the authors were based on samples taken within the upper 1m of tailings material. Hence, the oxidation depth in the tailings was far less than 1m, and more accurately, for the drained tailings profile (i.e., unsaturated), had advanced less than 0.5m at all locations measured over the 20 year period.

Authors report on pore-water chemistry and mineralogy of sulphide tailings within the Waite Amulet tailings impoundment near Noranda, Quebec, Canada[25], which is in a Dfb Köppen Geiger climate classification (humid continental climate). The mine ceased operations in the early 1970s, hence by the time of the author's study the tailings had drained and become unsaturated near surface and exposed to atmospheric conditions for approximately 25 years. At two different monitoring profiles, where the water table (phreatic surface) was approximately 2m below the tailings surface, oxygen concentration in pore-gas was 0% at depth ~0.5m below the surface, i.e., the oxidation front was at depth of 0.5m.

Tailings produced from a sedimentary exhalative (SEDEX) geologic system, which is particularly susceptible to acidity generation because of the abundance of sulfide minerals present relative to other geologic deposits also reports on sulphide oxidation depth[26]. This site is situated in a Dfc Köppen Geiger climate classification area (continental subarctic). This TSF received tailings from 1969 and 1998, but operated intermittently from 1982 to 1992, with final shutdown and cessation of tailings deposition in the TSF in 1998. Hence, the tailings have been exposed to atmospheric conditions for nearly 30 years. The authors of this publication estimate, based on field investigations, that over the nearly 30 years of atmospheric exposure the depth of the oxidation front in the tailings had advanced approximately 0.7m.

An Analogy for Oxygen Ingress into Mine Tailings Material

The preceding section presented unsaturated tailings oxidation front depths for TSFs over 20-to-30-year periods. While the list of sites presented is not exhaustive, and there are many more that could be listed, it is acknowledged that an extensive database for tailings material does not exist where the depth of oxidation, or rather the depth of an advancing oxidation front, has been measured and/or widely reported. However, an analogy can be utilized to gain further understanding of oxidation at depth as a result of oxygen ingress by diffusion; namely, the influencing factors for the depth of oxidation in geologic systems where chemical weathering has occurred over geologic time frames (i.e., the framework for exploring mineral deposits, interpreting climate history, and planning resource extraction). The influencing factors are not surprising: i) climate, ii) geology, and iii) hydrology influence oxidation depths of geologic systems. For example, in Saskatchewan, the depth of the oxidized zone, where minerals undergo chemical weathering and oxidation, varies considerably based on these three factors. In prairie regions of Saskatchewan, oxidation is typically confined to the upper soil layers (i.e., shallow), say on average perhaps 0.5m, and perhaps extending to 1.5m[27]. In regions of Saskatchewan with significant mineralization, such as the Athabasca Basin, oxidation extends deeper and up to perhaps 20m.

In the boreal forests of northern Alberta, the depth of geologic oxidation zones varies based on factors such as soil type, drainage, and permafrost presence[28]. For well drained uplands, oxidation depths in mineral soils can reach up to perhaps 2m (also influenced by microbial activity). For poorly drained lowlands, oxidation depths are limited to perhaps 0.3m.

Similar geologic oxidation depths are prevalent in the boreal forest of Quebec's Abitibi region[29]. This region is a historically significant mining district known for its gold, base metal, and volcanogenic massive sulfide (VMS) deposits. For these conditions, the typical geologic depth of oxidation generally ranges from 10m to 50m, and perhaps up to 100m depending on the influencing factors discussed earlier. In addition, the Archean volcanic, sedimentary and intrusive rocks of the region's greenstone belt, as well as extensive glaciation and post-glacial weathering, influence geologic oxidation depths.

In the Sonoran Desert of northwestern Mexico and extending into southwestern United States, which is a hot desert climate (Bwh Köppen Geiger climate classification), the depth of geologic oxidation zones varies significantly due to climate, topography, and mineralogy. In arid lowlands, oxidation depths can be minimal, confined to upper layers as a result of a hardened calcium carbonate layer. There is deeper geologic oxidation in mineralized zones, such as areas containing porphyry copper deposits; depths of 30m to 100m are common[30], depending on geology and the presence of sulphide minerals.

Cover Systems for Tailings Storage Facilities

The substantive knowledge of geologic oxidation depths, coupled with knowledge gained over the past 20 to 30 years on the depth of advancing oxidation fronts in tailings deposits, clearly points to tailings oxidation being a self-limiting mechanism. Further, during operations as one lift of tailings is placed on the other, atmospheric supply of oxygen to each underlying lift stops. It is only in very dry climate conditions that oxidation depths reach meters of depth; and even for these depths, it requires geologic time to reach these depths of oxidation.

Accordingly, in terms of conceptualizing oxidation of tailings in the mining industry, the presence of metals in mineral form within tailings must not be taken as being definitive to mobilize within tailings (i.e., oxidize to great depth), even when considering a timeframe of hundreds if not thousands of years into the future. Further, given typical TSF heights, and thus the thickness of tailings mass, as well as pore-water velocity, chemical attenuation mechanisms, and biological attenuation mechanisms, it must not be taken as definitive that metals released from their mineral form within tailings as a result of oxidation will be released into the environment (i.e., dissolved within vertical seepage from the footprint of a TSF).

The above conceptualization for tailings oxidation should lead a cover system designer to consider whether a cover system that manages oxygen ingress into tailings is required; the tailings material under the cover system is already self-limiting in respect to supplying oxygen to depth. This is not to state that oxygen ingress into tailings is not to be considered. Rather, it is to focus a cover system designer towards the most pronounced risk in respect of ML/ARD for tailings, which is likely not due to seepage from the tailings mass, but rather as a result of surface runoff from the landform, because net acidity and metals resulting from sulphide oxidation will be focused near the surface of the tailings landform. Hence, a cover system for a TSF should first consider management of surface water by isolating the tailings near surface pore-water conditions from adversely impacting surface runoff water quality. Additional considerations are as described earlier (i.e., tailings pore-water adversely influence plant water availability, vegetation rooting conditions, and permanent or ephemeral ponds on the TSF).

Discussion and Conclusions

This paper presents a robust, yet simple tool, to conceptualize performance of MRS and TSF landforms early in a mine development project, so that decisions on design that are incorporated into a project description or preliminary economic assessment are well informed. The framework is based on a hierarchy of engineering ease of conceptual model inputs; regional considerations and how the landform is constructed, and outputs; landform water balance and metal leaching, or in the case of geotechnical stability and landform stability (based on pore-water pressure regime from the landform water balance).

Perhaps equally as important, the conceptual model tool forces a designer at this early phase of project development to focus on accuracy, rather than focus on being precise, as is usually the case. Precision comes later in project development during pre-feasibility, feasibility, and detailed design. This conceptual model approach also provides a strong framework, and starting point, for pre-feasibility and feasibility studies, which will inevitably include numerical modelling.

Discussion on conceptualization of cover system performance for mine landforms included a similar hierarchy of 'engineering ease'; namely, climate, hydrogeologic conditions, materials, and vegetation. The differences in oxygen ingress into MRSs and TSFs was discussed in depth, resulting in a conceptualization that designers should strongly consider whether a cover system on tailings is needed to manage oxygen ingress, given that the tailings themselves are already self-limiting to oxygen ingress at depth.

In terms of MRS stockpile construction, it is concluded that early in project development, where inherently there is high uncertainty, and no specific understanding for the level of control to include into the design of an MRS, that designers must appreciate that decision making using a scenario planning approach is more prudent than focussing too quickly on a singular design path. Furthermore, in respect of MRS construction, build and MRS landform with a focus on source control (i.e., limiting re-supply of oxygen and thus sulphide oxidation) reduces uncertainty on seepage water flow and quality, thus reducing emphasis on reliance of cover systems and water collection, conveyance, storage and treatment to manage metal leaching and acid rock drainage risk during operations, closure, and post-closure.

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