

Climate Change and Mine Closure – A Practical Framework for Addressing Risk

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Abstract

The two largest disturbances mining presents which requiring addressing are disturbances to the water balance and energy balance; both of which will be influenced by climate change.

This paper presents a framework to incorporate climate change into mine closure planning from a risk perspective, as risk management will be a key component in decision making for mine closure designs. The newest Representative Concentration Pathway (RCP) emission scenarios allow for ranking climate change outcomes from “very likely” to “less likely” to occur. By combining the likelihood of occurrence for various climate outcomes with the magnitude of the potential failures, a risk based design criteria can be developed for each closure component. This paper will focus on cover systems as closure technology to illustrate application of the framework presented in this paper.

The creation of realistic and attainable design criteria begins on a conceptual framework, allowing non-technical persons to better understand complexities of detailed design. The framework presented utilizes the Köppen-Geiger climate classification system to differentiate climates, largely because of its ability to reflect seasonal differences. Boundaries are determined by a global dataset of long-term monthly precipitation and temperature records, which can be adapted to future climate change predictions. Understanding how climate is expected to change at a seasonal level is more valuable from a planning perspective than from an annual basis. Köppen-Geiger’s strong ties to landscape signals such as vegetation and water availability make it ideal for closure planning.

Implications for understanding the required equilibrium between the closure landscape and the existing landscape provide an indication of timescales involved. For example, it is not realistic to believe engineered structures will provide the expected performance following a glaciation event. Closure timeframes are typically 100 years, if not longer, therefore an appropriate framework to address the challenge of designing structures with defensible controls on identified risk is required.

Key words: Climate Change, conceptual design, cover systems.

Introduction

As with all engineering, in particular mine waste management, elements of a closure design are subject to failure and consequently have associated lifespans. To maximize longevity of designs, engineered systems have to be incorporated into landscapes to reach a long- term equilibrium. The two largest disturbances mining presents which require addressing are disturbances to water and energy balances. A mine typically features multiple mine closure domains, each with water and energy balances for creating design criteria. Climate change will act to change components of the water and energy balances and only through novel and innovative designs can one manipulate remaining water balance components to achieve the design criteria. Of fundamental importance, and the subject of this paper, is the overarching influence of site-specific climate conditions, more specifically a methodology for incorporating climate change on site-specific climate conditions for mine closure planning. To effectively plan for the next century and beyond, mine closure planning must incorporate climate change throughout its development.

Climate acts as stressor to designs when water balance components deviate beyond initial conditions towards a new equilibrium; one not anticipated and/or accounted for in the design. Generally, the more

closely a design, such as cover system design, is able to maintain equilibrium within the environment and climate, the greater the longevity. Suitably robust designs are therefore required to minimize imbalances through time, such as those imposed by climate change. Designs can be implemented to exploit or enhance attributes of the environment to make cover system designs more robust and resilient. For the purposes of this paper, a robust design refers to a system which can continue functioning in the presence of internal and external stressors without fundamental changes to the original system. In contrast, a resilient design is a system that can adapt to internal and external challenges by changing its method of operations while continuing to function. While components of the original system are present through time, there is a fundamental shift in mechanisms reflecting an adaptation to the new environment.

Therefore, to increase resilience and robustness in design, identification of dominant mechanisms of the cover system is required; then, climate change applied. In the context of climate change and the evolution of cover systems, designs will require a recognition that processes and mechanisms intrinsic to cover system function will evolve. Failure modes will be the result water balance components manifesting themselves in a way not supported by the cover systems design (i.e. runoff, evaporation, interflow, etc.).

Early recognition of risks climate change poses to designs will improve confidence in designs and allow refinement. Therefore, by introducing conceptual analysis of climate on conceptual designs, more front end loading is possible (Thomke and Fujimoto 2000). Here, the view is that design is an iterative process, driven by trial-and-error experiments that are guided by knowledge of underlying relationships between cause and effect. The more refined the starting scope of knowledge is, the more efficient a solution can be determined. To complete this task for mining landscapes, a framework must be used which communicates design risk under the influence of current and future climate.

Methods

The framework for incorporating climate change into mine closure planning as risk management tool will be a key component in decision making for closure designs. To evaluate risk, a formula such as Equation 1 must be considered.

$$Risk = Likelihood\ of\ Occurrence \times Consequence , \quad (1)$$

Likelihood:

Given that this tool will be used as a preliminary identification of risk, at a conceptual level, likelihood of occurrence can be qualitative measures based on the Representative Concentration Pathways (RCP) outlined by the IPCC (IPCC 2013). The IPCC attach no probability or likelihood of occurrence to the four different RCPs. The four scenarios are named after the radiative target forcing level for 2100, based on the forcing of greenhouse gases and other agents (Van Vuuren et al. 2011). These values are relative to pre-industrial levels with the lowest scenario, RCP2.6, requiring stringent global climate policies to limit emissions (Van Vuuren et al. 2011). Both RCP 4.5 and RCP6 represent forcing equating to several climate policies and most non climate policy respectively. The final scenario, RCP8.5, continues the current trend of increasing annual GHG emissions, representing the high range of non-action climate policy scenarios.

The RCPs can be qualified according to each designers/ stakeholders risk profile, however for the examples outlined in this paper, Figure 1 defines these likelihood qualifiers from “very likely” to “very unlikely” (Figure 1).

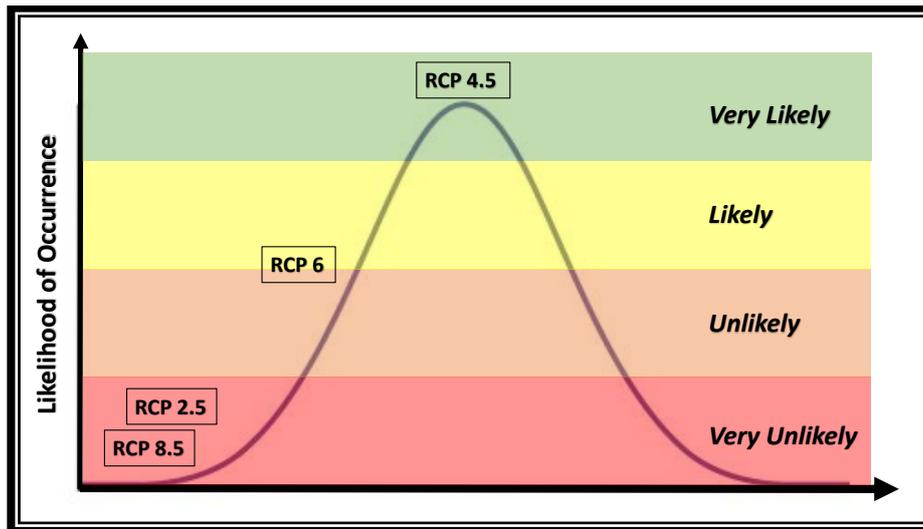


Figure 1 Proposed qualitative probabilities for using IPCC Representative Concentration Pathways (RCP) to evaluate risk at a conceptual evaluation stage.

Consequence:

Consequence of a specific failure is required to evaluate the risk of potential cover system designs. In terms of a consequence, it is defined as the qualitative performance metric assigned to the cover system. Typically for cover system design, control of net percolation (NP), oxygen ingress (O₂), and/or stability/erosion will be a design criteria. A continuum of performance for NP, O₂ and erosion rates for a cover system exists for different climate regimes. Within a single climatic regime, the same continuum may be a result of the influence of differing abilities of a cover system to evaporate water and to promote runoff from the landform. These mechanisms combined with attributes of the engineered design (i.e. landform and cover system) yield a performance metric based on climate.

Climate change stressors act on components of the water balance, which will differ for each mine location, between landforms and even across landforms. Conceptually understanding how changes in water balance components will influence design criteria is important because it will be these components that will be manipulated by designers to ensure design criteria for present and future climate are satisfied.

The continuum of cover system performance is presented conceptually in terms of “very low,” “low,” “moderate” and “high” NP, O₂ and erosion rates. The qualitative descriptors are common across sites and climates, although their nominal performance values will differ. For example, ‘very low’ NP for a cover system in a tropical climate will still exceed those for a cover providing very low rates in an arid environment.

By defining performance expectations in this qualitative way, designers will begin conceptually understanding early on, what realistic performance expectations are for a design based on climate. Once a conceptual basis for performance is understood, the consequences of not meeting the design criteria can then be assessed.

Therefore, a tool is required to assess the effects of climate on cover system hydrology at scales relevant to landform and cover system design. The Köppen-Geiger climate classification system (Köppen system) is such tool; capable of resolving differences in seasonal climate (Peel et al. 2007). It has been shown that utility of average annual conditions is limiting to cover system design, therefore incorporating seasonality provides a perspective landform hydrology (INAP 2016). Additionally, the Köppen system came into broad use largely through its strong connection to landscape vegetation signals, an important component for many cover system designs. Most sites have access to historical monthly precipitation and temperature data, or through a nearby meteorological organization.

Since the Köppen system system is defined by precipitation and temperature thresholds, it can be easily applied to global climate model output data to re-classify a site for future conditions. Climate change alters hydrology by changing the dominance or expression of certain mechanisms (i.e. runoff,

evaporation, etc.). Since the Köppen system can aid designers in understanding conceptually, dominant hydrological mechanisms required by the cover system, that same conceptualization can be applied to future conditions to investigate any differences required for cover system function. This early conceptualization refines design alternatives much earlier in the design process without the need for complex computer simulation. For example, if currently a cover system design is in the ‘very low’ range for NP performance, an increase to a ‘low’ or ‘moderate’ NP increases the consequence of that potential failure. With the likelihood and consequence determined, a conceptual form of risk can be qualified for a particular design into the future.

Risk:

By combining the likelihood of occurrence for various climate outcomes (RCPs) with the magnitude of the potential failures (i.e. ‘very low, ‘moderate’), a risk based design criteria can be developed for closure components (Figure 3).

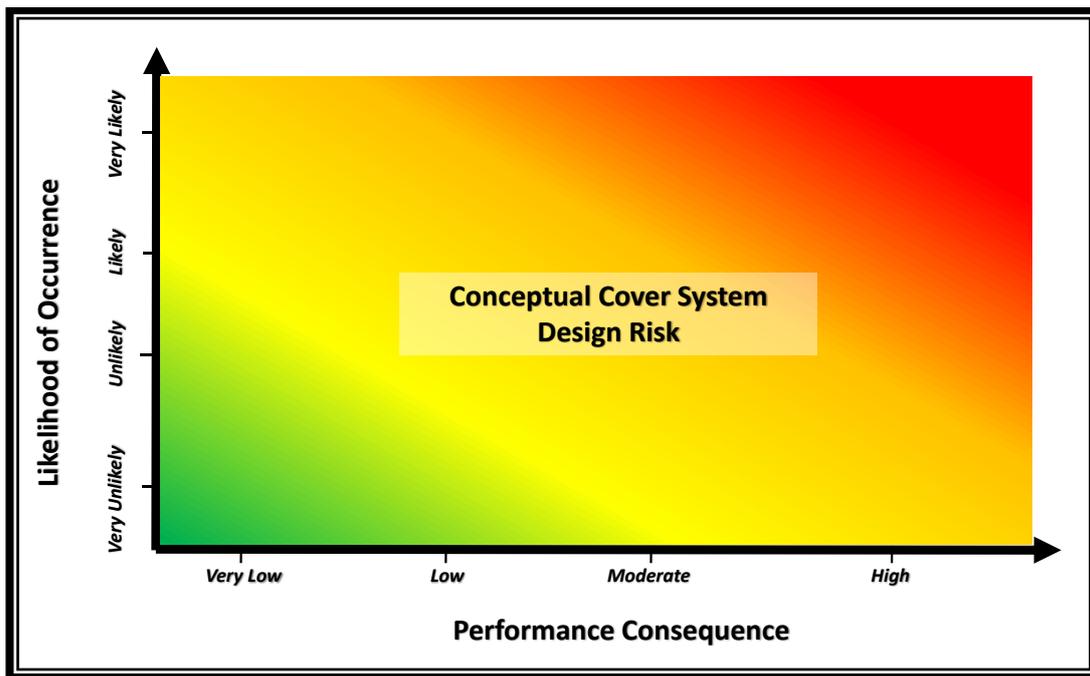


Figure 3 Qualitative risk assessment based on conceptual climate change understanding.

Although this approach can be applied to other mine closure activities, this paper focuses on cover systems. Once design risks have been identified, they may be deemed satisfactory by stakeholders, mitigated by additional design elements, or reduced through increased understanding. Activities such as field characterization programs may seek to reduce uncertainty in design elements, reducing risk. In this way, early conceptualization using a risk based approach helps focus future studies on only what is necessary.

This framework is able to incorporate climate change into mine closure planning from a risk perspective, as risk management will be a key component in decision making for mine closure designs.

Case Study- Temperate/Tropical Shift:

To demonstrate the framework’s utility for incorporating climate change in mine closure planning from a risk perspective, examples of its application, interpretation and result are presented. An example was selected based on prevalence throughout the mining industry in regards to climate, closure objectives and configuration. Generally, cover system design criteria focus on NP, O₂ and/or landform stability (erosion) and will be the focus the examples below.

Mining in South- Central Africa has long been a productive economy for resources such as copper, cobalt, gold zinc, lead, nickel, and iron to name a few. Countries such as Zimbabwe, Malawi and Zambia belong to geographies rich in these resources as well as mine waste. Zambia for example, contains ~77

million tonnes (388 ha) of waste rock and ~791 million tonnes of tailings (9125ha) (Environmental Council of Zambia 2004).

Likelihood ('Very Likely'):

These countries are located currently in what is classified as a humid subtropical climate (Cwa Köppen classification). Temperatures are considered intermediate with hottest months exceeding 10 °C and the coldest months between 18 °C and freezing. Summers are hot and coincide with the driest months which receive 10 % or less precipitation compared to wettest winter months. Figure 4 presents the range of climate scenarios possible for the region by 2075-2100. All future scenarios identify a shift to a tropical savannah climate. Therefore, a tropical savannah can be considered **'very likely'** to be expected if again we consider the RCP4.5 scenario.

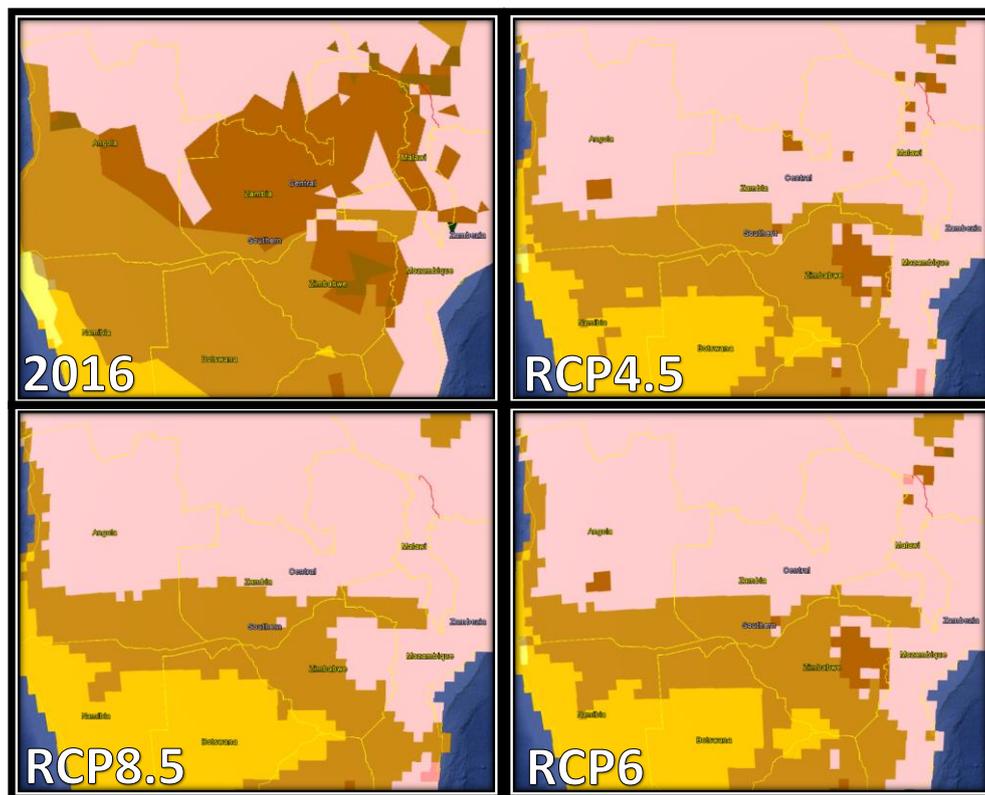
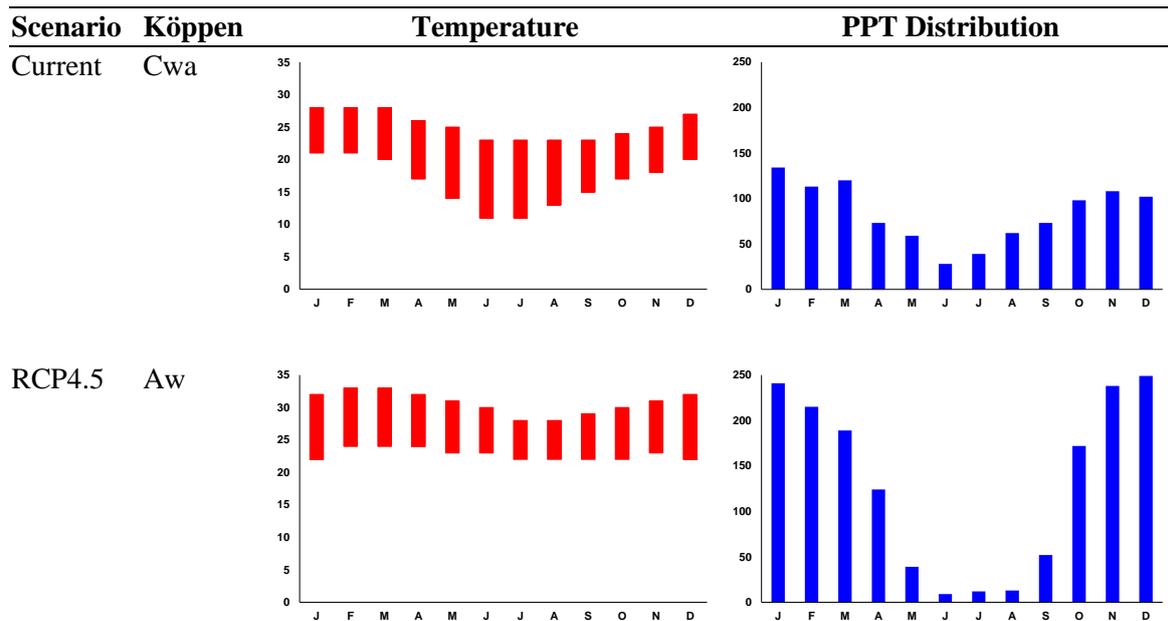


Figure 4 Köppen-Geiger climate classification for present and future climate change scenarios in Central Africa.

Consequence ('High'):

This early conceptualization for potential cover systems identifies that for parts of the year (winter), oxygen will be difficult to control due to the absence of water in the soil. Therefore, control of NP will be more appropriate as a design criteria of this cover system. Seasonal conceptualization is not possible when using annual averages, thus re-confirming the utility of the climate classification framework to be used in risk management. To further explore the predicted shifts in seasonal precipitation (PPT) and temperature regimes, Table 1 identifies key attributes of the climate expected to change most.

Table 1 Comparison of present and future climate for Zamia, Africa region.



A tropical savanna (Aw) climate has monthly mean temperatures above 18°C for every month with a pronounced dry season. In the tropical savanna climate there is a distinct dry winter season, and a wet summer season. In the future with an Aw climate, warmer temperatures prevail throughout the year, with loosely defined seasons. Consequently, potential evaporation can be expected to increase generally; not coinciding with a specific season. The most profound change in climate comes with large increases in precipitation (Table 1). Even though annual total PPT in this region is expected to increase by 50%, more applicable to mine closure planning is its distribution of the PPT throughout the year. An amplification of the bimodal distribution of monthly PPT signifies delivery of more water over shorter time periods to cover systems in the future.

To understand the consequence of this shift on future cover systems, a conceptualization of water balance components present and future is required. At present, a large range of cover system design alternatives exist to manage NP to a ‘very low’ or ‘low’ range for a temperate climate. Precipitation is relatively low compared to PE, thus store-and-release type cover systems are most practical to manage NP. However, without revision to the cover system design that accounts for future climate, the water balance components change. With PE increasing slightly over time in response to warming, precipitation increases though, un-proportionally. This discrepancy in PE and PPT has large implications for water the management involving cover systems.

With a surplus of water on the landform, it is diverted to runoff and/or transmitted as NP into underlying waste material. Conceptually, erosion and NP consequences have been identified. If only NP is considered, the difference in PPT and PE translates to a proportional increase in NP.

The original cover system design criteria under current climate may stipulate achieving very low to low NP was necessary. However, it is clear that by conceptually applying climate change to the same cover system, achieving a NP control in that range will no longer be possible without revisions to the design. More likely is that NP consequence will be ‘moderate’ to **‘high’**

Risk:

When risk is re assessed for the climate change scenario by taking the ‘very likely’ from the likelihood and agreement across all RCP scenarios and combining this with consequence of ‘high’ we end up in a zone of Very High Risk for this design in the future even though the design in the present climate represents a low risk (Figure 5).

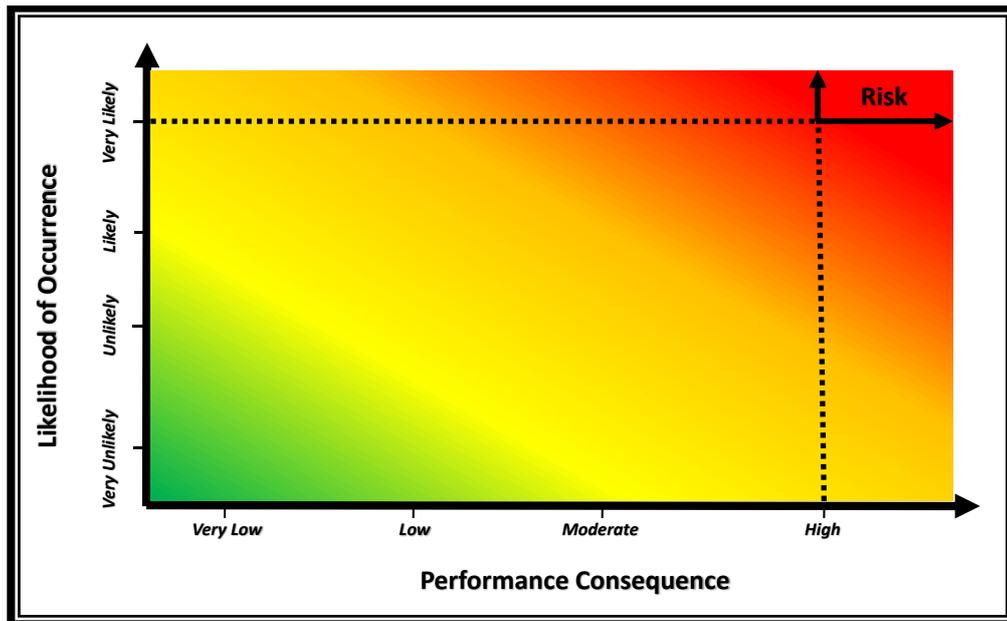


Figure 5 Qualitative risk assessment for case study example.

Given the risk ranking has materially increased in the climate change scenario, mechanisms of “failure modes” can be explored to determine what this increase in risk means for design, as well as assessment of design alternatives. By investigating this risk through potential failure modes, we are thus able to identify the mechanisms of the cover system contributing to a large amount of the risk. Those two mechanisms identified in this case are runoff and NP and the consequences for closure risk management are erosion and increased seepage. The realization of these risks will therefore depend on elements of landform design and thus landform design alternatives can then assessed based on the identified mechanisms that require management of risk:

- The exploitation of vegetation to help mitigate both erosion and NP can be explored given the potentially favorable climate that is considered as part of the climate change scenario. Vegetation changes over time need to be balanced with looking at performance over the short to medium term (or even current conditions) to determine if reliance on vegetation is appropriate as a risk management toll over both medium and long time scale as vegetation evolves and begins to take hold.
- The use of an engineered barrier technology can be considered to reduce NP can be explored, in this case the increased drying and wetting cycles inferred in the climate change scenario would reduce the likely performance of compacted clay layer technology and the associated effectiveness into the future. Geomembranes may be more appropriate than compacted clay technology, however, the use of this technology would then necessitate the use of surface and sub surface engineered drainage to transmit the higher precipitation event storms laterally off the landform that would otherwise cause erosion.
- Consideration of a variation on the existing design can also be explored, in this case thicker enhanced store and release cover systems with the aim to maximize the evaporative potential by keeping water accessible by increasing field capacity, and therefore reducing NP. This thickening would offer a larger potential for vegetation support which will be a necessary component to manage runoff induced erosion with the future precipitation regime.

As is evident, by combining conceptual components of future climate change effects and cover system performance, the framework presented allows for more detailed work such as modelling, to begin from a more informed perspective, yielding a more robust design informed by risk.

Conclusions

The creation of realistic and attainable design criteria first begins on a conceptual framework, allowing non-technical persons involved in closure planning to better understand complexities of detailed design. The framework presented within this paper utilizes the Köppen-Geiger climate classification system to differentiate climates, largely because of its ability to reflect seasonal differences. The framework is determined by a global dataset of long-term monthly precipitation and temperature records, which have incorporated the potential effects of future climate change predictions. Understanding how climate is expected to change at a seasonal level is more valuable from a planning perspective than from a strictly annual basis.

Implications for understanding the required equilibrium between the closure landscape and the existing landscape provide an indication of timescales involved. For example, it is not realistic to believe engineered structures will provide the expected performance following a glaciation event. However, given that closure timeframes are typically 100 years, if not longer, an appropriate framework to address the challenge of designing structures with defensible controls on identified risk is required.

Climate change is taken into account in a variety of mining projects. Approaches to incorporate climate change into closure design differ from site to site and are often limited in temporal length. There are currently no clear guidelines as to how to take into account climate change for the long term prediction of closure systems performance. What is presented in this paper is a conceptual tool that provides a greater awareness of climate change and its effects as it pertains to the management of water resources in the context of mine closure design and cover system technologies.

As is evident, by combining conceptual components of future climate change effects and cover system performance, the framework presented allows for more detailed work such as modelling, to begin from a more informed perspective, yielding a more robust design informed by risk. This mechanism allows a return full circle to ensure resilient design

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