Risk Management for Tailings Dam Safety: Considerations for Long-term and Post-closure Timelines

by

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ABSTRACT

Post-closure tailings dams are expected to remain on mine sites in perpetuity following mine closure. Combined with the lack of knowledge regarding how tailings dams will evolve over time, these long-time frames necessitate the development of risk management practices. The purpose of this research was to develop methodology to support the process of determining and assessing the long-term risks of tailings dams in Alberta as they transition into landforms. The research project evaluated the state of knowledge on the long-term behaviour of tailings dams and demonstrated the knowledge gap (and associated uncertainty) associated with the closure phase of a tailings dam. To address this, a risk management tool, referred to as the Generalized Failure Modes Effects Analysis (G-FMEA) framework, was developed. The G-FMEA framework was applied to a case study oil sands tailings dam to illustrate an example application for practitioners. Finally, seepage analysis was conducted on the case study oil sands tailings dam to demonstrate how modelling tools can be used in conjunction with risk management tools to reduce uncertainty.

To aid in the development of the G-FMEA framework, a detailed literature review and interviews with industry professionals were conducted. This process allowed for available information on the physical performance of tailings dams undergoing closure in Canada to be synthesized. Further, it allowed for the identification of hazards, triggers, failure modes, and uncertainties associated with tailings dam closure, which was a key element to the G-FMEA development. The interviews themselves clearly showed the lack of consensus amongst practitioners regarding long-term dam evolution. This emphasizes the uncertainty associated with closure and is a primary reason why comprehensive risk management practices must be developed.

The developed G-FMEA framework uses an element approach to conduct the FMEA, which allows for the relationships between different elements to be established. The G-FMEA framework includes four individual charts for the drainage system, foundation, dam body, and landform to assess the failure modes, triggers/causes, and failure effects for different elements. The G-FMEA framework requires the risk assessment to be conducted at four different temporal scales (immediate term, short term, medium term, and long term) that are anchored to different periods of management of the facility. A risk matrix was developed for use with the G-FMEA, which includes a likelihood rating table, consequence rating table, and risk rating table. The developed G-FMEA framework provides a systematic method to assess the risks following closure of tailings dams. The G-FMEA framework was applied to a case study oil sands tailings dam to illustrate how the framework could be used in practice. Two example failure modes were selected to show how the risk matrix could be used to assign risk ratings. For both of the example failure modes, the risk rating increased as the temporal scale increased, which is partially attributed to the increasing uncertainty over time.

Long-term seepage modelling was conducted on a case study oil sands tailings dam to evaluate how the phreatic surface may evolve in response to various factors (drain failure, pond formation, downstream slope erosion, and climate change). The results suggest that the phreatic surface has the potential to rise in the long term in response to different events, including drain failure and ponds forming on the reclamation surface. The seepage modelling was used to show how modelling could be used to inform risk management decisions by reducing uncertainty and allowed for the development of a framework for guidance on conducting long-term seepage modelling.

PREFACE

The research project, of which this thesis is a part of, received research ethics approval to conduct interviews from the University of Alberta Research Ethics Board (Project Name "Long-term behaviour of tailings dams after closure: implications for dam safety risk", Project No. Pro00079727; Approval: March 21, 2018).

Some of the research conducted for this thesis was completed through collaboration with others. Several chapters of this thesis were reproduced from publications (with modifications). The publications and author contributions for each chapter, included the following:

Chapter 3:

Schafer, H.L., Beier, N.A., and Macciotta, R. 2019. Closure and the Long-term Behaviour of Tailings Dams: Using Industry Experience to Fill in the Gaps. *In* Proceedings of the 72nd Canadian Geotechnical Conference. St. John's, Newfoundland, Canada, 29 September-2 October 2019.

Schafer, H.L., Macciotta, R., and Beier, N.A. 2020. Tailings dam closure scenarios, risk communication, monitoring, and surveillance in Alberta. CIM Journal, **11**(1): 80–90. Taylor & Francis. doi:10.1080/19236026.2020.1734406.

These two publications summarize the results of the interviews conducted as part of this research. I developed the interview protocol for the interviews, applied for Research Ethics Board approval, and conducted the interviews. Dr. Neeltje Slingerland participated in conducting some of the interviews. I compiled and evaluated all of the interview results and was responsible for the manuscript preparation for both publications. Dr. Nicholas Beier and Dr. Renato Macciotta contributed to review of the interview protocol and the Research Ethics Board application. They were also responsible for editing and review of the manuscripts.

Chapter 4:

Schafer, H.L., Beier, N.A., and Macciotta, R. 2021. A Failure Modes and Effects Analysis Framework for Assessing Geotechnical Risks of Tailings Dam Closure. Minerals, **11**(11): 1–35. doi:10.3390/ min11111234.

I developed the Generalized Failure Modes Effects Analysis framework and was responsible for the manuscript development. Dr. Beier and Dr. Macciotta edited and reviewed the manscript.

Chapter 5:

Schafer, H.L., Beier, N.A., and Macciotta, R. 2022. Applying a Generalized FMEA Framework to an Oil Sands Tailings Dam Closure Plan in Alberta, Canada. Minerals, **12**(3): 1-52. doi:10.3390/min12030293.

I applied the Generalized Failure Modes Effects Analysis framework to a case study site and was responsible for the manuscript development. Dr. Beier and Dr. Macciotta edited and reviewed the manscript.

Chapter 6:

Chapter 6 included a review of available dam safety reports for closed tailings storage facilities in British Columbia. Abigail Paul conducted an initial review of some of the sites and developed compilation summaries. I reviewed and interpreted Abigail Paul's summaries and expanded on them to incorporate additional sites and information. The remainder of Chapter 6 consisted of seepage modelling, which I was responsible for.

DEDICATION

To my husband and son

“From the head to the heart, you take me on a journey of letting go and getting lost in you”

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Two events have shaped my PhD experience as a whole: becoming a mom and a global pandemic. Because of this, my most important thank you goes to my husband, Matt, and my son, Blake. Thank you, Matt, for being the most amazing work from home partner (and partner in general), incredible dad, and my overall very best friend. Thank you for always engaging in tailings dam talk at the dinner table, for the countless hours spent quizzing me for my candidacy exam, and for always challenging my views.

Blake, you are a true light. More than anything, you have taught me about patience, perseverance, and determination. You have lifted me up when I am down, simply by giggling. Thank you for being a never-ending source of joy.

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Thank you to Scott Martens (Canadian Natural Resources Ltd.) and Tim Eaton (Alberta Energy Regulator) for their ongoing support throughout this research, including countless meetings, extensive review, and sharing your passion for responsible tailings dam management and closure.

Thank you to my colleagues and friends: Rima, Hilary, and Kevin. I wish I could have been back at the University following my maternity leave for many more coffee breaks and lunch dates. Thank you for shaping the early years of this program and making it so much more enjoyable. A special thanks to my undergraduate engineering friend group who have listened to me talk about tailings dams (and pretended to care), encouraged me, and laughed with me throughout this program.

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I am grateful for the financial support from scholarships that allowed me to focus full-time on my research. This includes the Vanier Canada Graduate Scholarship, University of Alberta President's Doctoral Prize of Distinction, University of Alberta Completion Scholarship, Golder Associates Mine Closure Scholarship, Coal Mining Research Company Graduate Scholarship, Canadian Foundation for Geotechnique Michael Bozozuk National Graduate Scholarship, Canadian Dam Association Gary Salmon Memorial Scholarship, and the University of Alberta Doctoral Recruitment Scholarship. A special thanks to the Vanier Canada Graduate Scholarship that allowed me the opportunity to take a parental leave during my program.

I am also grateful that I was able to be a part of the Dam Safety Research Program Creative Sentence that allowed me many opportunities from financial to field visits to interviewing fascinating industry professionals, without which this research would not have been possible. Lastly, I am thankful to the oil sands operator who provided the data necessary to perform the site specific case study application of the G-FMEA and the seepage modelling.

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LIST OF SYMBOLS AND ACRONYMS

θ	Volumetric water content
1D	One-dimensional
2D	Two-dimensional
3D	Three-dimensional
AER	Alberta Energy Regulator
ALARP	As low as reasonably practicable
ARD	Acid rock drainage
BAW	Beach above water
BBW	Beach below water
CDA	Canadian Dam Association
CST	Coarse sand tailings
CT	Composite tailings
CTMC	Consortium of Tailings Management Consultants
DIAC	Dam Integrity Advisory Committee
DOE	Department of Energy
DSI	Dam safety inspection
EPL	End pit lake
ETA	Event tree analysis
ETF	External tailings facility
FERC	Federal Energy Regulator Commission
FFT	Fluid fine tailings
FM	Failure mode
FMEA	Failure modes effects analysis
FMECA	Failure modes effects criticality analysis
FTA	Fault tree analysis
GCM	Global climate model
G-FMEA	Generalized failure modes effects analysis
H	Total head
HAZOP	Hazard and operability study
HDPE	High density polyethylene
H_m	Measured head
h_s	Simulated head
i	Gradient of total hydraulic head
IBA	Impact Benefit Agreement
ICOLD	International Commission on Large Dams
IEC	International Electrotechnical Commission
ILTT	In-line thickened tailings
INAP	International Network for Acid Prevention
IPCC	Intergovernmental Panel on Climate Change

ISO	International Organization for Standardization
ISSMGE	International Society of Soil Mechanics and Geotechnical Engineering
k	Hydraulic conductivity
k_{sat}	Saturated hydraulic conductivity
k_x	Hydraulic conductivity in the x-direction
k_y	Hydraulic conductivity in the y-direction
LCI	Land climate interaction
LDI	Landform Design Institute
LEM	Landscape evolution modelling
LOPA	Layers of protection analysis
LOS	Lean oil sands
MAC	Mining Association of Canada
MAE	Residual mean absolute error
ME	Residual mean error
MEND	Mine Environment Neutral Drainage
MFT	Mature fine tailings
MLSB	Mildred Lake Settling Basin
NOAMI	National Orphaned/Abandoned Mines Initiative
NRCAN	Natural Resources Canada
NST	Non-segregating tailings
OSTC	Oil Sands Tailings Consortium
OSTDC	Oil Sands Tailings Dam Committee
PFMA	Potential failure modes assessment
PMF	Probable maximum flood
PoF	Probability of failure
PRA	Probabilistic risk analysis
PrHA	Preliminary hazard assessment
PWP	Porewater pressure
q	Specific discharge
Q	Applied boundary flux
r	Residual
RCA	Root cause analysis
RCP	Representative concentration pathways
REB	Research and ethics board
RMSE	Root mean squared error
SA	Scenario analysis
SAGD	Steam-assisted gravity drainage
SFR	Sand to fines ratio
SWCC	Soil water characteristic curve

SWIFT	Structured ‘what-if’ technique
t	Time
TFT	Thin fine tailings
TMF	Tailings management facility
TSF	Tailings storage facility
UMTRA	Uranium Mill Tailings Remedial Action
UMTRCA	Uranium Mill Tailings Radiation Control Act
USACE	US Army Corps of Engineers
VWP	Vibrating wire piezometer
WISE	World Information Service on Energy
WT	Whole tailings

1 INTRODUCTION

The purpose of the research is to develop methodology to support determining and assessing the long-term risks associated with tailings dams as they transition into a landform. Tailings dams have historically been designed to account for geotechnical failure modes that could occur during the mine's active life with little consideration given to the post-closure time frame. This historical approach has resulted in many tailings dams that are in a poor position for closure with limited information on how they may change and evolve over time. Consequently, there are significant uncertainties associated with closure and decommissioning of tailings dams. This research will aid in closing the knowledge gap surrounding the decommissioning of tailings dams with the intention of producing a risk assessment tool for practitioners to improve public safety and environmental protection by reducing the probability of failure. Ultimately, this will allow the long-term risks associated with tailings dams to be evaluated and managed such that the design can account for these risks. This research is a result of the Dam Safety Research Project creative sentence that originated from a tailings dam failure at the Obed Mountain Coal Mine.

1.1 Background

The mining process produces large volumes of waste known as tailings that generally consist of different combinations of sand, fines, and water (McRoberts 2008). The tailings are stored in containment structures referred to as tailings storage facilities (TSFs). The most common type of TSF consists of aboveground tailings dams that contain tailings ponds, referred to as external tailings facilities (ETFs). These structures are often constructed at the onset of mining when revenue is low. Combined with the fact that these structures do not generate profit, they tend to be constructed with the overburden and low-grade ore from mining or with tailings. This results in variation in the construction materials, which further complicates design and closure. These structures can have heights greater than 100 m with surface areas significantly larger than 100 km^2 (ICOLD Tailings Dam Committee 2013). The large footprints allow for the containment of large volumes of potentially mobile tailings that vary in chemical and physical composition and often contain high concentrations of heavy metals, salts, and other contaminants (Hancock and Willgoose 2004). As a result, tailings dams pose a significant design challenge and are a public and environmental hazard. This is clearly shown by a number of recent tailings dam failures, including the Brumadinho failure in Brazil in 2019, the Fundão Dam failure in Brazil in 2015, the Mount Polley failure in British Columbia in 2014, and the Obed Mountain Coal Mine failure in Alberta in 2013 (Cooke et al. 2016, Vick 2017, WISE Uranium Project 2020).

Following the closure of a mine, tailings dams remain on the site, eventually becoming part of the landscape. In general, these structures are designed by geotechnical engineers with consideration of failure mechanisms that can occur during the mine's active life, which is significantly shorter than the life of the tailings structure. This is problematic as failure of these structures can still occur long after the closure of a mine site, causing fatalities and extensive contamination. Further, the importance of reclamation and decommissioning through the processes of sustainable mining practice is a relatively recent development in the mining industry. Despite this, there is limited information regarding how a tailings dam ages in perpetuity. This knowledge gap poses an unprecedented environmental, public, and financial risk, especially when combined with the serious consequences associated with the failure of tailings dams. As a result, it is vital that the long-term behaviour and the associated risks of tailings dams be understood and incorporated into the design.

In Alberta, the mining industry consists primarily of coal and oil sands extraction. The mines are at varying points in their life cycles and may have tailings dams being constructed, operated, progressively reclaimed, or in the final stages of closure works. Consequently, this research is well-timed as it aims to respond to the identified knowledge gap regarding the long-term behaviour of tailings dams through the development of a structured risk assessment tool for assessing the long-term risks associated with these facilities. This tool will provide insight into the long-term behaviour of tailings dams by providing a reasonably comprehensive evaluation of long-term failure modes.

1.2 Obed Mountain Coal Mine Failure and Creative Sentencing

This research is part of the Dam Safety Research Project – a project formed from one of the creative sentences originating from the tailings dam failure at Obed Mountain Coal Mine near Hinton, Alberta (Provincial Court of Alberta 2017a). With creative sentencing, a company found guilty of an environmental offence is penalized, whereby the penalty is used to benefit the environment. The tailings dam failure resulted in the release of about 670,000 m^3 of waste water and 90,000 tonnes of sediment into two tributaries of the Athabasca River (Provincial Court of Alberta 2017b). When the failure occurred, the mine was classified as being in a period of care and maintenance, where operations had been suspended due to poor economic conditions. This failure demonstrates the importance of long-term risk management of tailings dams.

1.3 Research Objectives

In Alberta, there are tailings dams at varying stages of their life cycles, with some in the process of being progressively reclaimed or nearing the final stages of closure works. There is significant uncertainty associated with how these facilities will evolve over time, especially when combined with the long-time frames associated with closure. This poses a risk to the environment and the public given the serious consequences associated with failure. As a result, the purpose of this research is to develop a framework to support determining and assessing the long-term risks associated with tailings dams in Alberta for coal and oil sands mines as they transition into a landform. To achieve this purpose, the research project was broken down into the following objectives:

1. Synthesize available information on the physical performance of tailings dams undergoing closure in Canada.
2. Identify the broad potential failure modes and largest uncertainties associated with closure of tailings dams in Alberta, based on polling opinions of industry professionals.
3. Develop a risk-based tool to aid decision-making for tailings dam closure strategies and assessment, based on the widely applied failure modes effects analysis (FMEA) method (referred to as the Generalized-FMEA (G-FMEA)).
4. Illustrate the application of the G-FMEA for a typical tailings dam in Alberta to provide an example application for practitioners.
5. Demonstrate how the phreatic surface in a tailings dam may evolve over time using seepage modelling to illustrate a method that could be used to reduce uncertainty in the G-FMEA.

1.4 Methodology

The research methodology varied for each research objective. Objective 1 and 2 involved a comprehensive literature review and interviews with industry professionals to learn from their experiences. This required the development of an interview protocol, application to conduct the interviews with the Research and Ethics Board (REB), recruitment of interviewees, and assessment of the interview responses to develop themes and conclusions.

Objective 3 utilized the interview results, a detailed literature review, brainstorming sessions, and hazard mapping to develop a comprehensive system definition and hazard and trigger list. In combination with the fundamentals of failure modes effects analysis, this was used to develop the risk assessment tool, referred to as the Generalized Failure Modes and Effects Analysis (G-FMEA) framework. The framework was developed for use by industry professionals and incorporates different time frames to account for potential long-term behaviour scenarios (changes to hazards, triggers, and failure modes over time).

Objective 4 used the detailed methodology from Objective 3 to demonstrate how the G-FMEA framework could be used in practice on a case study tailings dam in Alberta to aid in making risk-informed decisions about tailings dam closure.

Objective 5 employed seepage modelling on a case study site to demonstrate how the phreatic surface of a tailings dam may respond to long-term system changes. Combined with a literature review, this was used to provide detailed guidance on areas of uncertainty that may impact the ability to forecast the long-term phreatic surface and recommendations for what information must be collected and considered when making assumptions about the phreatic surface. Objective 5 demonstrates how modelling may be used to support the G-FMEA.

1.5 Thesis Organization

The thesis is a hybrid of a traditional and a paper-based format and includes seven chapters. Paper-based chapters (Chapter 3, 4, and 5) include precursory statements. Chapter 1 introduces the research problem, provides background information, and describes the research objectives and methodology.

Chapter 2 provides a literature review relevant to the research objectives. Chapter 3 summarizes the results of the interviews and includes a journal paper that was published in CIM journal and a conference paper that was published in the 2019 Canadian Geotechnical Conference.

Chapter 4 summarizes the development of the risk assessment tool (the G-FMEA framework). This work was published in the Minerals Journal in the Tailings Dams: Design Characterization, Monitoring, and Risk Assessment Special Issue.

Chapter 5 demonstrates how the G-FMEA framework can be applied to a case study tailings dam and shows the implications to the processes of tailings dam closure. This work was published in the Minerals Journal in the Tailings Dams: Design Characterization, Monitoring, and Risk Assessment Special Issue.

Chapter 6 provides an assessment of the long-term development of phreatic surfaces in a tailings dam.

Chapter 7 provides final conclusions to the thesis, a summary of contributions, and recommendations for future research.

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2 LITERATURE REVIEW

2.1 General

This chapter provides a summary of literature relevant to this research project. The terminology used in this research study is summarized to provide clarity for the remainder of the research. The mining industry in Alberta is discussed to provide context for the research. Available literature on the long-term behaviour of tailings dams is reviewed to identify specific knowledge gaps. The concept of risk management of tailings dams is reviewed, including a discussion on failure modes effects analysis (FMEA) and risk matrices. Finally, literature related to seepage modelling approaches is introduced.

2.2 Life Phases of a Tailings Dam

Various organizations define the life phases of a tailings dam differently. These phases aid in supporting and defining the dam de-registration framework. The differences between organizations have important implications as it can result in confusion in the industry when approaching closure. The beginning phases (site selection and design to construction to operation) are all similar, but deviate when closure is initiated.

The Mining Association of Canada (MAC) (2019) has broken down the life of a TSF into six phases: project conception and planning, design, initial construction, operations and ongoing construction, standby care and maintenance, closure, and post-closure. In this case, closure is defined as beginning when tailings are no longer deposited into the facility (MAC 2019). At this point, key aspects of the closure plan are implemented, which includes: transitioning operations to permanent closure; removal of key infrastructure on site; changes to water management or treatment; and re-contouring or re-vegetation of tailings and any containment structures (MAC 2019). The post-closure phase then begins when this decommissioning work is completed, key aspects of the closure plan have been implemented, and the facility has transitioned to a state of long-term surveillance and maintenance (MAC 2019). MAC (2019) notes that a tailings dam could be transferred back to the regulator during this phase. MAC (2019) provides detailed guidance on managing TSFs during these stages, but states that different jurisdictions may have different regulatory requirements that should be followed.

The International Commission on Large Dams (ICOLD) Tailings Dam Committee (2013) focused on the post-closure phase, which is defined as the period following the completion of tailings dam operation into its final form. This phase is further divided into an active and passive care period. The active care period in this case is the period where active intervention and monitoring are required to achieve a final sustainable form (ICOLD Tailings Dam Committee 2013). During this period, monitoring is used to show that the tailings dam is fulfilling the requirements of the final closure design (ICOLD Tailings Dam Committee 2013). After the tailings dam has proven to adhere to the closure objectives, the passive care period commences. ICOLD Tailings Dam Committee (2013) notes that this period has no set time limit and will continue until the relevant authorities determine that the tailings dam is physically, chemically, ecologically, and socially stable and no longer poses a risk to life or to the environment. During the passive care period, some monitoring is still typically required to show that the tailings dam is fulfilling the closure requirements over time (ICOLD Tailings Dam Committee 2013). Following the passive care period, the tailings structure should no longer pose a risk to life or to the environment without active or ongoing monitoring (ICOLD Tailings Dam Committee 2013). Unfortunately, most tailings dams require some degree of long-term monitoring following passive care.

The Canadian Dam Association (CDA) (2014) has broken down the life of a tailings dam into seven phases, including: site selection and design, construction, operation, transition, closure – active care, closure – passive care, and landform. CDA (2014) defines closure as:

> *"Closure is the process of establishing a configuration for the dam with the objective of achieving long term physical, chemical, ecological, and social stability and a sustainable, environmentally appropriate after use. This configuration can be achieved during or after mine operations."*

CDA (2014) notes that there is a difference between reclamation/rehabilitation and decommissioning where reclamation/rehabilitation refer to modifications of a tailings dam to meet the closure objectives. In contrast, decommissioning refers to the closure of a tailings dam, including removing or breaching the dam so that it does not contain tailings or water (CDA 2014). According to CDA (2014), closure includes three periods: transition, active care, and passive care. The transition period begins when the tailings dam reaches capacity and is no longer receiving tailings or when the mine is closed permanently (CDA 2014). The purpose of this phase is to prepare the tailings dam for the active and passive care periods through intervention and may involve the following activities: breaching the dam; modifying the dam, spillway or discharge structures to accommodate a water cover or water treatment system; or modifying the dam, spillway, or discharge structure to remove a pond and not allow a pond to remain on the surface while still safely accommodating floods (CDA 2014). During the transition phase, if it can be proven that the material contained by the tailings dam is not liquefiable and will not flow in the case of a breach, then it will no longer be considered a dam (CDA 2014). The transition period may take anywhere from one year to decades to complete (CDA 2014). The active care period will begin when the measures required for closure (including modifications) have been implemented (CDA 2014). The active care period may take anywhere from decades to centuries to complete and includes monitoring, inspection, water management, and operation of any water treatment system with limited intervention (CDA 2014). During the active care phase, the tailings dam should achieve a steady state condition with respect to porewater pressures, deformations, and erosion at which point the dam could potentially move into the passive care period (CDA 2014). In the passive care period, there is no active operation or changes to the tailings dam and the dam is considered to be in a steady state (CDA 2014). This period is expected to require limited maintenance and monitoring; however, it will still require some level of inspection, dam safety reviews, and emergency response and may last for hundreds of years (CDA 2014). During this period, the dam may be eligible for transfer back to the crown if allowed by the jurisdictional authorities (CDA 2014). Ideally, a tailings dam could be designed and constructed to become a landform that would no longer be considered a dam and would no longer require regulatory oversight (CDA 2014).

Oil Sands Tailings Dam Committee (OSTDC) (2014) breaks the life of a tailings dam into nine phases, including: mine planning and site selection, design, construction, operation, cessation of operation, active care, passive care, reclamation, and certification as public land. Throughout these phases, the OSTDC (2014) considers a transition in the state of the tailings structure from a tailings dam to a landform as an indication of the progression of the life of the TSF. The facility is considered a tailings dam from mine planning and site selection to the end of operations. The cessation of operations phase begins when the active tailings dam transitions into a non-operating dam where it is no longer actively receiving tailings, but the water level in the dam may still need to be controlled (OSTDC 2014). Following the cessation of operations, the structure will enter a decommissioning phase where intervention is used to convert the dam into a solid earthen structure such that it no longer meets the definition of a dam (OSTDC 2014). The decommissioning phase includes the active and the passive care period. The active care period involves monitoring and intervention measures to achieve a final solid earthen structure (OSTDC 2014). According to OSTDC (2014), a structure can move into the passive care period once it has been de-licensed and is no longer considered a dam, but instead has been classified as a solid earthen structure. During the passive care period, the performance of the solid earthen structure is monitored to ensure it satisfies the closure objectives (OSTDC 2014). It should be noted that this period has no set time limit, but instead will continue for as long as is necessary to prove that the structure is physically, chemically, and ecologically stable with a performance and a residual risk that is compatible with the surrounding environment (OSTDC 2014). Following the passive care phase, the structure may move through the final reclamation phase to prepare for qualification for certification as a landform so that it may receive a Reclamation Certificate (OSTDC 2014). During the reclamation phase, the structure will no longer be classified as a solid earthen structure, but will instead be referred to as a landform. When the landform meets the provincial and federal closure criteria, it may be able to obtain a Reclamation Certificate from the regulator at which point the land is transferred back to the Crown as public land (OSTDC 2014).

As discussed, these organizations all have similar beginning phases but deviate in terms of the life phases at closure. In ICOLD Tailings Dam Committee (2013) and OSTDC (2014) the active care period is the same as the transition and active care period combined in CDA (2014). In contrast, MAC (2019) does not define an active or passive care phase. Further, some guidelines provide more detailed guidelines in terms of time frames and acceptable activities in the different phases. While all guidelines tend towards creating a safe and stable end structure with the intent of 'walk-away closure', the fact remains that they do have inconsistencies between them. Ultimately, these inconsistencies result in confusion amongst industry.

Another term with some variation in the definition is decommissioning. The Alberta Dam Safety Directive refers to decommissioning as the "complete removal or breach of a dam or canal so that the structures can no longer retain, store, or divert water, including water containing another substance such as fluid waste or flowable tailings that may pose safety or environmental concerns" (Government of Alberta 2018). This definition slightly contradicts some definitions used within the mining industry, which focus more on the term decommissioning as a means to reach the closure process. For example, OSTDC (2014) describes closure as the process where various measures may be implemented to convert the tailings dam and deposit area into a mine waste structure during the closure process. This may include breaching of the dam, removal of the fluid or tailings, construction of outlet structures, removal or operational structures, or other closure measures.

The lack of clarity regarding the life phases of a dam and associated closure terminology is important. Combined with the non-prescriptive nature of the Alberta Energy Regulator (AER) Dam Safety department, this lack of clarity may result in poorly developed closure objectives and plans that are challenging for the AER to assess based on conflicting terminology and approaches to closure.

Overall, the organizations suggest that the management of a tailings dam should be conducted with a risk-based approach and that closure should be considered and incorporated into the design in the first life phase for success (ICOLD Tailings Dam Committee 2013, CDA 2014, OSTDC 2014, MAC 2019).

2.2.1 Dam or No Dam

According to the Alberta Water (Ministerial) Regulation, a dam is "a barrier that is designed and is or is to be constructed for the purpose of retaining, storing or diverting water, including water containing another substance, fluid waste or flowable tailings…" where flowable tailings are defined as "residual materials, including process effluents, left behind after the resources from an ore have been extracted at a processing plant and whose characteristics allow the materials to flow" (Government of Alberta 2021). The Alberta Water (Ministerial) Regulation notes that a dam will be regulated according to the Regulation if it satisfied one or more of the following criteria (Government of Alberta 2021):

a) "that provides a live storage capacity of 30 000 cubic metres or more and is 2.5 metres or more in height when measured vertically to the top of the barrier,
    i. from the bed of the water body at the downstream toe of the barrier, where the barrier is across a water body, or
    ii. from the lowest elevation at the outside limit of the barrier, where the barrier is not across a water body,

b) that is classified as being a significant, high, very high or extreme consequence structure in the Safety Directive, or

c) that exists for the purpose of storing flowable tailings."

While the description of what classifies a dam as a dam is generally clear by governmental bodies, as in the case of the AER, it is often unclear when a dam may be able to be de-regulated as a dam. Regardless of the organization, the end goal of the life cycle phases is typically the creation of a landform, which is generally described as being physically, chemically, ecologically, and socially stable (ICOLD Tailings Dam Committee 2013). In an attempt to bridge the gap between the point where a facility is regulated as a dam and the point where it could be classified as a landform and undergo custodial transfer back to the crown, OSTDC (2014) and Al-Mamun and Small (2018) propose an intermediate step whereby the dam is converted to a mine waste structure (Al-Mamun and Small 2018) or a solid earthen structure (OSTDC 2014). This process is advantageous as the facility would no longer be regulated as a dam and thus would no longer need annual performance reviews or inspections. Al-Mamun and Small (2018) presented the work of the Canadian Dam Association Mining Dams Committee, which proposes that a tailings dam could be converted to a mine waste structure assuming that it satisfied the following non-dam criteria:

1. *"Ponded water could not be available to a possible failure of the perimeter structure that can propagate the failure.*
2. *Tailings located upstream of the perimeter structure cannot flow if the perimeter structure is removed (i.e. are not fluid like).*
3. *Tailings that may be located upstream of the perimeter structure cannot migrate through the structure or the foundation.*
4. *That conditions will not develop in the future that could violate the previous three criteria."*

Criteria 4 proposed by Al-Mamun and Small (2018) is difficult to assess and poses a challenge for industry as there is still significant uncertainty regarding the long-term behaviour of these facilities. The life cycle of a tailings dam using the intermediate step of a mine waste structure is provided in Figure 2-1. The significant uncertainty associated with this framework supports the use of a risk-based framework.

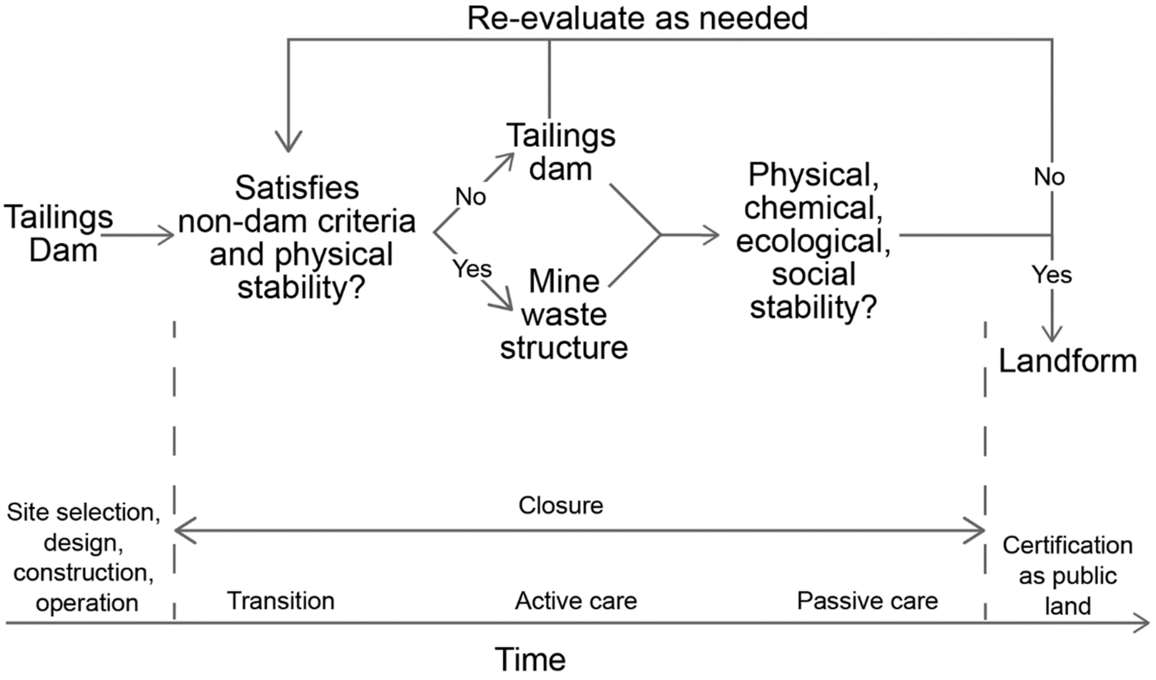

Figure 2-1: Tailings dam life cycle – from dam to landform according to Al-Mamun and Small (2018)

In 2019, Manual 019: Decommissioning, Closure, and Abandonment of Dams at Energy Projects (Manual 019) was released (AER 2020). Manual 019 is intended to be used in conjunction with the new Water (Ministerial) Regulation and the Alberta Dam and Canal Safety Directive released in 2018 (Government of Alberta 2018, 2021) and focuses on providing guidance on the processes of decommissioning, closure, and abandonment of a tailings dam. Manual 019 discusses the guidance from Al-Mamun and Small (2018) with an associated discussion on how it relates to the Directive. Overall, Manual 019 recognizes the significant uncertainty associated with tailings dam closure and expects all decommissioning, closure and abandonment (DCA) plans to be supported by risk assessments, which should consider long-term physical failure modes. The operator is expected to continue active management of the facility until the regulator accepts the completion report (AER 2020). At this time, the operator would no longer be required to actively manage and report on the structure as a dam (AER 2020). It should be noted that some tailings dams may require long-term active management depending on the residual risks (AER 2020).

2.3 Terminology

The terminology used in this study is provided in this section to promote clarity as there can be discrepancy between different organizations resulting in confusion in the industry. It is critical that an appropriate technical glossary is used and followed (Oboni and Oboni 2016). Terminology related to tailings dam closure and risk practice is provided.

The tailings dam closure terminology adopted for this research aligns with the Alberta Energy Regulator (AER) and considers guidelines from the Oil Sands Tailings Dam Committee, the International Committee on Large Dams, and the Canadian Dam Association. The following are some of the most important terms and definitions used in this research related to tailings dam closure.

Ultimate failure: collapse of tailings dam leading to catastrophic failure.

Catastrophic failure: as defined by Global Tailings Review (2020):

> *"A tailings facility failure that results in material disruption to social, environmental and local economic systems. Such failures are a function of the interaction between hazard exposure, vulnerability, and the capacity of people and systems to respond. Catastrophic events typically involve numerous adverse impacts, at different scales and over different timeframes, including loss of life, damage to physical infrastructure or natural assets, and disruption to lives, livelihoods, and social order. Operators may be affected by damage to assets, disruption to operations, financial loss, or negative impact to reputation. Catastrophic failures exceed the capacity of affected people to cope using their own resources, triggering the need for outside assistance in emergency response, restoration and recovery efforts."*

Serviceability failure: failure to perform as intended.

Failure modes: the way in which a tailings dam could fail to contain its contents.

Failure mechanism: the mechanism by which a hazard progresses to a failure mode (from failure mode initiation to failure).

Trigger: that which leads initially to the failure mechanism.

Hazard: a condition that has the potential to cause an undesirable consequence.

Tailings dam: retaining structure that stores water and tailings resulting from the mining process.

Mine waste structure: a tailings dam can transition into a mine waste structure when it has met the non-dam criteria provided by Al-Mamun and Small (2018).

Landform: a tailings dam can be classified as a landform when it has met the non-dam criteria as per Al-Mamun and Small (2018) **and** has been proven to be physically, chemically, ecologically, and socially stable.

Closure: closure of a tailings dam involves intentionally ceasing tailings deposition into the tailings dam and modifying the tailings dam to achieve long-term physical, chemical, ecological, and social stability.

De-registration: the process where a governmental body in charge of regulation assesses the structure and determines it can be removed from the dam and pond registry and no longer regulated as a dam. Other common alternatives used in literature are de-license used by OSTDC (2014) and de-regulate used by Oberle at el. (2020).

Active Care: the period when active intervention and monitoring is required to achieve a stable, sustainable landform.

> *Passive Care:* the period after active care where the tailings dam is monitored to ensure compliance with the closure objectives. It should be noted that this period can last for hundreds of years as the structure must prove to be physically, chemically, ecologically, and socially stable before it can receive a Reclamation Certificate.
>
> *Reclamation:* the process of modifying or upgrading the tailings structure to meet the closure objectives.
>
> *Final Reclamation:* the process of modifying or upgrading the tailings structure such that the structure can qualify for certification as a landform and consequently receive a Reclamation Certificate.
>
> *Reclamation Certificate:* in order to attain a reclamation certificate, the final landform must meet all provincial and federal criteria as determined by the AER. This will require the final landform to be physically, chemically, ecologically, and socially stable. After attaining a reclamation certificate, the land is transferred back to the Crown.

The risk practice terminology adopted for this study aligns with the terminology developed by the International Society of Soil Mechanics and Geotechnical Engineering (ISSMGE) Technical Committee on Risk Assessment and Management, and the following relevant terms are quoted from Fell et al. (2005):

> *"Risk: Measure of the probability and severity of an adverse effect to life, health, property, or the environment. Quantitatively, Risk = Hazard x Potential Worth of Loss. This can also be expressed as 'Probability of an adverse event times the consequences if the event occurs.'*
>
> *Risk Management: The systematic application of management policies, procedures, and practices to the tasks of identifying, analyzing, assessing, mitigating, and monitoring risk.*
>
> *Risk Assessment: The process of making a decision recommendation on whether existing risks are tolerable and present risk control measures are adequate, and if not, whether*

alternative risk control measures are justified or will be implemented. Risk assessment incorporates the risk analysis and risk evaluation phases.

Risk Mitigation: A selective application of management policies, procedures, and practices to the tasks of identifying, analyzing, assessing, mitigating, and monitoring risk.

Consequence: In relation to risk analysis, the outcome or result of a hazard being realized.

Probability: Measure of the degree of certainty. This measure has a value between zero (impossibility) and 1.0 (certainty). It is an estimate of the likelihood of the magnitude of the uncertain quantity, or the likelihood of the occurrence of the uncertain future event."

2.4 Mining in Alberta

2.4.1 Climate

The climate has an immense impact on the design and performance of a tailings dam, especially from a long-term perspective as climate change occurs. It is expected that climate change will lead to changes in the hydrology in an area, including changes to the annual precipitation and the ratio of water sources from rain, snow, or extreme events (NRCAN 2008, MEND 2011). In the event that the precipitation decreases and evapotranspiration increases, drought conditions may develop (NRCAN 2008, MEND 2011). Ultimately, this may impact the closure surface and increase the probability of fires occurring.

The application of climate change information to closure scenarios may be complicated due to the availability of appropriate data and downscaling of global climate models (GCMs) (MEND 2011). GCMs are developed using global emission scenarios generated by the Intergovernmental Panel for Climate Change (IPCC). Downscaling is defined as "a method that derives local-to regional-scale (up to 100 km) information from larger-scale information coming from GCMs" (IPCC 2014). IPCC provides results from a hierarchy of climate models ranging from simple idealized models to models of intermediate complexity to comprehensive GCMs including earth system models that also simulate the carbon cycle. GCMs simulate many climate aspects, including temperature of the atmosphere and the oceans, precipitations, winds, clouds, ocean currents and sea-ice extent. GCMs use Representative Concentration Pathways (RCPs), which are time dependent scenarios of greenhouse gas emissions and atmospheric concentrations, air pollutant emissions, and land use (IPCC 2014). There are four commonly used RCPs representing different emission scenarios, including: RCP 2.6, RCP 4.5, RCP 6.5, and RCP 8.5 (IPCC 2014). RCP 2.6 represents the most stringent mitigation scenario, RCP 8.5 represents the highest emissions scenario, and the other two scenarios represent intermediate scenarios (IPCC 2014).

According to MEND (2011), risks associated with climate change are higher for the closure and post-closure phases of a mine life cycle. Generally, climate change is not expected to impact the operation phase drastically due to the relatively short time frame; however, this becomes problematic with the lengthy time frames associated with closure. In general, it would be ideal to design tailings dams for post-closure climate change conditions at or before closure using "anticipatory adaptation" as opposed to "reactive adaptation" (MEND 2011). For design of spillways using this approach, MEND (2011) suggests that the ideal approach would be to build spillways for plausible future conditions (based on predicted climate change effects) and/or incorporate additional conservatism into the design, but notes that this may be difficult to implement.

Climate change projections indicate that the mean annual precipitation may increase for many areas of Canada (including Northern Alberta) and will primarily occur in the winter months with an increasing ratio of rain over snow as the source (MEND 2011). Figure 2-2 illustrates the median seasonal change in mean annual precipitation for Canada by the 2050s from MEND (2011). It is expected that vegetation would develop deeper root systems and may be accompanied by vegetation shifts towards plants that are more tolerant of drier growing seasons (i.e., grasses as opposed to trees) (MEND 2011). This expected vegetation shift is due to the anticipated increased in mean annual precipitation and the increase in plant growth rate and evapotranspiration from higher temperatures and carbon dioxide levels (MEND 2011).

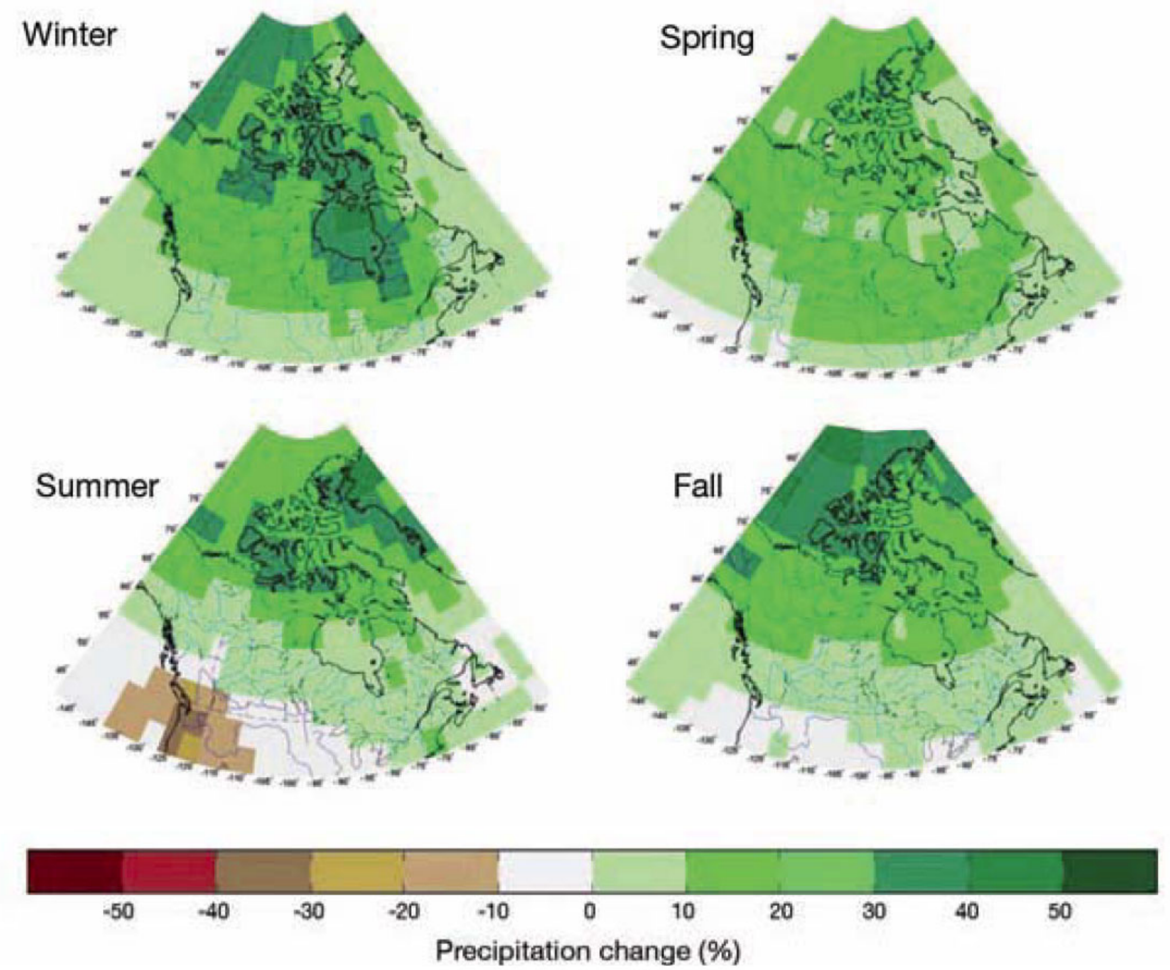

Figure 2-2: Median seasonal change in precipitation by the 2050s (relative to 1961-1990) for Canada (from MEND (2011))
Republished with permission of Mine Environment Neutral Drainage, from Climate Change and Acid Rock Drainage – Risks for the Canadian Mining Sector, Mine Environment Neutral Drainage, 2011.

Changes in the intensity and frequency of extreme events (NRCAN 2008) is expected to result in an increase in surface erosion leading to deepening of gullies (MEND 2011). MEND (2011) notes that this can be readily monitored for and repairs conducted if needed. In theory this is true, but this concept of monitoring and repairing as needed is not applicable in scenarios where walk-away closure is proposed.

According to MEND (2011), the post-closure effects of climate change can be summarized as:

1. Larger flows should be expected through hydraulic structures (i.e., spillways). If the spillway has insufficient capacity, this could lead to a dam failure.
2. Increased percolation through covers.
3. Increased percolation and/or erosion for soil covers on potentially-acid generating mine waste.
4. Changes in vegetation types.
5. Thawing of frozen cores causing settlement and increased seepage through tailings dams
6. Thawing of permafrost causing increased percolation

Climate change conditions identified that are relevant to tailings dam stability are outlined in Figure 2-3 (NRCAN 2008, MEND 2011, IPCC 2014).

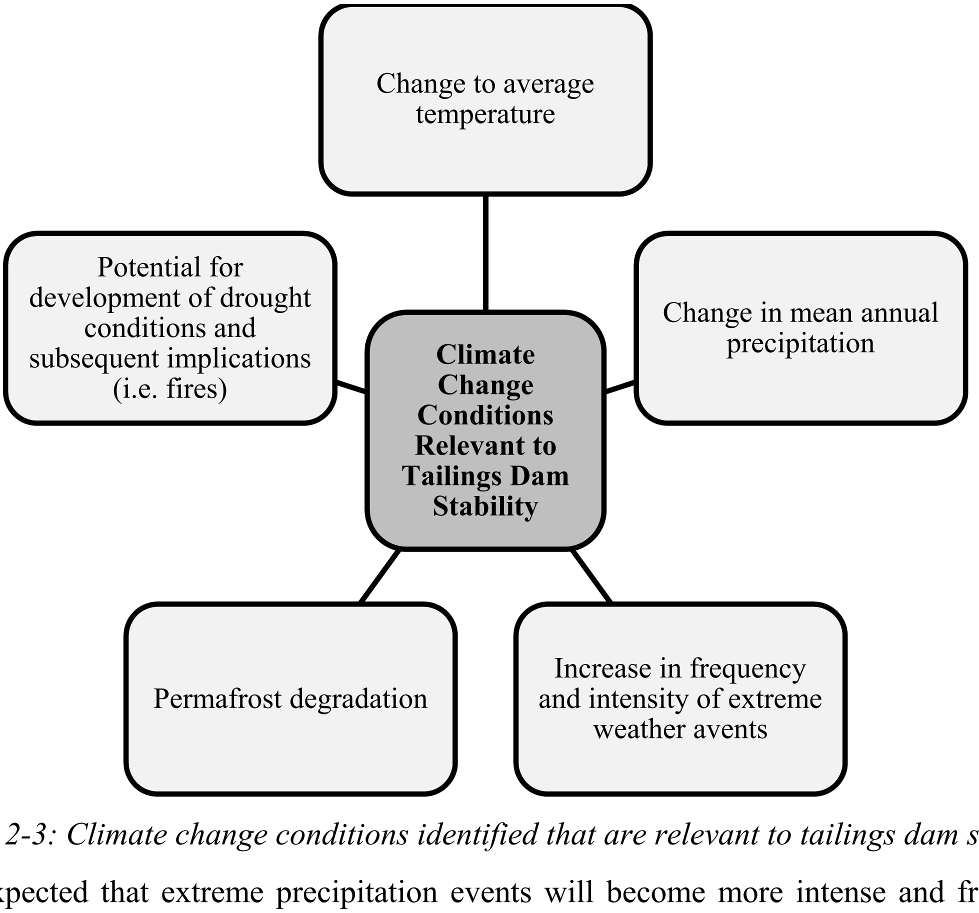

Figure 2-3: Climate change conditions identified that are relevant to tailings dam stability

It is expected that extreme precipitation events will become more intense and frequent (IPCC 2014). A complication with extreme events lies with an inability to predict the way in which these events will change over time (MEND 2011). Subsequently, this makes it difficult to select design events for closure scenarios in perpetuity.

2.4.2 Construction Methods

Tailings dams are generally constructed in stages throughout the life of the mine (although not always). The construction of the dam generally begins with a starter dyke, which is typically constructed using natural material. As the tailings storage requirements increase over time, the dam is raised to accommodate the increasing demand. A variety of materials can be used for the dam raises, including overburden, mine waste, or tailings. Dam raises are conducted using a variety of methods depending on site and project specific considerations, including:

- Upstream construction;
- Downstream construction;
- Centreline construction;
- Modified centreline construction; or
- A combination of the above methods.

The construction method category depends on the direction that the crest of the dam moves relative to the starter dyke as the dam increases in height (Vick 1990). As tailings dams do not generate profit, decisions related to construction method and design are often tied to cost considerations. Consequently, tailings dams are often constructed using tailings sand or mine waste to reduce costs associated with fill material (Patnayak and Alam 2016). A brief description of the different construction methods is provided here. Decisions related to the construction method are dependent on several factors including the availability of borrow material, footprint area, and deposition plan (Patnayak and Alam 2016). It should be noted that these factors (and associated regulations) may change throughout the life of the structure, and thus the construction method may change as well.

For upstream construction, tailings are discharged upstream from the crest of the dam (beginning first with the starter dike) to form a beach that becomes the foundation for subsequent raises. This process is continued as the dam height increases. Figure 2-4 shows how the sequential dam raises proceed in the upstream direction, and the advantages and disadvantages of the upstream construction method are provided in Table 2-1. The upstream construction method is simple and inexpensive, but also has a number of limiting constraints. Upstream construction can be used to great success with careful design and monitoring. A key to the success of upstream construction is control of the phreatic surface. The phreatic surface location in an upstream dam is impacted by the permeability of the foundation compared to the tailings, the degree of grain-size segregation and lateral permeability variation within the deposit and the location of the ponded water relative to the embankment crest (Vick 1990). These factors can be mitigated by cycloning to promote segregation of sands from the fines in the tailings, using underdrains to increase the foundation permeability, and carefully controlling the pond water location during operations (Vick 1990). Another limitation of upstream construction is the rate of rise that can be employed.

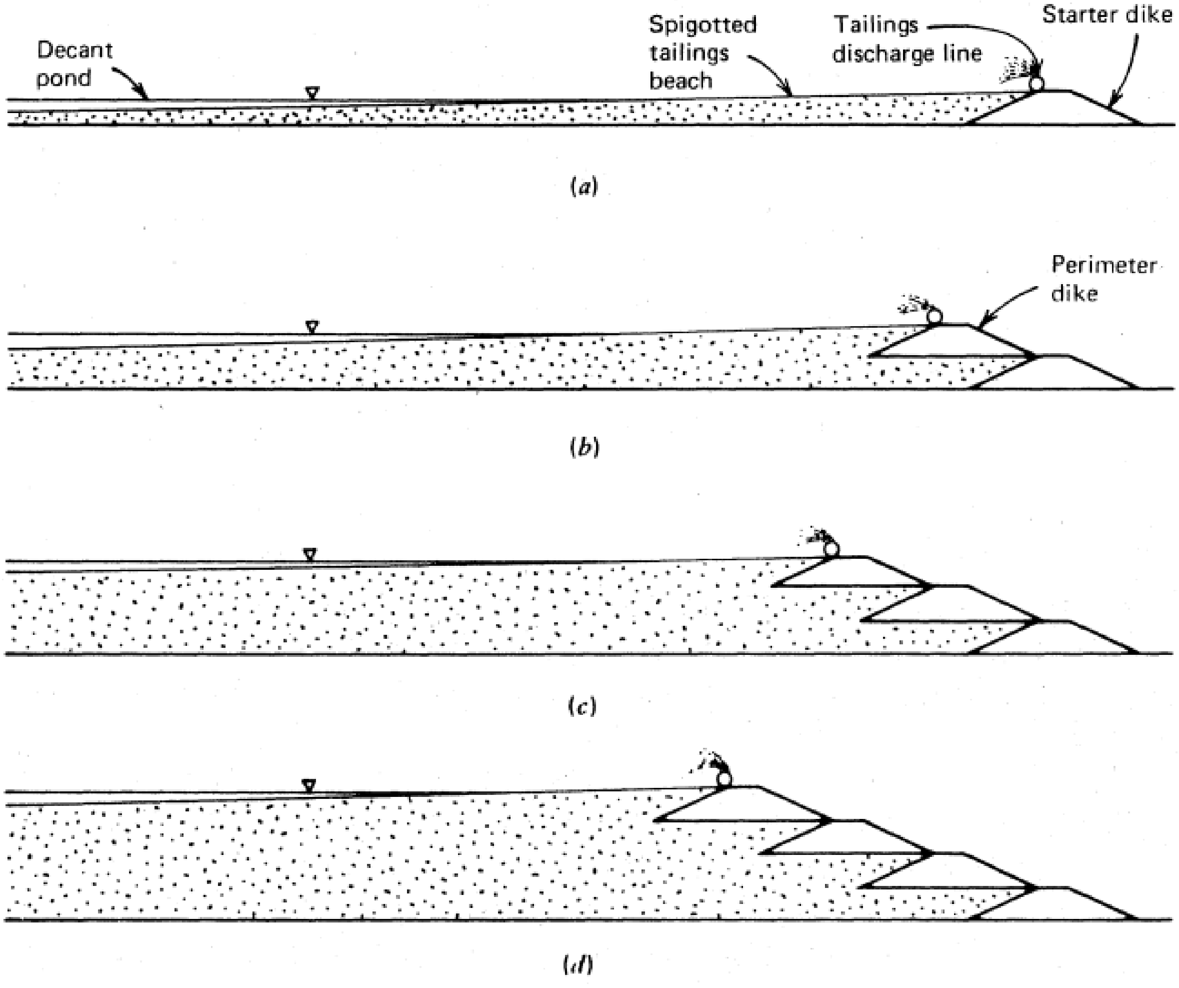

Figure 2-4: Upstream construction (from Vick (1990))
"Figure 3.2 Sequential raising, upstream embankment" in Planning, Design, and Analysis of Tailings Dams by Steven Vick is licensed under CC BY-NC-ND 4.0

For downstream construction, the dam is raised by placing fill on the downstream slope, which causes the crest of the dam to move in the downstream direction. Using downstream construction, the dam can be constructed using structural elements, including an impervious core and drains, to lower the phreatic surface (US EPA 1994). Downstream tailings dams have a similar structure to water retention dams. Figure 2-5 shows how the sequential raises of a dam proceed downstream. The advantages and disadvantages of downstream dams are summarized in Table 2-1. A major advantage of downstream dams is the ability to achieve high density, strength, and lower compressibility. However, this comes at a high cost requiring a large aerial footprint with a large material fill requirement.

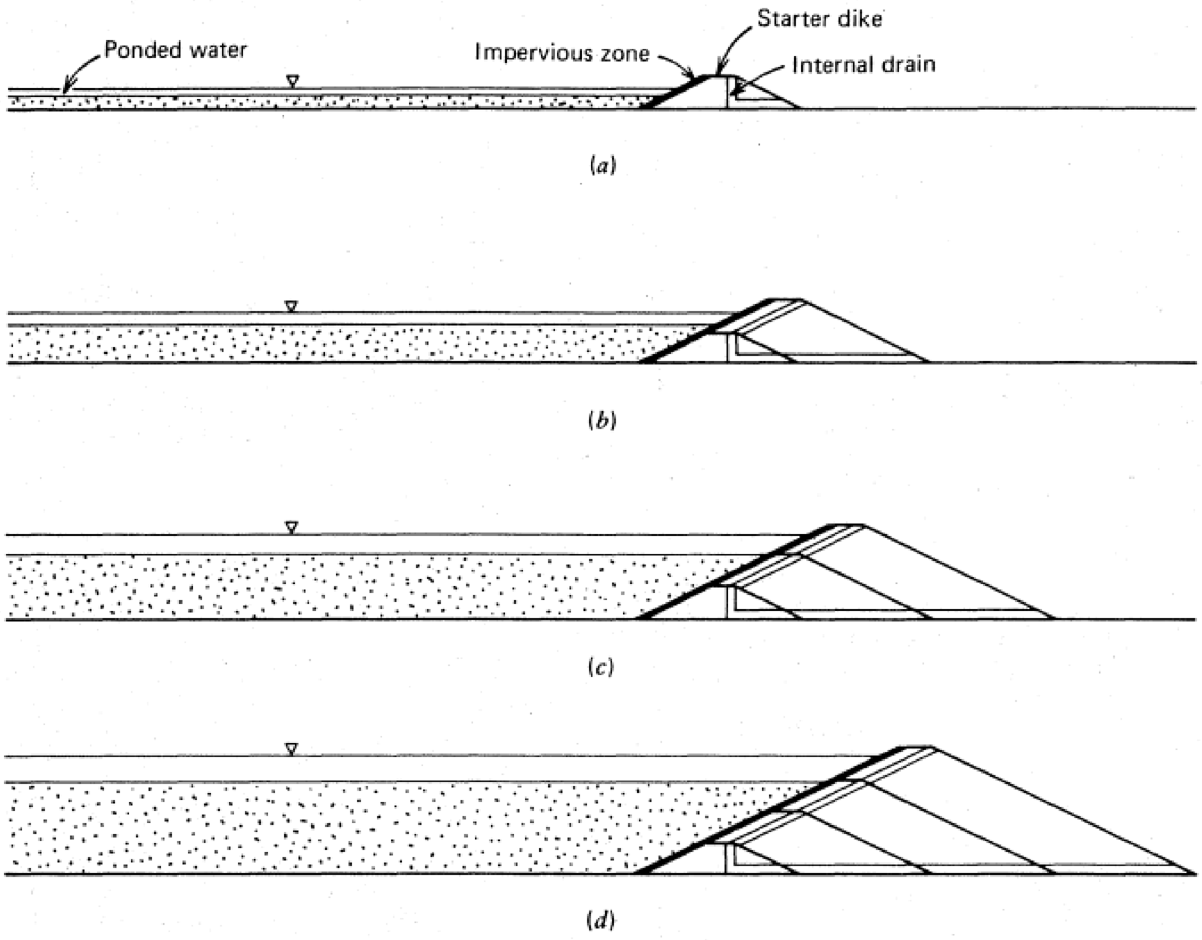

Figure 2-5: Downstream construction (from Vick (1990))
“Figure 3.4 Sequential raising, downstream embankment” in Planning, Design, and Analysis of Tailings Dams by Steven Vick is licensed under CC BY-NC-ND 4.0

Table 2-1: Advantages and disadvantages of different construction methods

Construction Method	Advantages	Disadvantages
Upstream	Inexpensive Simple Minimal fill requirements Minimal construction effort Use of tailings as construction materials Smaller footprint	Difficult phreatic surface control Water storage capacity Seismic liquefaction potential Least stable method of construction Poor foundation conditions High level of monitoring and instrumentation required Limited rate of rise
Downstream	Significant water storage High strength Compaction control Ability to achieve high density, strength, and lower compressibility No restriction on rate of rise	Requires a large footprint Large material requirement Expensive

The centreline construction method is a combination of the two methods. Tailings are discharged in the upstream direction to form a beach. To conduct a raise, fill is then placed on the beach and on the downstream slope of the dam. Due to this method of raising the dam, the centreline of subsequent raises remains at the same position relative to the starter dyke. The centreline method aims to capitalize on the advantages of the upstream and downstream methods while mitigating the disadvantages (Vick 1990). The centreline method allows for the construction of structural zones for internal drainage to control the phreatic surface. As a result, the centreline method is less sensitive to the location of ponded water than the upstream method (Vick 1990). As the method still employs placement of fill on the upstream side of the dam, a competent and above water beach is necessary to provide an adequate foundation for future raises (Vick 1990). The cost and the amount of fill required for construction for centreline dams falls in between that of upstream and downstream dams. Figure 2-6 shows sequential dam raises occur in a centreline constructed dam.

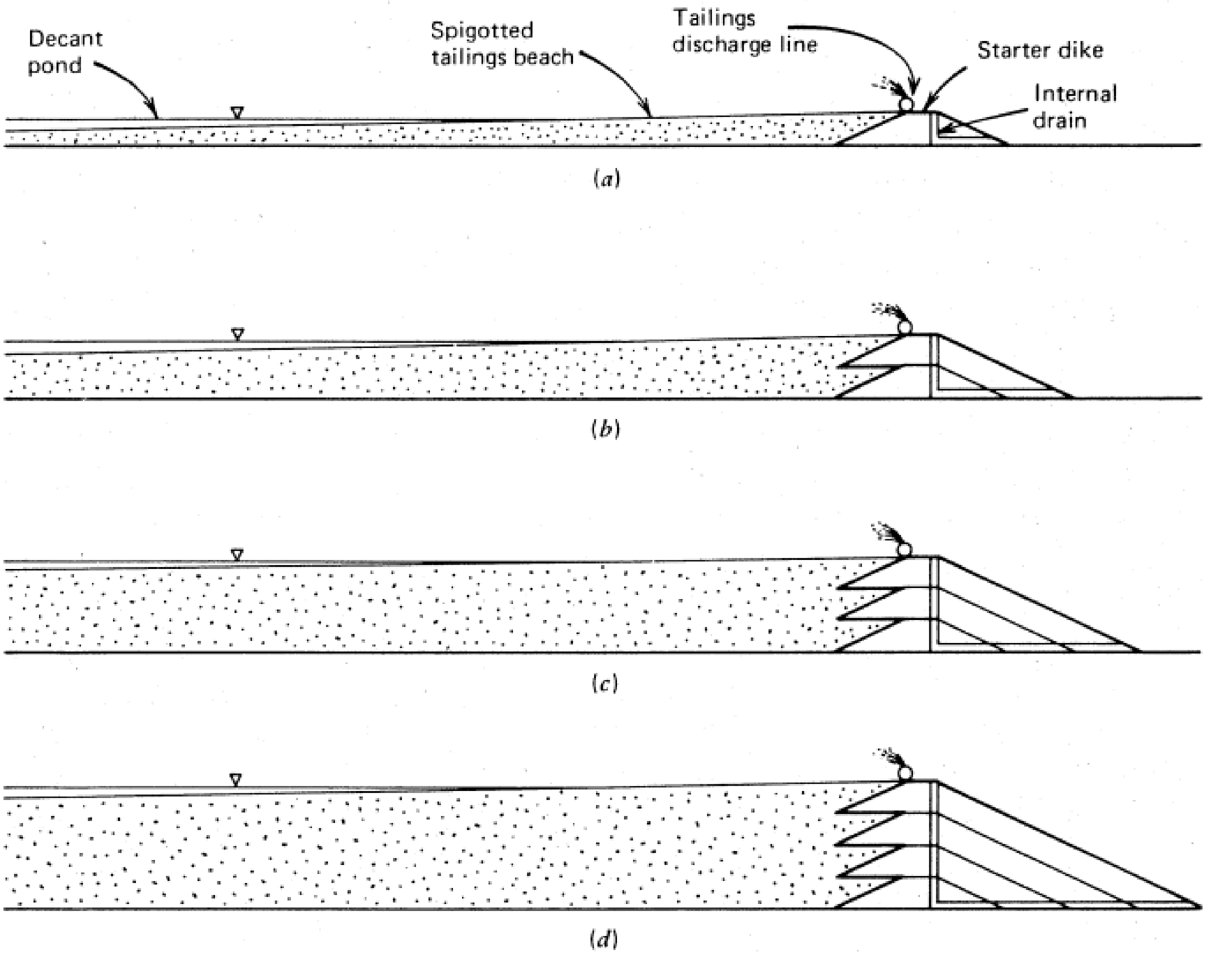

Figure 2-6: Centreline construction (from Vick (1990))
"Figure 3.4 Sequential raising, centerline embankment" in Planning, Design, and Analysis of Tailings Dams by Steven Vick is licensed under CC BY-NC-ND 4.0

The modified centreline method is similar to conventional centreline construction; however, the centreline of the dam slopes slightly upstream with subsequent raises, which reduces the amount of fill required when compared with conventional centreline construction (Haile and Brouwer 1994).

It should also be noted that the construction method may be unknown in some cases, specifically in the case of the coal mining industry where a number of the historical structures lack construction records. It should also be noted that a tailings dam can be constructed to full height prior to the beginning of tailings deposition and resemble a typical water-retention dam with internal zoning, which may include impervious cores, drainage zones, filters, upstream riprap, etc. (Vick 1990).

As discussed, Alberta has oil sands mines and coal mines with the majority of tailings dams located at oil sands mines. Oil sands mines typically employ upstream construction, modified centreline, or a combination of methods for tailings dam construction. As discussed, the construction method is dependent on a number of factors including the deposition plan and the materials available for construction. Syncrude and Suncor use tailings sand and mine waste, including overburden and interburden (material with little to no ore that lies between ore layers), for construction (Patnayak and Alam 2016). Consequently, these operations largely employ cell construction for deposition and construction of the dam. In contrast, CNRL's Horizon Oil Sands mine uses mine waste (overburden and interburden) for tailings dam construction using the downstream method with typical overburden construction methods (Sisson et al. 2012, Patnayak and Alam 2016)**.** Various depositional methods for construction are discussed in Section 2.4.2.1 with a focus on methods used in the oil sands.

It should be noted that the construction method, materials, and deposition method employed by a mining operation is not always straightforward and may undergo extensive change throughout the life of the structure as the design evolves. This could be due to a number of factors including increases in the final design elevation of the dam, changes to the tailings or materials available for construction, changes to best available technology or practice, nearby ore deposits, etc. This emphasizes the importance of proper documentation for these facilities that clearly explains the reasons that certain decisions were made. For example, construction of Syncrude's Mildred Lake Settling Basin began in 1978 (Yano and Fair 1988). Throughout the duration of construction, a number of substantial changes were made to the design of the dam, such as a realignment centreline of the west tailings dyke in 1981 and a change from the use of modified centreline construction to centreline construction in 1982 (Yano and Fair 1988). The adjustment of the construction method involved a stepover of the compacted shell of the dam on to the beach (Yano and Fair 1988).

2.4.2.1 Deposition Methods

Depositional methods for dam construction can largely be broken down into two categories: overburden construction and hydraulic fill construction. Within the hydraulic fill construction category, the following methods will be discussed:

- Spigotting;
- Cycloning with direct deposition of underflow; and
- Cell construction.

Spigotting can be used to construct dams using the upstream, downstream, and centreline methods, but it is most commonly used with the upstream method. This method of deposition involves discharging tailings from a number of points along a tailings header line (Lighthall et al. 1989). As the tailings flow out from the spigot, coarser tailings will settle first on the beach. Ultimately, this results in the formation of two deposits: beach above water and beach below water. Historically, the beach below water (BBW) has been assumed to be liquefiable while the beach above water (BAW) deposit has been assumed to be nonliquefiable. In light of recent tailings dam failures, the assumption that the BAW deposit is nonliquefiable is being challenged. This method of deposition results in a beach that has variable gradation, solids content, hydraulic conductivity, density, etc. (Lighthall et al. 1989). It should also be noted that the characteristics of a beach deposit depends on a number of factors (tailings gradation, solids concentration, etc.) and careful consideration is required in determining the beach profile for the overall dam design. Beach design will not be discussed further.

Cycloning involves separating tailings into coarse (underflow) and fine (overflow) fractions. When cycloning is combined with direct deposition, the sand (coarse fraction) is deposited on the embankment or placed mechanically and compacted (Lighthall et al. 1989). While cyclones are used in the oil sands to separate whole tailings into coarse and fine fractions, they are not used for direct deposition and will not be discussed further.

Cell construction is used extensively in the oil sands at mines that use tailings sands for construction. The exact method of cell construction varies from operator to operator, but the goal is to create a compacted shell and nonliquefiable beaches to contain the pond and internal loose beach deposits (Martens and Lappin 2008). Regardless, the method involves tailings discharge to a cell where the solids settle and water and fines are decanted (Lighthall et al. 1989). Dozers are used to spread and compact the sand in the cell by the vibration of moving repeatedly across the surface and maintain containment dykes (Lighthall et al. 1989, Martens and Lappin 2008). The water and fines that do not settle flow to the end of the cell and through a weir structure to the beach (Yano and Fair 1988). Once the lift has advanced to within a certain specified distance of the weir, the end containment dyke is breached and tailings discharge continues in another cell (Yano and Fair 1988). During times when cell construction is not occurring, an overboard discharge line discharges tailings directly to the beach off the upstream crest of the compacted shell (Yano and Fair 1988). This method of construction allows for control over tailings placement, allows materials to be compacted to limit liquefaction potential, allows for control of slope angle, and limits costs (Lighthall et al. 1989). Contained beaching, a modification of cell construction, may also be used for structures that are not intended to retain fluids where the cells are larger and are constructed using higher lifts with minimal compaction requirements (List 1996).

While it is common for tailings dams to be constructed using tailings and hydraulic fill construction techniques, many dams are also constructed using borrow sources, which may include overburden, interburden, etc. Depending on several site-specific considerations (size of dam, seepage considerations, material contained, etc.), these dams may be zoned or homogeneous and may be constructed to full height prior to tailings deposition or constructed in stages throughout the life of the facility. Depending on the dam, compaction may occur with traditional civil equipment. In the oil sands, compaction typically occurs with heavy haul trucks, which have shown to provide effective compaction with larger lift thicknesses (Patrick and Sisson 2010). An example of an overburden tailings dam in the oil sands is CNRL's Dyke 10 at Horizon Mine. Dyke 10 is being constructed from local overburden and interburden with a maximum height of about 64 m (Patrick and Sisson 2010, Sisson et al. 2012). Dyke 10 has an inclined low permeability core, a chimney filter drain, a horizontal blanket drain that is elevated above the dam foundation, and a very flat downstream slope due to the weak foundation (Sisson et al. 2012).

The method of construction, deposition for construction, construction materials, and elements present in the dam for stability all play an important role in how a tailings dam ages in the long term and must be considered from a risk management perspective.

2.4.3 Oil Sands Mining

The majority of the oil sands in Northern Alberta are located in three regions: Athabasca, Cold Lake, and Peace River. The oil sands ore can be extracted using in situ methods or surface mining techniques depending on the depth of the deposit. Large commercial surface mining operations began in Northern Alberta in the late 1960s by Great Canadian Oil Sands Ltd. (now Suncor Energy Inc.) (McRoberts et al. 2017). According to Alberta Environment and Parks (2021), there are eight active oil sands surface mining operations in Alberta as shown in Table 2-2.

Table 2-2: Oil sands surface mines in Alberta (Alberta Environment and Parks 2021)

Mine Owner	Mine Name	Status of Mine	Dams
Syncrude Canada Ltd.	Mildred Lake	Active	Yes
Suncor Energy	Base Operations	Active	Yes
Canadian Natural Upgrading Limited	Jackpine	Active	Yes
Canadian Natural Upgrading Limited	Muskeg River	Active	Yes
Syncrude Canada Ltd.	Aurora North	Active	Yes
Canadian Natural Resources Ltd.	Horizon	Active	Yes
Suncor Energy	Fort Hills	Active	Yes
Imperial Oil Ventures Limited	Kearl Lake	Active	Yes

Surface mining techniques involve extracting oil sands ore from the ground, crushing the material, and mixing it with hot water so that it can be transported to the extraction plant using pipelines (Birn and Khanna 2010). The bitumen is then removed from the oil sands ore using a process based on the Clark Hot Water Extraction Process. This process results in the production of different tailings streams with varying proportions of minerals, dissolved organic salts, and residual organics (Kasperski and Mikula 2011). These tailings streams are then deposited in tailings impoundments or used as construction materials, where appropriate. One of the tailings streams produced is whole tailings (WT), which may be passed through a hydrocyclone to produce a coarse tailings stream from the underflow and a fines dominated stream from the overflow (CTMC 2012). The coarse tailings stream consists primarily of sand and is used for dam and beach construction or for the production of composite tailings (CT) or non-segregating tailings (NST) (Sorta et al. 2013). The extraction process also results in the production of a froth-treatment stream consisting of process-affected water, sand, fines, and residual bitumen solvent (Kasperski and Mikula 2011). The WT, fine tailings, and froth-treatment stream can be discharged to a tailings pond where the coarse fraction will settle quickly forming beaches and dykes and the fine fraction will flow into the centre of the pond (Jeeravipoolvarn 2010, Kabwe et al. 2014). The fine fraction that flows into the centre of the pond can be described as having a low solids content and may be referred to as thin fine tailings (TFT) (CTMC 2012, OSTC 2012). According to CTMC (2012), TFT have a low sand to fines ratio (SFR) (less than 0.3) and a solids content of approximately 15 percent to 30 percent by mass (CTMC 2012, OSTC 2012). Over time (3 to 5 years), the TFT will settle to form mature fine tailings (MFT) with a solids content of about 30 percent to 40 percent by mass (Spence et al. 2015). Tailings materials that behave as fluids are commonly referred to as fluid fine tailings (FFT), which have a solids content greater than 5 percent by mass with an undrained shear strength less than 5 kPa (Government of Alberta 2015).

Over time, technology has developed to promote dewatering of tailings as consolidation of MFT proceeds very slowly and may take potentially hundreds of years to reach a state that would be considered suitable for reclamation. One method of dewatering tailings involves adding a flocculant to FFT and processing the material using a centrifuge to create a centrifuge cake with a solids content of about 50 percent to 55 percent by mass (OSTC 2012). An additional method of dewatering involves in-line flocculation of FFT to create in-line thickened tailings (ILTT). Further, FFT may be flocculated and then thickened using a mechanical thickener creating thickened tailings (OSTC 2012). Finally, FFT may be combined with sand slurry using flocculants or coagulants to prevent segregation to create CT (combination with MFT) or NST (combination with thickened tailings) (OSTC 2012). A description of different types of tailings is provided in Table 2-3.

Table 2-3: Formation, use, and composition of oil sands tailings

Tailings	**Formation and Use**
Whole tailings	Underflow of primary separation vessel Discharged to tailings pond where sand settles rapidly forming dykes and beaches and the remaining fines and bitumen flow into the centre
Froth-treatment tailings	Results from the addition of solvent to the bitumen froth Discharged to the impoundment with the WT or the fine tailings stream
Coarse tailings stream	Underflow of WT in hydrocyclone Use for dam and beach construction Used for the production of composite tailings (CT) or non-segregating tailings (NST)
Fine tailings stream	Overflow of WT in hydrocyclone Discharged to tailings pond where sand settles rapidly forming dykes and beaches and the remaining fines and bitumen flow into the centre
Thin fine tailings	Formed by the fine portion of the fine tailings and whole tailings when they flow into a tailings pond
Mature fine tailings	Formed when the fine tailings settle in the tailings pond to a solids content of about 30 to 40% after about 3 to 5 years
Fluid fine tailings	Tailings stream that behave as fluids (TFT, MFT)
Non segregating tailings	Blend FFT with sand slurry using flocculants of coagulators to prevent segregation Thickened tailings are mixed with the sand slurry
Composite tailings	Blend FFT with sand slurry using flocculants of coagulators to prevent segregation MFT mixed with the sand slurry
Thickened tailings	Flocculate FFT and thicken in a mechanical thickener
In-line thickened tailings	In-line flocculation of FFT
Centrifuge cake	Flocculant added to FFT and processed using a centrifuge cake

Tailings dams may also contain petroleum coke (coke), which is generated as a by-product of upgrading bitumen to synthetic crude oil (Furimsky 1998). The composition of the coke material can vary and is dependent on a number of geographical and operational factors, including the coking technique used (Onder and Bagdoyan 1993, Scott and Fedorak 2004). Coking techniques are typically separated into delayed coking techniques and fluid coking techniques that rely on the process of thermal cracking whereby complex hydrocarbons are broken down into smaller units (Scott and Fedorak 2004). Syncrude uses fluid coking techniques, and Suncor uses delayed coking techniques. Delayed coking involves rapidly heating the material in a furnace under conditions that correlate to the material's thermal cracking temperature (Onder and Bagdoyan 1993). Following this process, the feedstock is transferred to a coking drum where the liquids and solids are allowed to separate (Scott and Fedorak 2004). The remaining solids form the coke. In contrast, fluid coke involves spraying the feedstock through steam injection onto hot coke particles from a previous cycle (Onder and Bagdoyan 1993, Scott and Fedorak 2004). This process results in thermal cracking and the formation of the coke. The fluid coke tends to have a spherical and uniform shape with medium to fine sized particles (Scott and Fedorak 2004, Fedorak and Coy

2006). In contrast, the delayed coke produced by Suncor will have large, non-uniform lumps and will be well-graded sandy gravel to large chunks (Scott and Fedorak 2004, Fedorak and Coy 2006). Further, the coke produced by the delayed coking process tends to have a lower specific gravity (Fedorak and Coy 2006). The unique properties associated with coke has resulted in its use in reclamation design (Suncor Pond 5) as opposed to simply being stored in an ETF. The Suncor Pond 5 reclamation design consists of a floating coke cap overlying geosynthetics (Pollock et al. 2010, Wells et al. 2010, Abusaid et al. 2011). Coke was identified as being a potential cover material due to its availability and the low specific gravity, which allowed it to be placed over the underlying tailings (Pollock et al. 2010). Coke may also be present within the dam structure as a component of the drainage system (McRoberts et al. 2017). For example, Suncor's Pond 1 used coke as a filter around perforated galvanized metal pipes in the early stages of design (McRoberts et al. 2017).

As the industry has evolved over time, it is expected that the construction materials and the tailings discharged to a facility will also have changed resulting in spatial variation. Further, oil sands operators are subject to a zero-effluent discharge policy. As a result, there is expected to be an ongoing decrease in water quality over time. It is important to understand the properties of the tailings used as construction materials and contained within a tailings impoundment as this may have important implications on the long-term behaviour of the facility.

The first tailings dam in the Alberta oil sands was Pond 1 (Tar Island) located along the Athabasca River at Suncor's Base Operation Mine. The initial design for the pond required a 12 m high dam constructed of overburden (Anderson et al. 2010). Over time, this design was adapted as tailings began to accumulate faster than the dyke could be raised resulting in continual increases in the height (final height was 97.5 m) and a switch to tailings sand as the construction material (Anderson et al. 2010). This adaptation over time was largely due to a lack of understanding of how the tailings would behave over time. As the oil sands industry has evolved, the number and size of tailings dams has grown.

2.4.3.1 Oil Sands Geology

The local geology underlying a dam forms the foundation and thus plays an important role in the stability over the life cycle of a dam and impacts key design elements of the structure (drainage systems, stabilization measures such as slopes or berms, etc.). This discussion will focus on the general geology and associated design considerations in the Athabasca region where the majority of surface mining occurs in the oil sands. The general geology consists of muskeg overlying surficial soils, which includes muskeg, Holocene and Pleistocene glaciolacustrine clays and silts, Pleistocene glaciofluvial sands and gravels, and Pleistocene glacial till (Allen and Sanford 1973, Carrigy 1973). There may also be areas of ice-thrusted bedrock (Isaac et al. 1982). The surficial soils overly the Grand Rapids formation, Clearwater formation, and the McMurray Formation, which is underlain by the Devonian formation. The soils overlying the mineable oil sands can be broadly classified as overburden. The mineable oil sands are located in the McMurray formation, which includes economic and uneconomic reserves. The Wabiskaw formation is also present in some areas at the base of the Clearwater formation and contains significant oil sands reserves (Flach 1984).

Muskeg deposits are often present across an oil sands mine site. The muskeg deposits are typically composed of silts, peat, and organic soils containing roots, wood fragments, and trace clay with a fibrous texture (Stephens et al. 2006). Depending on the dam, these deposits may be fully stripped below the starter dyke, stripped below the upstream or downstream toes, or left in place (Eshraghian and Martens 2010, Sisson et al. 2012) This may have potential impacts on the design in cases where the muskeg is left in place as these materials are highly deformable, which can result in large settlements and alterations in permeability over time.

Glaciolacustrine soils may be present across the site with varying amounts of clay, silt, and sand and are typically medium to high plastic (Stephens et al. 2006). As with the muskeg, glaciolacustrine deposits may be stripped, partially stripped, or left in place under the dam footprint. Important considerations for design include the preconsolidation pressure and the range of undrained shear strengths and pore pressure responses. Glacial till may also be present below a dam footprint. The glacial till may vary from clayey till to silty till to sandy till or Clearwater-derived till (Stephens et al. 2006).

A number of dams in the Alberta oil sands are situated over or in the vicinity of buried meltwater channels, which may significantly impact the design, including the need for elements such as pressure relief wells, pumping well, liners, and cut off walls (Stephens et al. 2006). These channels are often composed of sands and gravels. Due to this, the high permeability of the channel may result in the need for extensive seepage mitigation to limit potential seepage pathways of process affected water (Stephens et al. 2006). This is necessary to achieve the zero-discharge policy required of mine operators. Further, these fluvial meltwater channels may be overlain by glaciolacustrine deposits or glacial till, which has the potential to create artesian porewater pressures within the channel as the tailings dam and pond level is raised (Stephens et al. 2006). In these cases, measures may be required to reduce the artesian pressures such as pressure relief wells (Stephens et al. 2006). In cases where extensive measures have been taken to improve the stability or control seepage, the long-term sustainability must be assessed.

The Clearwater formation has major implications for the overall design and performance of a tailings dam throughout its life cycle as it is composed of heavily overconsolidated clay shales that can have very low strength along pre-sheared surfaces and a high pore pressure response to loading (Martens and Charron 2007). The Clearwater formation generally consists of high plasticity clays with varying proportions of silt, very fine-grained sand, cemented siltstones, and layers with minor amounts of glauconitic sand (Isaac et al. 1982, Martens and Charron 2007). Geologically speaking, the Clearwater formation is bedrock; however, it is classified as a clay shale as it can be described as a hard soil or an extremely weak rock (Martens and Charron 2007). The Clearwater formation is pre-sheared from a variety of processes including "valley rebound, glacial drag, deep solution collapse of underlying evaporate and limestone formations, stress relief from overburden erosion, and differential consolidation" (Martens and Charron 2007). This can be problematic or beneficial depending on the orientation of the shear planes relative to different design scenarios. It should be noted that some potential factors that may impact the design of structures situated on the Clearwater formation are: low residual friction angles, horizontal continuity of weak bedding planes, high clay content and high plasticity, and high pore pressure responses to loading (Martens and Charron 2007). The Clearwater formation has been subdivided into different units from oldest to youngest based on specific marker beds determined from natural gamma and density geophysical logs: Kcw and Kca to Kcg (Isaac et al. 1982, Stephens et al. 2006, Martens and Charron 2007). The Kcw unit is also referred to as the Wabiskaw formation, which is a glauconitic, interbedded, fine-grained sand that may contain minor amounts of clay shale (Isaac et al. 1982, Bayliss et al. 2013). Due to the weak foundation conditions associated with the Clearwater

Formation shales, dams constructed on this deposit often require shallow slopes and careful monitoring of performance throughout construction.

It should also be noted that there may be glacial rafts present in surficial soils overlying the Clearwater shale. Glacial rafts are formed when they detach from their parent rock and are transported to a different location via glacial activity (Bayliss et al. 2013). Consequently, they tend to have similar geotechnical properties and fabric to their parent material (Bayliss et al. 2013). The formation of glacial rafts is discussed extensively by Bayliss et al. (2013). Depending on the depth, distribution, and thickness, glacial rafts have the potential to impact the overall design of a tailings dam. In the oil sands, glacial rafts may originate from the Clearwater formation. As previously discussed, the Clearwater formation is a heavily overconsolidated clay shale with low strength and a high porewater pressure response to loading. These characteristics may then be seen in glacial rafts that originate from the Clearwater formation.

The McMurray formation is commonly distributed into 3 members including the lower, middle, and upper members as shown in Figure 2-7 (Flach 1984). The McMurray formation comprises the mineable oil sands and consists of interbedded Cretaceous sands and shales that are impregnated with bitumen (Bayliss et al. 2013). In many cases, the McMurray formation may be deep enough that it will not impact the stability of an ETF. In general, the McMurray formation can have clay shale layers that are intact, partially sheared, or ubiquitously sheared with the potential for brittle failures, rapid strength loss, and progressive failure. Further, sandy layers in the McMurray formation can be very dense and strong (Isaac et al. 1982).

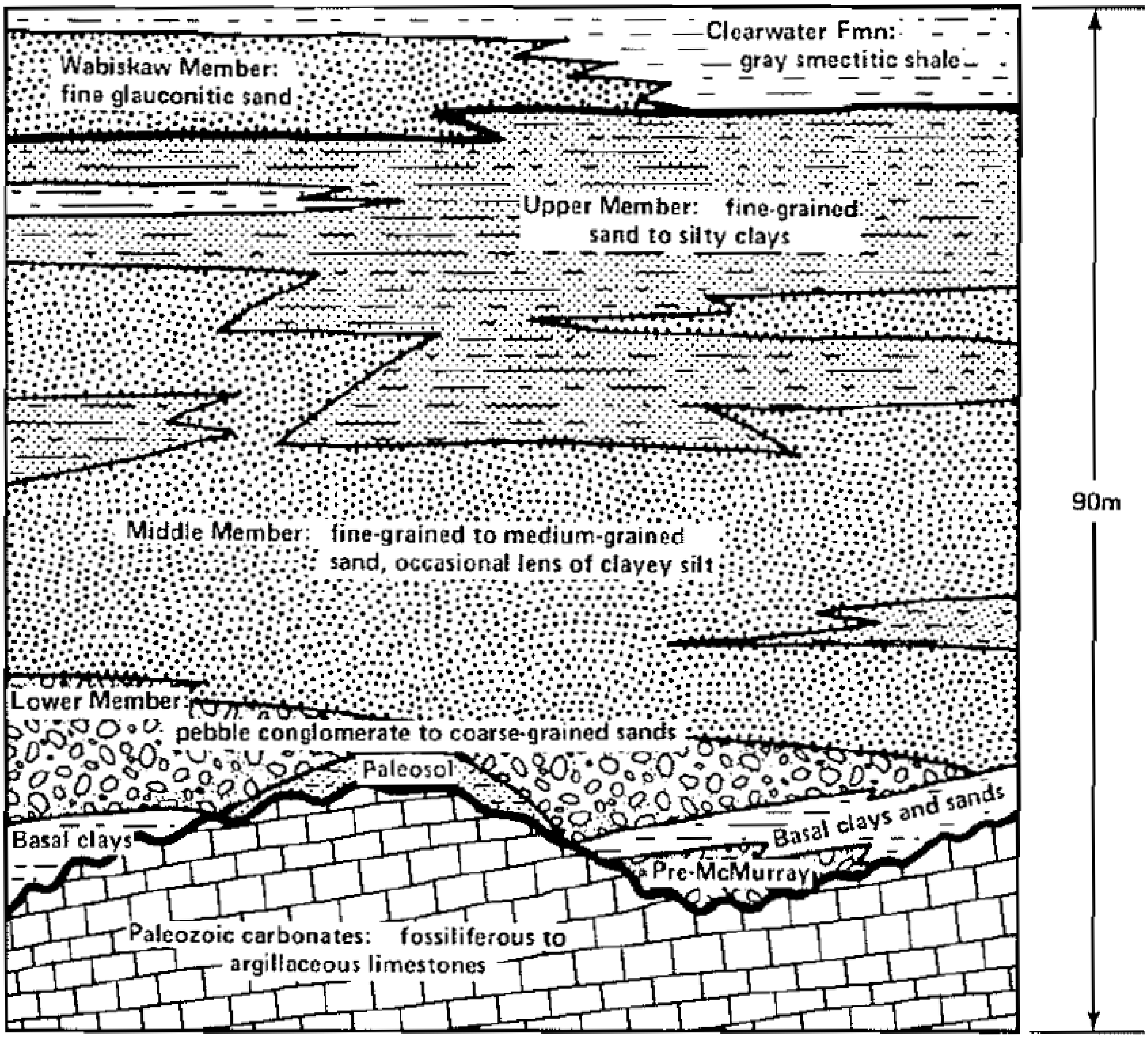

Figure 2-7: Hypothetical McMurray formation cross section (from Dusseault and Morgenstern (1978))
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The Devonian Limestone formation underlies the McMurray formation. Due to the depth of the deposit, it is generally expected that it would primarily pose hazards for mining activities and in-pit dykes. However, this formation does have the potential to impact external tailings facilities as it can lead to ground collapse that can materialize as sinkholes and faults. In the short term, this may not be viewed as high risk, but as these structures transition into becoming permanent landforms on the landscape this may be an important consideration for design. It should be noted that dissolution of the most soluble units is complete at many of the eastern mine sites, and these areas are at low risk for future collapse (Barton et al. 2016, Walker et al. 2017). The Devonian Limestone formation is made of a variety of units. The Prairie Evaporite Formation is one of these units, which can consist of over 200 m of halite with anhydrite, dolomite, shale, and limestone (Schneider and Cotterill 2017). These deposits may be subject to salt dissolution effects resulting in collapse, subsidence, or areas of karst (Schneider and Cotterill 2017). Ongoing dissolution is occurring slowly along a dissolution front (Schneider and Cotterill 2017).

The advantage of long-term management of tailings dams lies in having a comprehensive understanding of the foundation conditions and performance over time.

2.4.3.2 Construction Materials

The selection of construction materials is dependent on a number of conditions, including the construction method, the availability of material, site constraints, and foundation conditions. Dams in the oil sands may be constructed with tailings, overburden, interburden, coke, or a combination (OSTDC 2014). Overburden and interburden material may include lean oil sand (non ore-grade), clay shale, or till (OSTDC 2014).

Construction of tailings dams is often complicated by design revisions that occur throughout the life of the structure. As a result, it is important that the design is flexible as demonstrated by facilities such as Mildred Lake Settling Basin, Southwest Sand Storage, Sand Dump 8, and Horizon Dyke 10 (List 1996, List et al. 1996, Sisson et al. 2012, Pollock et al. 2014). These design revisions may be driven by a number of different factors, including an attempt to prevent ore sterilization, stabilization, a change in availability or quality of material, or seepage concerns. Ultimately, this can lead to changes in the construction materials over time. For example, Syncrude's Mildred Lake Settling Basin (MLSB) underwent a number of substantial design revisions throughout its construction (realignment of the dyke centreline, change in construction method, increase in crest elevation, and increase in footprint through construction of toe berms) (List 1996). In this particular case, the construction method switched to centreline construction part way through. This required the compacted shell to be 'stepped-out' onto the beach by performing cell construction over the beached sand (List 1996). Further, a toe berm was constructed to address foundation concerns. Toe berms are commonly constructed as a stabilization measure at mine sites (i.e., Suncor's South Tailings Pond (Stephens et al. 2006)). For example, a toe berm was constructed at the ETF at CNRL's Jackpine using mine waste and coarse sand tailings (Bayliss et al. 2014). The construction material used for stabilization berms will depend on available material at a particular mine site.

At Jackpine Mine, the ETF is split into three dedicated areas: the Dedicated Disposal Facility 1 (DDA1), Sand Cell 1 (SC1), and Sand Cell 2 (SC2) (Bayliss et al. 2014). These areas have different characteristics. DDA1 was constructed using centreline methods with overburden and coarse sand tailings to contain thickened tailings and coarse sand tailings (CST) (Bayliss et al. 2014). In contrast, SC1 and SC2 were both constructed using upstream methods and coarse sand tailings (Bayliss et al. 2014). These facilities were designed to store coarse sand tailings and process affected water (Bayliss et al. 2014). The starter dykes for all three areas are zoned structures constructed from mine waste (Bayliss et al. 2014).

Dams may also include shear keys for stabilization that may include additional materials as is the case with the external tailings facility (ETF) at CNRL's Jackpine Mine (Bayliss et al. 2014). As with toe berms, the materials used for the shear key will depend on site specific considerations and may vary greatly between sites. Regardless, it is important to recognize the presence of these structures.

Lean oil sand may be used as a construction material, which typically contains fines and a modest amount of bitumen (Pollock et al. 2014). Due to these characteristics, lean oil sands may be used as a low permeable fill (Pollock et al. 2014). This material can then be used in combination with tailings sand where the tailings sand may act as a filter for the lean oil sand (depending on the gradation) (Pollock et al. 2014). Suncor's Sand Dump 8 underwent a multitude of changes throughout the design and construction due to mine planning, technology, and regulatory changes (Pollock et al. 2014). Pollock et al. (2014) provides a comprehensive overview of these design changes. One of these changes included an increase in the rate of rise of the structure up to 20 m per year, which had not been accomplished in the oil sands at that time for this type of construction. This proved to be problematic due to the BAW deposits, which are commonly assumed to be non-liquefiable due to the density of the material (Pollock et al. 2014). In this particular case, this assumption was not valid due to the rapid rate of construction (Pollock et al. 2014). This lead to a further re-design involving an upstream compacted shell (Pollock et al. 2014).

While it is common for dams in the oil sands to use upstream or centreline construction methods with hydraulically placed tailings sands, there are structures that follow more conventional zoned embankment dam design such as CNRL's Horizon Dyke 10. This structure was constructed using overburden and interburden, and has six different zones (Sisson et al. 2012).

As with all aspects of dam design, it is important to recognize the weaknesses and sensitivities of different construction materials. These weaknesses and sensitivities should be evaluated over long time scales carefully. Further, it is important to recognize the potential for cracking of various construction materials (i.e., low permeability cores) and the impact this may have on stability, especially when evaluating the long-term stability of these structures.

2.4.3.3 Seepage Control

Various elements may be employed in tailings dam design to aid in controlling seepage, including the phreatic surface. The location of the phreatic surface has important implications to stability under different loading conditions and influences the stability against seepage-related failures, including internal erosion or piping. Internal erosion is a major concern for failure of tailings dams where soil particles in the dam or foundation are transported downstream by seepage flow when erosive forces from hydraulic loads exceed the resistance to erosion (ICOLD 2017). This process may occur through the embankment, along structures that penetrate the structure (i.e., drainage features), through the foundation, or at the embankment into or at the foundation (ICOLD 2017). The mechanisms by which internal erosion may initiate includes concentrated leaks, backward erosion, contact erosion, and suffusion (ICOLD 2017). Regardless of the way in which internal erosion develops, it typically develops rapidly. As a result, it is generally not appropriate to utilize an observational approach for internal erosion. Instead, defensive measures should be employed wherever appropriate. Three basic categories of defensive measures (Klohn 1979) are:

- Seepage reduction measures to reduce water pressures and seepage forces, including impervious cutoffs (i.e., low permeability cores), grout curtains, and upstream impervious blankets;
- Drainage to reduce water pressure in the dam and foundation, including vertical drains, horizontal blanket drains, strip drains, toe drains, and relief wells; and
- Filters to reduce the risk of piping and heaving.

In terms of seepage reduction measures, low permeability cores are sometimes used in the oil sands. They can be used with downstream and centreline construction methods and may be inclined or centred depending on the facility. In order to construct a low permeability core, there must be sufficient low permeability material available. Depending on the site, this may limit the adoption of this technique for phreatic surface control. Within the oil sands, lean oil sand is often used as a core material. Regardless of the material used, it is common for the material to be specified as non-dispersive to limit the risk of internal erosion. As a result, the Clearwater Formation is typically avoided for use as in the core as it is generally dispersive (Sisson et al. 2012).

Internal drainage zones may also be used to lower the phreatic surface, which typically consists of a higher permeability zone that will help convey flow. Internal drainage zones may broadly be broken down into two categories: chimney drains and blanket drains (Vick 1990). Chimney drains run upwards through the dam and may be vertical or inclined. These structures may also act as a crack stopper or a filter (Pollock et al. 2014). In contrast, blanket drains run horizontally and may be used alone or in combination with a chimney drain (Vick 1990). Finger or strip drains are a variation of a blanket drain but are discontinuous along the dam centreline (Vick 1990). Syncrude's Mildred Lake Settling Basin is an example of a facility that uses strip drains (List 1996). Drains may be combined with pipes to increase discharge capacity. Vick (1990) noted that pipes should be used with caution where foundation settlement is a concern or where corrosion or chemical precipitation could occur. While chimney drains and blanket drains are easily employed in downstream and centreline dams, their application and utility are more difficult in upstream dams. Upstream tailings dams may use the tailings materials themselves as a way to control the phreatic surface whereby the slimes and sands are analogous to a core (slimes) and drains (sands) (Vick 1990). Different drainage options employed in the oil sands will be discussed using examples of various facilities.

Filters may also be employed in tailings dams to prevent migration of fines between zones of different permeability (Vick 1990). As a general rule, filters must be sufficiently fine to prevent migration, but permeable enough to discharge seepage. These are typically designed using standard retention and permeability filter criteria. Filters may consist of granular soils or geosynthetics (Vick 1990).

Geosynthetics are commonly used in seepage control applications. While a useful tool, it should be noted that FEMA (2008) advises against using geotextiles in locations where performance of the geotextile is critical to the safety of the dam. With regard to long-term performance of a dam facility, careful consideration must be given to areas where geotextiles have been used. For example, if a tailings dam requires drain performance for long-term stability, geotextiles should be avoided.

In the oil sands, seepage control systems are often complex and may change over time as the design evolves or as material availability changes over time. Pollock et al. (2014) provides an overview of different dams within the oil sands, including the dams associated with Suncor's Pond 1, Pond 5, and Sand Dump 8. The drainage systems at these facilities all vary. For example, Tar Island Dyke at Pond 1 has three coke drains at different elevations and a clay core in the upper portion of the structure (Pollock et al. 2014). Dyke 8 at Pond 5 originally was designed as an overburden structure with a core and a chimney and blanket drain (Pollock et al. 2014). This design evolved drastically over time eventually consisting of compacted overburden and tailings sand with an overburden core and a series of drains (Pollock et al. 2014). This structure also has a unique feature in that the low permeability core was eliminated at a certain elevation due to lack of appropriate material and the remainder of the dam was constructed with a geosynthetic liner in place of the core (Pollock et al. 2014). Dyke 11 at Sand Dump 8 was originally designed to include a chimney filter (Pollock et al. 2014). As with Dyke 8 at Pond 5, this design evolved drastically overtime and eventually included a chimney drain and a drain that sat above the chimney drain (Pollock et al. 2014). In this particular case, the chimney drain was rendered redundant due to a change in the purpose of the facility to act as a sand dump (Pollock et al. 2014).

As previously noted, CNRL's Horizon Dyke 10 is an overburden dyke. This structure has an inclined low permeability core and chimney drain (Sisson et al. 2012). The chimney drain is connected to a horizontal drainage blanket that has a perforated high density polyethylene (HDPE) collection pipe wrapped in filter fabric running along the entire length of the dam near the end of the horizontal blanket (Sisson et al. 2012). Outlet finger drains are connected to the collection pipe and convey seepage from the chimney and blanket drain to the exterior of the dam (Sisson et al. 2012). The outlet finger drains consist of a pipe or synthetic drain surrounded by filter sand (Sisson et al. 2012). Seepage from the finger drains and surface runoff are collected in a seepage collection ditch that runs around the perimeter of the dam (Sisson et al. 2012). This structure has an innovative design feature in that the horizontal blanket drain is elevated above the dyke foundation with the finger drains extending from the end of the horizontal blanket to the downstream face (Sisson et al. 2012). It was recognized that this design posed a higher piping risk and a mitigation plan was developed to install pumping wells in the chimney drain to lower the phreatic surface if necessary. The structure also has a shallow seepage cut-off trench to limit seepage through the foundation (Sisson et al. 2012).

Suncor's South Tailings Pond overlies a confined channel called the Wood Creek Sand Channel (Stephens et al. 2006). It was expected that artesian pressures could develop in the channel as the dam was constructed and the pond was increased. To mitigate this, pressure relief wells were designed to reduce the artesian pressure (Stephens et al. 2006). The pressure relief wells are advantageous as they are flexible from a design perspective (Stephens et al. 2006). Further, they are a passive system and do not require power or pumping (Stephens et al. 2006).

It should also be noted that some facilities in the oil sands take a no filter approach. In these cases, overbuilding is conducted to suppress hydraulic fracturing across high specification core zones by increasing the total stress in these zones (McRoberts 2008). These approaches require extensive construction specification (McRoberts 2008). An example of a structure without a filter in the oil sands is Syncrude's Highway Berm. Syncrude's Southwest Sand Storage was also designed such that it would not have an extensive internal drainage/filter system (List et al. 1996).

2.4.4 Coal Mining

Coal can be extracted using underground mining or surface mining techniques. Underground mining was primarily used in Alberta until the 1950s when surface mining became more prevalent due to the development of massive earth-moving machines (Alberta Culture and Tourism 2018a). Large scale surface mining began in 1962 at Whitewood Mine near Wabamun Lake west of Edmonton and supplied coal for Calgary Power's Generating Plant (Alberta Culture and Tourism 2018b). As large scale surface mining began, storage dams for water and waste became necessary. According to Alberta Energy (2019), there are currently nine active surface coal mines in Alberta as shown in Table 2-4. Mines that are in the process of being reclaimed and have licensed dams present on the mine site are also indicated on Table 2-4. Depending on the mine, coal may be extracted from the ground using different surface mining techniques, including open cast (strip) mining, open pit mining, or a combination of the two methods. The selected method is dependent on the natural, spatial, and geologic characteristics of the coal deposit and will impact the type of equipment used in the mining process (Hartman and Mutmansky 2002). Typically, draglines, shovels, and trucks are commonly associated with strip mining techniques where as shovels and trucks are generally used for open pit mining operations (Hartman and Mutmansky 2002). For example, the Coal Valley Mine uses a combination of open pit (truck/shovel) and modified strip (dragline) mining methods as the coal seams are steeply dipping (Coal Valley Resources Inc. 2008).

Table 2-4: Coal mines in Alberta (Alberta Energy 2019, AER 2022)

Mine Name	Status of Mine	Dam	Main Use
Cheviot	Active	Yes	Export: Metallurgical
Coal Valley	Active	Yes	Export: Thermal
Dodds	Active	No	Small-scale Sales
Genesee	Active	Yes	Electricity: Genesee Generating Station
Grande Cache	Active	Yes	Export: Metallurgical
Highvale	Active	Yes	Electricity: Keephills and Sundance Generating Stations
Luscar	Reclaiming	Yes	Export: Metallurgical
Obed	Reclaiming	Yes	Export: Thermal
Paintearth/Vesta	Active	Yes	Electricity: Battle River Station
Sheerness	Active	Yes	Electricity: Sheerness Generating Station
Vista	Active	No	Export: Metallurgical

After being extracted from the ground, the coal may undergo a variety of processes on site that range from crushing to washing to processing to being transported directly off site after extraction. For example, at Coal Valley Mine, the raw coal is sent to the coal preparation plant to be washed to a desired specification by removing rock, partings, and fine sediments before being transported off site (Coal Valley Resources Inc. 2008). This results in the generation of a coarse and fine reject stream (Coal Valley Resources Inc. 2008). The fine reject stream, also known as tailings, is deposited in mined out pits or tailings ponds (Coal Valley Resources Inc. 2008). Overall, the mining method, the final coal use (metallurgical, thermal, or energy), and the process following mining extraction impact the volume of tailings, process affected water, and raw water on site. The volume of these fluids, the site configuration, and local topography dictates if a mine site will require dams for containment. In fact, many of the currently active coal mines in Alberta do not have any licensed dams constructed within their mine leases. Table 2-4 shows the coal mines in Alberta that have dams regulated by the AER on their mine leases.

The difference between the coal and oil sands industry in terms of dam safety is substantial from both a design and regulation perspective. In a 2015 audit completed by the Auditor General of Alberta, it was noted that the majority of coal mining tailings dam had not been inspected since the 1980s and 1990s (Auditor General of Alberta 2015). Further, it was noted by the Auditor General of Alberta (2015) that the Obed Tailings Dam failure involved the failure of the Red Green Pit dam, which was not being regulated or operated as a dam at the time of the failure even though it met the specifications of a dam in the Water Act. From a design perspective, it appears that many of the licensed coal dams were not designed or constructed to be a dam. The Obed Tailings Dam failure is a good example of this. Ultimately, this results in a lot of issues from a risk management perspective. For starters, the construction material throughout the entire dam may be unknown as there may not have been quality control measures used. Additionally, the majority of the structures do not include drains or filters as they were not originally intended to operate as dams. Further, some of the structures may include unexpected elements such as pipes or culverts.

The use of coal for power generation in Alberta is projected to be phased out by 2030 to reduce greenhouse gas emissions. This is expected to result in the closure of a number of coal mines where the coal is used for energy, but should not impact operations that export the coal for metallurgical or thermal purposes. As a result, it is expected that a number of coal dams will be decommissioned in the coming years. Advancements must be made to understand how these dams behave in the long term, especially given the lack of knowledge surrounding their design and construction.

2.5 Long-term Behaviour of Tailings Dams

The aim of tailings dams is often to maximize storage within the context of the operating and risk management strategy while maintaining regulatory requirements (Bayliss et al. 2014). Ultimately, this can result in long-term challenges being overlooked. There is limited information available on the long-term behaviour of tailings dams. This is further complicated by the fact that each dam will have site specific considerations and circumstances that may not be applicable to other sites. Additionally, there is sometimes a lack of willingness amongst owners to share data on their sites. Ultimately, this contributes to an information gap and a lack of readily available published data on the physical behaviour of tailings dams in the long term. This section provides a review of some sources of available data on the long-term physical behaviour and utilizes site specific information where possible.

The long-term behaviour of tailings dams is highly dependent on the surrounding environment as much as it is dependent on the individual characteristics of the facility. For example, beaver dams may develop at surrounding lakes and result in the development of conditions that have the potential to place the dam in a critical state, such as at the Matachewan Consolidated Mine in Ontario. An upstream tailings dam at the mine failed in 1990 and released tailings (approximately 190,000 m^3) into Davidson Creek and Montreal River (Baker et al. 1996). Following 1953, the site was left unmanaged until the failure occurred (Baker et al. 1996). As part of the development, a channel was constructed to divert water from a nearby lake (Otisse Lake) and prevent it from flowing through the facility (Baker et al. 1996). The primary cause of the failure was the growth of a beaver dam at the outlet of the Otisse Lake that prevented water from flowing away from the tailings area (Baker et al. 1996). Instead, the water level in the Otisse Lake continued to rise until the tailings area was largely covered by water (up to the crest elevation of the dam) (Baker et al. 1996). Ultimately, the slow but continuous rise led to the development of conditions necessary for failure to occur (Baker et al. 1996). Baker et al. (1996) speculates that the failure may not have occurred if the beaver dam had been removed periodically or if the beavers were trapped. While this is likely true, the practicality of it from a long-term perspective depends on the custodial care of the site and would not be possible from a 'walk-away' closure perspective. This suggests a need for more robust designs, which may include design aspects such as 'beaver bafflers'.

Samatosum Mine, located near Barriere in British Columbia, has been in the closure phase since 1992 when the mill was permanently shut down (Piteau 2017). At the time, the mine was owned by Minnova Inc. (Piteau 2017). Following this, the mine went through a change of ownership multiple times from Minnova Inc. to Inmet Mining Corporation to First Quantum Minerals Ltd. and is currently undergoing decommissioning work (Piteau 2017). This continuous change of ownership is common with mines and may pose a threat to long-term stability. Samatosum Mine demonstrates a number of key problems that may emerge with long-term management or stability of TSFs. It should be noted that the reclamation strategy for the facility consists of a permanent water cover (First Quantum 2017). In the 2016 Dam Safety Inspection Report, Piteau (2017) noted that there were cattle tracks present near the tailings impoundment due to cattle accessing the site from damaged perimeter fences. The reality is that cattle, people, or wildlife may access closed sites despite fences. This factor must be considered from a long-term perspective. Piteau (2017) notes the importance of vegetation on the crest and downstream faces in preventing surface erosion and stabilizing surficial soils, but indicates that small shrubs should be removed as they may impede visual inspection of the dam. Further, the report notes that trees growing in the embankment should be removed due to the potential for windfall and subsequent erosion (Piteau 2017). This strategy would only be feasible with someone caring for the site and not with walk-away closure in mind. Piteau (2017) also noted that there were several gopher holes on the downstream face of the dam that were concentrated in the drainage blanket with lengths up to 3.5 m. They concluded that the effects of the burrows on the stability of the dam were negligible but noted that burrowing near the upstream face could increase the risk of local piping and erosion (Piteau 2017). To mitigate gopher activity, galvanized mesh was installed on the upstream and downstream faces, and there is an ongoing population control program (Piteau 2017).

The Sullivan Mine, located in Kimberley, British Columbia, has been closed since 2001 and is owned by Teck Metals Ltd. (Marsland et al. 2004, Peterson et al. 2015, KCB 2017a). Reclamation activities began on the facilities in 1990 and were mostly complete by 2008 (KCB 2017a). The site has 15 dams and dykes that form 7 separate facilities (including water and tailings retaining facilities) (KCB 2017a). In preparation for closure, the facilities at Sullivan Mine were designed using the probable maximum flood, the probable maximum precipitation, and the maximum credible earthquake (KCB 2017a). Further, the facilities were designed for a minimum FS of 1.5 against long-term static stability and 1.1 for seismic stability with liquefaction of tailings (KCB 2017a). There are currently three operating facilities: the ARD Storage Pond, the Emergency Storage Pond located within the Iron Pond dyke and the Sludge Pond. The remaining facilities have been decommissioned and are undergoing reclamation, which includes covering the pond surfaces with a multi-layer cover system of float rock and till and the construction of spillways and channels that are designed to pass the probable maximum flood (PMF) (KCB 2017a). To mitigate erosion, the channels are lined with riprap and have stilling basins where required (KCB 2017a). Consequently, the only ongoing activities are care and maintenance, which includes cleaning of ditches, removal of trees and shrubs from dike slopes, and maintenance of seepage collection systems (KCB 2017a). According to the 2016 Dam Safety Inspection, the ditch north of the North Dam of the acid rock drainage (ARD) Pond had filled with debris and needed to be cleaned out (KCB 2017a). There was also a buildup of algae in the ditch south of the South Dam that needed to be cleaned out (KCB 2017a). It was suspected that the algae may have impacted flow of seepage in the ditch (KCB 2017a). Piezometers at various structures showed an increase in 2011 to 2014, which is attributed to increased precipitation and snowpack during those years (KCB 2017a). Gopher holes were observed at the toe of one of the dikes (KCB 2017a). The 2016 Dam Safety Inspection indicates that the main concerns for failure are overtopping during major flood events and piping (KCB 2017a). Regardless, this is considered a low risk due to the closure design, which incorporates conservative design values, such as the PMF, drainage channels, and spillways. Following closure, a site-wide adaptive risk management plan was implemented to check that closure objectives were being met with regard to groundwater, surface water, vegetation and aquatic biota (Peterson et al. 2015). Based on the paper presented by Peterson et al. (2015), it does not appear that the adaptive risk management plan was applied to the geotechnical stability of the TSFs.

Pinchi Lake Mine, located in central British Columbia, is a closed mercury mine owned and operated by Teck Metals Ltd. (KCB 2017b). The tailings storage facility is a side hill impoundment, and reclamation and closure works on the tailings storage facility were completed in 2011 (KCB 2017b). The dam was originally a homogeneous dam constructed with glacial till, but during a dam raise in 1975, a transition zone and rockfill were placed on the downstream slope (KCB 2017b). The dam is approximately 3 m to 15 m high (KCB 2017b). The tailings in the impoundment have been covered with till and vegetation and is currently being referred to as a 'landform' (KCB 2017b). The facility does not impound water and has a riprap lined open channel closure spillway (KCB 2017b). Despite the conversion of the dam to a 'landform' as described in the 2016 Dam Safety Inspection (DSI), the facility is still classified as a dam with a Significant consequence classification based on the 2007 Dam Safety guidelines (KCB 2017b). The dam previously had a decant system that was backfilled with soil (KCB 2017b). Erosion was noted in a number of different locations in the 2016 DSI over time (KCB 2017b). The recommended action for remediation of the erosion was typically to place erosion protection such as rip rap. In the nearby diversion channel, the rip rap was shown to be degrading over a relatively short time frame (reclamation was completed in 2011) (KCB 2017b). Due to this, the question needs to be asked if recommending rip rap protection for erosion control can be viewed as a long-term reliable solution. There was a previously observed slump on the downstream slope of the dam (KCB 2017b). This is an interesting observation as the facility had been closed for 36 years at the time of reclamation works in 2011, which clearly shows that the dam is still changing and evolving. During clearing of vegetation on the downstream slope of the dam, a manhole-like concrete structure was observed at the toe of the dam (KCB 2017b). It is believed that this is from an old sewage system that existed before the dam was built (KCB 2017b). Further, the facility had a decant system that was abandoned (KCB 2017b). These types of structures (unknown or abandoned) may pose a long-term hazard to the facility. Previously, the dam only had one piezometer installed, which was destroyed in 2008 (KCB 2017b). It was noted in the 2014 and 2015 DSIs that this piezometer would not be replaced as the dam had been converted to a landform (KCB 2014a, 2016a). This attitude towards monitoring is concerning when it comes to the potential for the facility to undergo custodial transfer back to the crown. The mine owner should be able to prove that the facility is behaving as expected.

may potentially indicate that the phreatic surface has not lowered over the 8-year period. This is problematic as Donald et al. (2013) noted that "the geotechnical stability was improved during the site reclamation program by lowering the phreatic surface within the dam and tailings impoundment area by installing an active spillway". In the absence of instrumentation, this does not seem to be proven, and in fact, the instrumentation data from 2016 shows that the phreatic surface has not lowered if taken at face value. If mine owners are relying on assumptions, such as the phreatic surface behaviour, to validate stability, the assumptions must be supported by data. Vegetation on the structure is also regularly removed (KCB 2017b). This type of decision should be evaluated from a long-term maintenance perspective. Is maintenance envisioned to occur in a perpetual manner? If it is not, then alternatives to regular vegetation removal must be evaluated.

Red Mountain Mine, located in southeastern British Columbia is a closed molybdenum mine with two tailings storage facilities, including: Good Friday and Jumbo (KCB 2014b, Ministry of Energy and Mines 2016). The mine operated from 1966 and 1972 and is under the Ministry of Energy, Mines and Petroleum Resources care (KCB 2014b). At the time of the 2014 DSI, an inspection had not been conducted since 2004 (KCB 2014b). Since the time of closure, a ski resort area has been developed nearby with the ski lodge located approximately 800 m from the Good Friday TSF (KCB 2014b). This development demonstrates how there can be changing populations, consequences, and stakeholders as time passes following closure. The Good Friday TSF is a side valley impoundment with a dam that has a maximum height of 20 m and is composed of compacted till and coarse rock fill (KCB 2014b). The 2014 DSI indicates that it seems as if a portion of the dam was raised using upstream construction and a portion was raised using downstream construction (KCB 2014b). This type of situation is not dissimilar to the coal mining industry in Alberta where there are often not definitive records of design or construction and shows the importance of data management and records as mine sites change ownership. The Jumbo TSF is a cross valley (Little Sheep Creek valley) impoundment with a rockfill dam that has a maximum height of 28 m (KCB 2014b). The rockfill dam has upstream fine and coarse filters and a basal blanket drain (KCB 2014b). A corrugated metal pipe runs under the Jumbo TSF to divert the Little Sheep Creek (KCB 2014b). In 1999, a sinkhole formed on the impoundment surface due to the failure of the corrugated metal pipe diversion (KCB 2014b). Following this event and an overtopping event at the Good Friday TSF, the Ministry of Energy and Mines started reclamation works using INCO Technical Services, which were carried out from 1998 to 2004 (KCB 2014b). Reclamation works involved armouring drainage and spillway channels, rockfill toe berms as required, grouting a portion of the Little Sheep Creek Diversion underneath the Jumbo TSF, removing and grout backfilling decant structures, installation of subsurface drains, revegetation, and installation of monitoring wells and v-notch weirs (KCB 2014b). The OMS Manual, developed in 2005, provides recommended annual OMS tasks (KCB 2014b). As of the 2014 DSI, KCB noted that it did not appear that any of these tasks had been undertaken since 2004, including reading of the instrumentation (KCB 2014b). This observation clearly shows the risk associated with not having appropriate systems in place for owners defaulting, including adequate funds and processes for required ongoing maintenance. The 2014 DSI notes that the design of the surface water management plan is to provide a long-term, low maintenance system (KCB 2014b). While this is positive and should be the goal for reclamation, it seems that there has been a missed opportunity at this mine to assess performance of a reclaimed structure in the long term and compare it to predicted behaviour for learning across the mining industry. It was noted during the 2014 DSI that there was seepage exiting above the seepage collection pipe at two locations at the Good Friday dam. Due to a lack of monitoring over time, no definitive causes of this seepage were noted by

KCB (KCB 2014b). Vegetation was noted to be growing in various places across the two TSFs (i.e., crests, downstream slopes, spillway channels), but were not noted to be a concern for stability of the facilities (KCB 2014b). However, it was noted that trees and shrubs in spillway channels may reduce the discharge capacity of the channels (KCB 2014b). The 2014 DSI provided a number of recommendations to be completed at the two TSFs. In an inspection conducted in 2016 by the Ministry of Energy of Mines it was noted that "the designated Mine Manager for MEM committed to completing the recommendations and provided a course of action and schedule for each one as outlined in the following table. It should be noted that none of the recommendations were completed in 2015" (Ministry of Energy and Mines 2016). Further, the inspector indicated that in their opinion, the existing TSF management practices at the mine do not meet current best practices (Ministry of Energy and Mines 2016). It is not known at this time if management practices at the Red Mountain Mine have improved. If anything, the Red Mountain Mine clearly demonstrates the dangers of not having systems or funds in place for abandoned/orphaned mines, which may result in irregular monitoring, maintenance, and care.

The National Orphaned/Abandoned Mines Initiative (NOAMI) (2010) conducted a review to provide guidance for mine closure and management of long-term liabilities. Based on the review, it was suggested that greater effort needs to be put into the development of post-closure policy, regulations, and procedures (NOAMI 2010). NOAMI (2010) notes that Saskatchewan is the only province to have a process, regulations, and policies regarding long-term care and monitoring. NOAMI (2010) performed a questionnaire with various regulating bodies across Canada to determine the existing legislation/regulations/policies/practices for mine closure across Canada. Based on the questionnaire, they noted that "while several agencies report they will not accept properties with ongoing water treatment/contamination concerns, there is little discussion on how these sites will be maintained (funding and management) once the proponents ultimately disappear" (NOAMI 2010). This is an interesting observation and is applicable to Alberta with regard to the transition of dams to mine waste structures or landforms. There does not seem to be a plan or acknowledgement for scenarios where dams cannot be classified as a mine waste structure and the owner defaults in the long term. They also note that some jurisdictions have provision for relinquishment of mining lands to the Crown but that the process seems to be subjective in some cases (NOAMI 2010). NOAMI (2010) emphasizes the importance of closure objectives noting that they are fundamental to determine what is in the closure plan, the required work, and how much it will cost. NOAMI (2010) also notes that "the other difficulty from a long-term care perspective is unplanned events such as storm surges on tailings areas causing run-off and erosion or even a run-out of tailings. It is difficult to accurately predict what may occur, when it may occur, extent of damage, and the actual cost. However, some allowance should be made for contingency purposes". This is an important consideration when it comes to evaluating long-term behaviour and the potential for walk-away closure scenarios of tailings dams.

Historically, tailings dams were designed and constructed for the mine's active life. While closure is now considered in the design of many tailings dams, there still remains issues with many sites when it comes to completing reclamation. One such issue is that many mine operators do not leave sufficient room for adjustments and tailings dams are often located adjacent to lease boundaries resulting in little room for changes to the facility for closure and for expansion or deposition of eroded material (Slingerland et al. 2018c). For example, the Aurora South Mine project is proposed to be developed southeast of the ETF at the Jackpine Mine (Bayliss et al. 2014). The current proposed offset between the ETF at Jackpine Mine and the mine surface lease of Aurora South Mine is 200 m (Bayliss et al. 2014). This offset will impact risk management strategies (including contingency measures) for the ETF at Jackpine Mine (Bayliss et al. 2014). Further, the ETF at Jackpine Mine is surrounded by an infrastructure corridor (Bayliss et al. 2014). All of these factors would limit adaptation of the dam slope and shapes for successful closure (Bayliss et al. 2014).

Erosion has the potential to have devastating impacts on the stability of a tailings dams in the long term, especially in the absence of care and maintenance. This is critical in the oil sands as many of the structures are composed of highly erodible sand. Over time, it is expected that landforms will be geomorphically altered from the combined effects of nature (climate, precipitation, vegetation, wind, etc.). Slingerland et al. (2018a, 2018b) conducted a study to investigate erosion of a sand dam in the Alberta oil sands using a Landscape Evolution Model (LEM) to aid in assessing their long-term geomorphic stability. The results of the study for a 200-year simulation period indicated that the morphology of the structure was well established within 60 years with gullies most frequently forming in areas of concentrated flow (i.e., horizontally concave dam sections) and retrogressively travelling inward towards the pond (Slingerland et al. 2018a, 2018b). The development of erosional features on a dam may be impacted by the dam height (including the length of the slope), the grain size distribution of the material, and climate (Slingerland et al. 2018b). The results showed that some potential areas of concern in the long-term may be substantial sediment discharge off-site, the formation of deep gullies (greater than 15 m deep), and the filling of drainage channels (Slingerland et al. 2018b). The results also suggested that it would be advantageous to grade dams such that surface water is collected and directed toward armoured swales and transported to the perimeter channel as opposed to having a uniform slope that allows sheet flow (Slingerland et al. 2018b). A couple of key observations from the modelling were (Slingerland et al. 2018a):

- Gullies were 20 m deep in some locations with gullies being common where flow was concentrated;
- Changes to the plateau were minimal after approximately 30 years; and
- The main drainage was impacted by erosion over almost the entire length to a depth of over 10 m in some locations.

The research also showed that vegetation played a huge role in reducing erosion. Overall, major gullies started to form before the vegetation matured with no major gullies forming following vegetation maturity (Slingerland et al. 2018a). Erosion gullies began to form near the bottom of the slope as the soil typically has a higher water content resulting in the flow transitioning from dispersive flow to centralized, efficient flow paths (Slingerland et al. 2018a). This centralized flow allows the water to gain speed and increases its erosive power (Slingerland et al. 2018a). Erosion gullies also formed from surface water being directed and concentrated in one location and then finding the easiest route to travel (Slingerland et al. 2018a). Overall, the results of the study indicated that erosion in the long term may result in the structure not functioning as designed, which could lead to failure of the structure to retain tailings. This indicates a potential need for ongoing maintenance of the structure. Consequently, this research poses a number of interesting questions. First, will walk-away closure be possible given the ongoing impacts of erosion? Do mine owners need to adjust the time that they have allowed for maintenance of tailings dams following mine closure? Second, given situations where the facilities are not maintained, what would the impact of erosion be on the geotechnical stability of the facility? Could erosion trigger catastrophic failure of the tailings dam? Could significant erosion gullies form that are deep and long enough to intersect the former impoundment such that water and tailings are able to mobilize?

An additional issue that must be considered with assessing the long-term stability of a tailings dam is the way in which the dam materials and contents age over time. This is a complex issue that may require in depth knowledge of the geochemistry and the way that the seepage regime evolves over time. Soils may be subject to a variety of changes: saturation, permeability, stress-strain behaviour, shear strength, etc. For example, there were water-retention dykes in Manitoba that were constructed in 1929 and exhibited irregular instability after being heightened in the late 1940s (Man et al. 2011). Ultimately, it was determined that the instability was caused by leaching of gypsum that led to increased brittleness and strain softening behaviour (Man et al. 2011).

There is a large global inventory of TSFs with some sources indicating that there are over 3,400 active TSFs worldwide (Franks et al. 2021). Many of these TSFs are old and were designed and constructed with little consideration of closure. This historical approach to mining has resulted in TSFs that are in a poor position for closure or have been abandoned/orphaned all together. The consequences of this are well recognized as noted by Asia-Pacific Economic Corporation (APEC) (2018) as follows:

- Physical hazard of mine structures;
- Environmental impacts of mine waste;
- Vegetation re-growth may be slow resulting in reduction of biodiversity on some sites; and,
- Negative social impacts on surrounding communities.

The negative consequences associated with poor mine closure practices has resulted in a push towards sustainable mining practice with an emphasis on closure. The importance of sustainable mining practice is now reflected in regulations in various jurisdictions and guidelines produced by different organizations. The extent of regulations in different areas varies greatly with some jurisdictions having little to no regulation while others adhere to a robust governance framework (APEC 2018).

Overall, the literature review reveals that there is a lack of published academic data demonstrating how tailings dams behave in the long term. This gap should be filled to aid in closure planning and long-term risk management. The industry would be greatly benefited by published case studies that demonstrate how a tailings dam is behaving following closure – especially if the behaviour could be compared to initial projections in the design process. In the absence of this, industry professionals can be used to aid in filling in the identified knowledge gap by drawing on their experience.

2.6 Risk Management

Risk management is a systematic process that involves the application of policies, procedures, and practices to aid in identifying, analyzing, assessing, mitigating, and monitoring risk (Fell et al. 2005). This is a complex process; however, when done correctly risk management can aid in reducing the potential for failure of tailings dams. Risk management and risk communication are outlined in Figure 2-8. This research focuses specifically on physical failure of tailings dams.

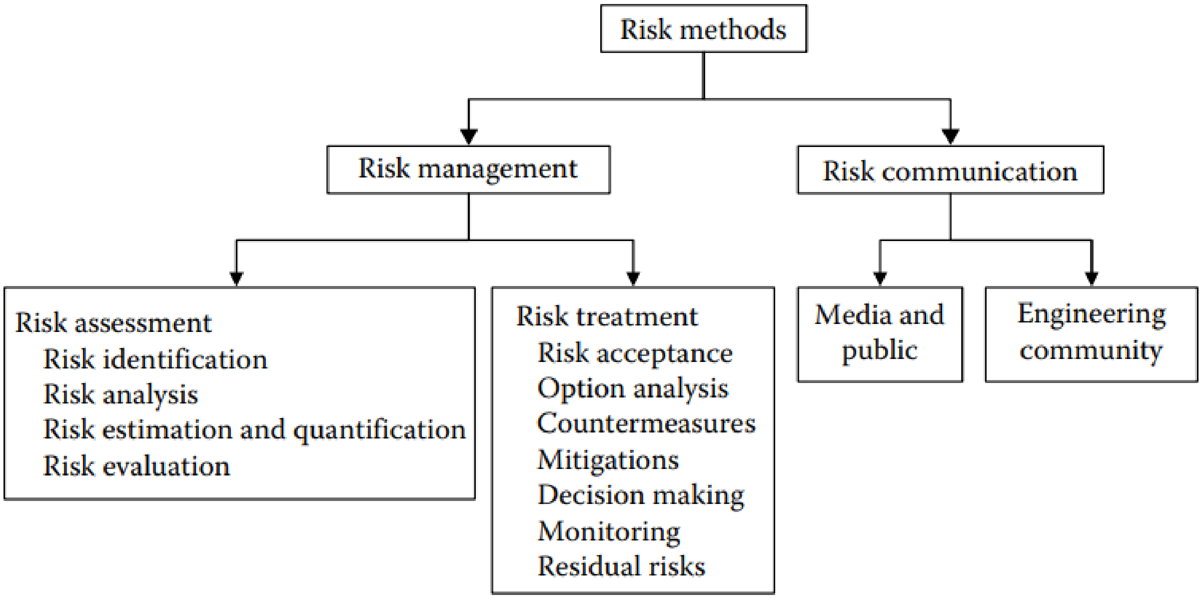

Figure 2-8: Basic risk management process (from Ayyub (2014))
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2.6.1 Risk Assessment

Risk assessment is the process of determining if existing risks are acceptable and if risk control measures are sufficient (Fell et al. 2005). If not, alternative risk controls are evaluated and implemented. Risk assessment is a technical and scientific process that includes risk analysis and risk evaluation (Ayyub 2003). Risk analysis includes hazard identification and risk estimation. This analysis involves developing an understanding of the causes and sources of risk, their positive and negative consequences, and the likelihood that those consequences occur (ISO 2009). Risk analysis can be undertaken to different levels of detail and can be qualitative, semi-quantitative, quantitative, or a combination (ISO 2009). The level of detail and the type of analysis depends on the risks, the purpose of the analysis, and available information (ISO 2009). Although risk is understood as the likelihood of an event multiplied by the potential negative consequences, risk management is ultimately about managing uncertainty. Consequently, risk management is integral to the success of tailings dam closure, given the significant uncertainties associated with tailings dam evolution over long time frames.

Risk evaluation then uses the outcomes of risk analysis to aid in making decisions regarding the need for risk control measures. This process compares the level of risk identified during risk analysis with previously defined risk criteria (ISO 2009). This then allows decisions to be made regarding if the risk threshold is acceptable or if controls are required.

As noted by Whitman (1984), systematic application of an analysis is important to the overall understanding of the major sources of risk. When completed at the beginning stages of a project, risk management allows for meaningful decisions to made based on identified risks and guides the process of establishing design criteria (Whitman 1984). Risk management decisions require a careful considerations of the allowable risk, which can be used to dictate the required level of conservatism (Whitman 1984).

The risk assessment process generally involves the use of formal methods to aid in hazard identification and risk estimation. The following is a list of different risk assessment methods (Ayyub 2003, Valis and Koucky 2009):

- Safety/review audit;
- Checklist;
- What if/then;
- Structured ‘what-if’ technique (SWIFT);

- Scenario analysis (SA);
- Layers of protection analysis (LOPA);
- Hazard and operability study (HAZOP);
- Preliminary hazard analysis (PrHA);
- Probabilistic risk analysis (PRA);
- Root cause analysis (RCA);
- Failure modes and effects analysis (FMEA);
- Risk matrices;
- Fault tree analysis (FTA);
- Event tree analysis (ETA);
- Bow tie analysis;
- Delphi technique;
- Interviewing;
- Experience-based identification; and
- Brainstorming

Further details on these risk assessment tools can be found in Ayyub (2003) and Valis and Koucky (2009). It should be noted that this list is not considered exhaustive. As discussed in Section 1.3, Objective 3 of this research is to develop a risk assessment tool based on failure consequence and probability for closure of external tailings facilities, similar to a Failure Modes and Effects Analysis (FMEA). This process requires the identification of failure modes as a tailings dam transitions into a landform following mine closure. FMEA was chosen as the basis for this tool based on its prevalence of use in industry and its ability to identify all potential failure modes, consequences of these failure modes, the mechanisms of failure, and how the risks associated with the failures can be avoided or controlled (Valis and Koucky 2009).

2.6.1.1 Failure Modes Effects Analysis (FMEA)

FMEA allows for systematic identification and analysis of the different failure modes and their associated consequences (Ayyub 2003, Robertson and Shaw 2006). FMEA aims to identify all potential failure modes, the consequences of these failure modes, the mechanisms of failure, and how the risks associated with the failures can be avoided or controlled (Valis and Koucky 2009).

FMEA can be combined with a criticality analysis to form a failure mode effects criticality analysis (FMECA), which allows for the different failure modes to be ranked with consideration of the probability and consequences of failure (Hartford and Baecher 2004). The entire process is based on determining what happens if a specific component or element of the system fails (Hartford and Baecher 2004). When extended to apply to a dam, FMEA focuses on developing a clear picture of the dam, including the various components and how they interact, in a systematic way (Hartford and Baecher 2004). Using this basis, FMEA can be used to evaluate how component failures could lead to overall system failures, the consequences of component and system failures, and the criticality of various components for risk control (Hartford and Baecher 2004).

FMEA is generally site specific and considers site data, construction method, construction materials, and past behaviour of the structure (Küpper et al. 2013). As a result, it can be a time-consuming, complex process. Additionally, FMEA has an incapacity to include time dependence and depreciation of performance of system components (Santos et al. 2012). Despite this, it has proven to be a useful tool as it allows risks to be assessed and managed. As shown by Santos et al. (2012), FMEA is effective in demonstrating potential failure modes of all components of a tailings dam system that then allows for the development of a comprehensive dam monitoring and surveillance system. Ultimately, the desired outcome of an FMEA is the development of worksheet that provides a structured, repeatable, and documented process (Martin and Davies 2000, Santos et al. 2012). The aim of this is to facilitate effective communication between different project employees (i.e., technical versus front-line). To conduct an FMEA, the following structure can be used (Hartford and Baecher 2004):

1. Define the system, including all components.
2. Based on component interaction, de-aggregate the system into functional sub-systems.
3. Break the sub-systems down into key elements and functions.
4. Analyse the failure modes of the different elements.
5. Assess the failure effects and consequences of the various elements.
6. Summarize findings.
7. Repeat as necessary.

Step 4 and 5 involve analyzing the failure mode, effects, and consequences of the different elements. This is an important step as it allows the effect of component failure modes on other components of the sub-system and the overall system to be evaluated. This process is represented in Figure 2-9, which shows that FMEA can be carried out to a variety of depths and thus the system definition is very important to success. In Figure 2-9, the dam system has been broken down into a series of sub-systems whereby the failure effects at a lower level become the failure modes for the next highest level in the system (Hartford and Baecher 2004).

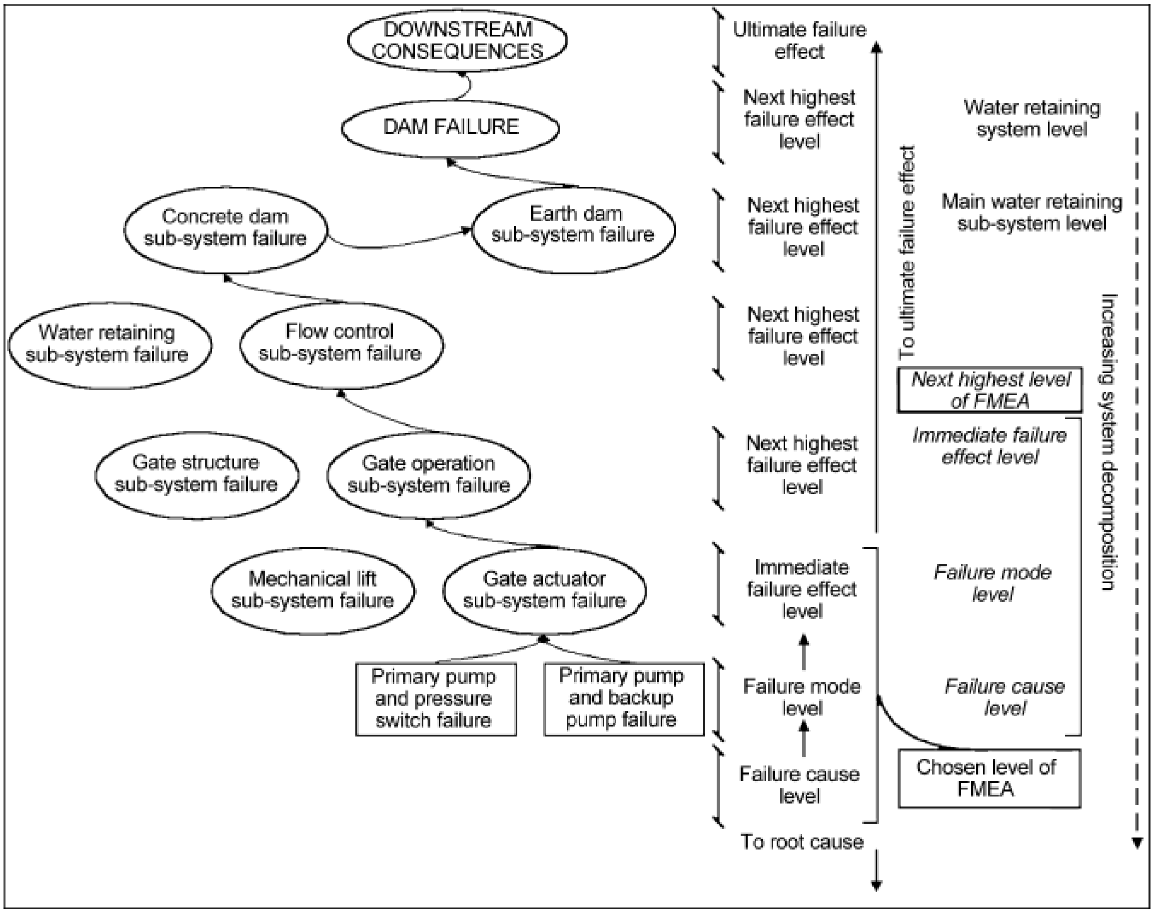

Figure 2-9: FMEA process for dam system and sub-systems (from Hartford and Baecher (2004))
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As discussed, FMEA can be extended to include criticality analysis where the various failure modes are ranked according to the consequences and probability of failure (Hartford and Baecher 2004). In order to estimate the likelihood and consequence of different failure modes, qualitative risk matrices are often used. Risk matrices are discussed further in Section 2.6.1.2

2.6.1.1.1 Learnings from the PFMA Process

The Federal Energy Regulator Commission (FERC) provides guidance on conducting a potential failure modes assessment (PFMA) to identify all potential failure modes (the chain of events that result in unsatisfactory performance of the dam or a portion of it) (FERC 2017). Throughout this process, there are important questions that need to be answered, including (FERC 2017): how could the dam fail? What could happen if it fails? Are the identified potential failure modes recognized and being monitored for? What actions can be taken to reduce or mitigate dam failure probability or consequence? The PFMA involves identifying, describing and discussing all potential failure modes and then classifying them according to 4 different categories, as follows (FERC 2017):

- Category I: Highlighted potential failure modes that are considered to be of the greatest significance;
- Category II: Potential failure modes considered to be credible, but are not highlighted;
- Category III: More information or analyses is needed in order to classify these potential failure modes; and
- Category IV: Potential failure mode ruled out.

The PFMA process presented by FERC (2017) is used across the United States and had been employed at the Oroville Dam when the Oroville Spillway Incident occurred in 2017. Following the incident, the Independent Forensic Team evaluated the PFMA process and identified a number of shortcomings and provided suggestions for improvement (France et al. 2018). The identified gaps include:

- PFMAs tend to focus on uncontrolled release of the reservoir and often overlook PFMs associated with component failures that would not result in uncontrolled reservoir release. The issue with this is that these failures could still involve serious consequences to both the dam owner and the public. This means that failure modes may be excluded simply due to the definition of failure;
- PFMAs are dependent on the quality of the provided information and the overall knowledge and experience of the individuals participating in the workshop;
- PFMAs may overlook components (e.g., spillways);

- PFMAs have difficulties characterizing risks for large or complex systems and have difficulty accounting for human and operational aspects of failures;
- The current PFMA process does not explicitly consider how broader organizational factors can contribute to failure;
- PFMAs tend to simplify failure modes as a simple chain of events that can oversimplify complex failure modes that involve multiple interactions of system components;
- Expert opinion may be heavily relied on during the PFMA process;
- Aspects of group-think can compromise judgement and decision making;
- PFMAs are only as good as the input data, time available, and people involved;
- Normalization of deviance can be an issue; and
- Compliance with regulatory requirements for risk assessments is not sufficient to manage risk.

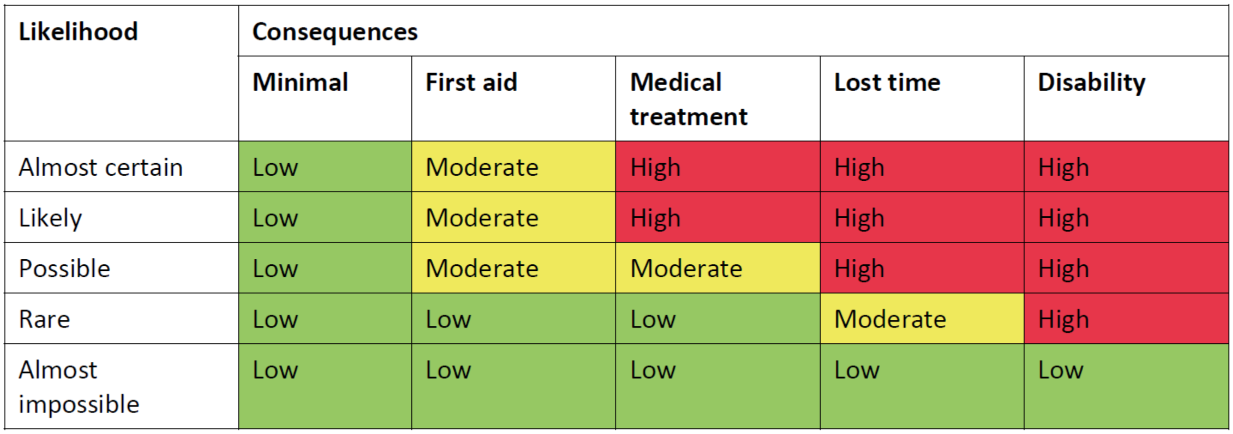
It should be noted that the US Army Corps of Engineers (USACE) used PFMA as an initial step in conducting risk-informed decision-making processes, followed by quantitative or semi-quantitative risk analyses (France et al. 2018). In contrast, FERC uses PFMA as a standalone process for all of its licensed hydropower dams (France et al. 2018). PFMAs are supposed to be used as an initial step towards risk assessment, but FERC never applied this methodology. France et al. (2018) provided suggestions for improvement of the PFMA process. While the PFMA process is different from FMEAs (France et al. (2018) notes that they are less structured), some of these suggestions can be considered for integration into improving the FMEA process, including:

- A broader definition for failure should be adopted and used to guide the PFMA process;
- More complex systems with multiple types of factors (including human and operational aspects) should be considered;
- Owners must have a full understanding of all consequences, extending beyond loss of life;
- The PFMA process must focus on all structures; and
- Develop a master list of generic potential failure modes as a starting point and checklist for developing project-specific potential failure modes. This should include the knowledge of failure modes that have occurred in the past. It is important that the master list does not limit the scenarios for the PFMA that are developed and considered.

2.6.1.2 Risk Matrices

Risk matrices are visual tools that allow different categories of likelihood of occurrence and consequence to be defined such that a risk rating can be determined (Ayyub 2003). This risk rating can then be used to determine risk control measures that should be implemented. In order to be effective, all components of the risk matrix must be clearly and unambiguously defined. Some example risk matrices, include Brown (2019), Hadjigeorgiou (2019), Griffin (2017), MEND (2012), and OSTDC (2014).

Brown (2019) provided an example of a typical risk assessment matrix, but did not provide descriptions for the different likelihood and consequence ratings or provide details on the intended application. Hadjigeorgiou (2019) also provided a risk matrix, as shown in Figure 2-10, for an underground hard rock mine used by personnel for mining activities where the personnel are expected to complete the risk matrix prior to an activity. The absence of clear descriptions of the likelihood and consequence ratings is problematic. Brown (2019) and Hadjigeorgiou (2019) (Figure 2-10) both used the terms ‘almost certain’, ‘likely’, and ‘possible’, but it is unclear if these are intended to have the same definition. Further, verbal probability terms such as these are not universally understood to have the same meaning amongst practitioners (Reagan et al. 1989). Consequently, the developed risk matrix for this research will provide clear descriptions of the likelihood and consequence ratings and describes the development of the different categories.

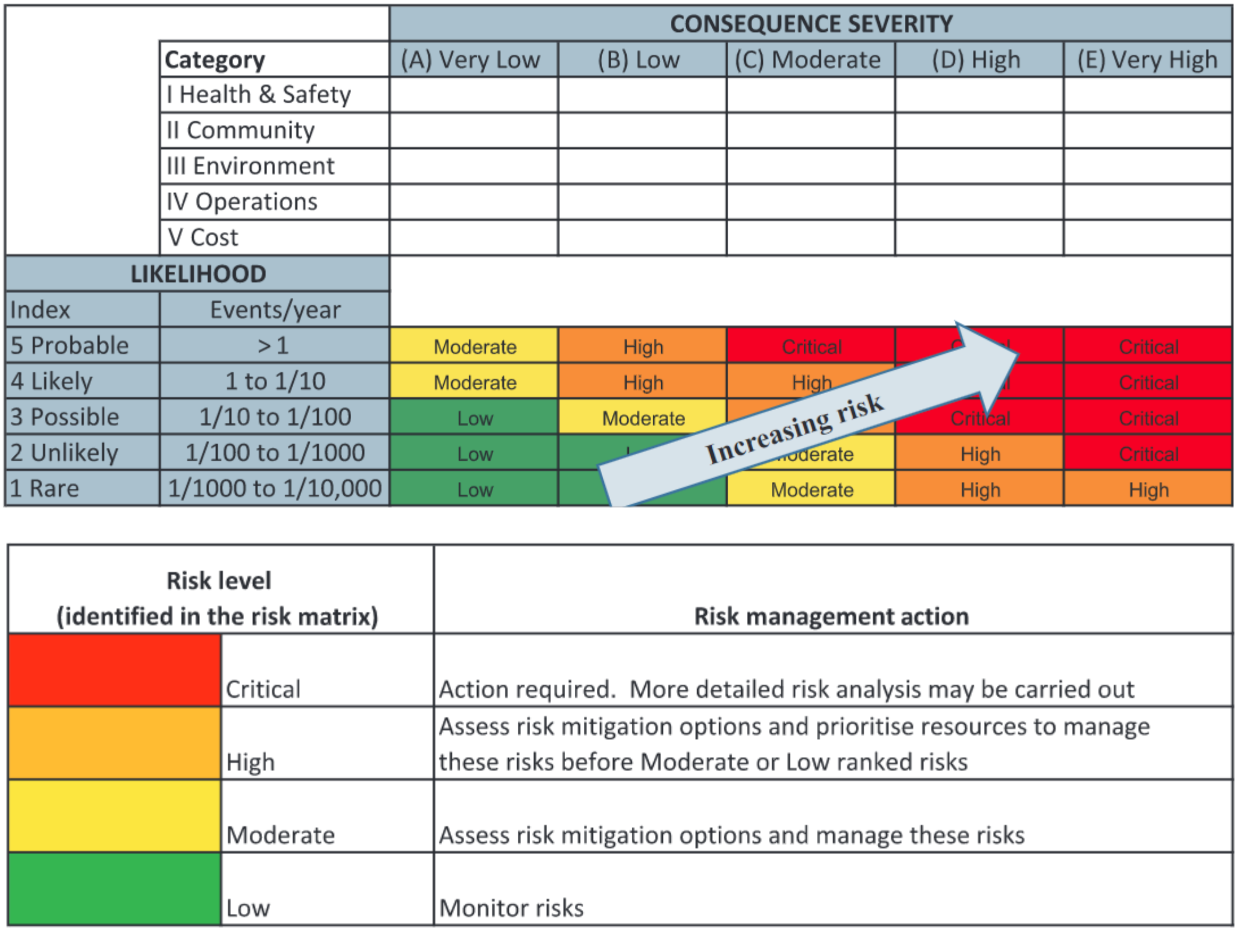


Likelihood	**Consequences**				
	Minimal	**First aid**	**Medical treatment**	**Lost time**	**Disability**
Almost certain	Low	Moderate	High	High	High
Likely	Low	Moderate	High	High	High
Possible	Low	Moderate	Moderate	High	High
Rare	Low	Low	Low	Moderate	High
Almost impossible	Low	Low	Low	Low	Low

Figure 2-10: Example of a risk matrix for underground mining activities used by personnel (from Hadjigeorgiou (2019))

Republished with permission of Hadjigeorgiou, J., from Understanding, managing and communicating geomechanical mining risk, Hadjigeorgiou, J, 2019.

The Guidelines for Mine Waste Dump and Stockpile Design provide a risk matrix format example as shown in Figure 2-11 (Griffin 2017). This guideline provides details on the likelihood rating, assigning an events/year rating to each qualitative descriptor. Further, it shows that the consequence rating should be assessed in terms of health and safety, the community, the environment, operations, and cost. It also provides a description of the risk management action that should be taken given the determined risk level. This risk matrix provides a much better basis to work off compared to the risk matrix shown in Figure 2-10 and depicts an example of a risk matrix used within a similar industry (Mine Waste Dump and Stockpile Design). However, based on the consequence categories, it seems likely that this risk matrix was intended to be used for assessing risk during operations.



		CONSEQUENCE SEVERITY				
	Category	(A) Very Low	(B) Low	(C) Moderate	(D) High	(E) Very High
	I Health & Safety					
	II Community					
	III Environment					
	IV Operations					
	V Cost					
LIKELIHOOD						
Index	Events/year					
5 Probable	> 1	Moderate	High	Critical	[illegible]	Critical
4 Likely	1 to 1/10	Moderate	High	High	[illegible]	Critical
3 Possible	1/10 to 1/100	Low	Moderate	[illegible]	Critical	Critical
2 Unlikely	1/100 to 1/1000	Low	[illegible]	Moderate	High	Critical
1 Rare	1/1000 to 1/10,000	Low	[illegible]	Moderate	High	High

Risk level (identified in the risk matrix)		**Risk management action**
🟥	Critical	Action required. More detailed risk analysis may be carried out
🟧	High	Assess risk mitigation options and prioritise resources to manage these risks before Moderate or Low ranked risks
🟨	Moderate	Assess risk mitigation options and manage these risks
🟩	Low	Monitor risks

Figure 2-11: Risk matrix and associated risk levels provided by the Guidelines for Mine Waste Dump and Stockpile Design (from Griffin (2017))

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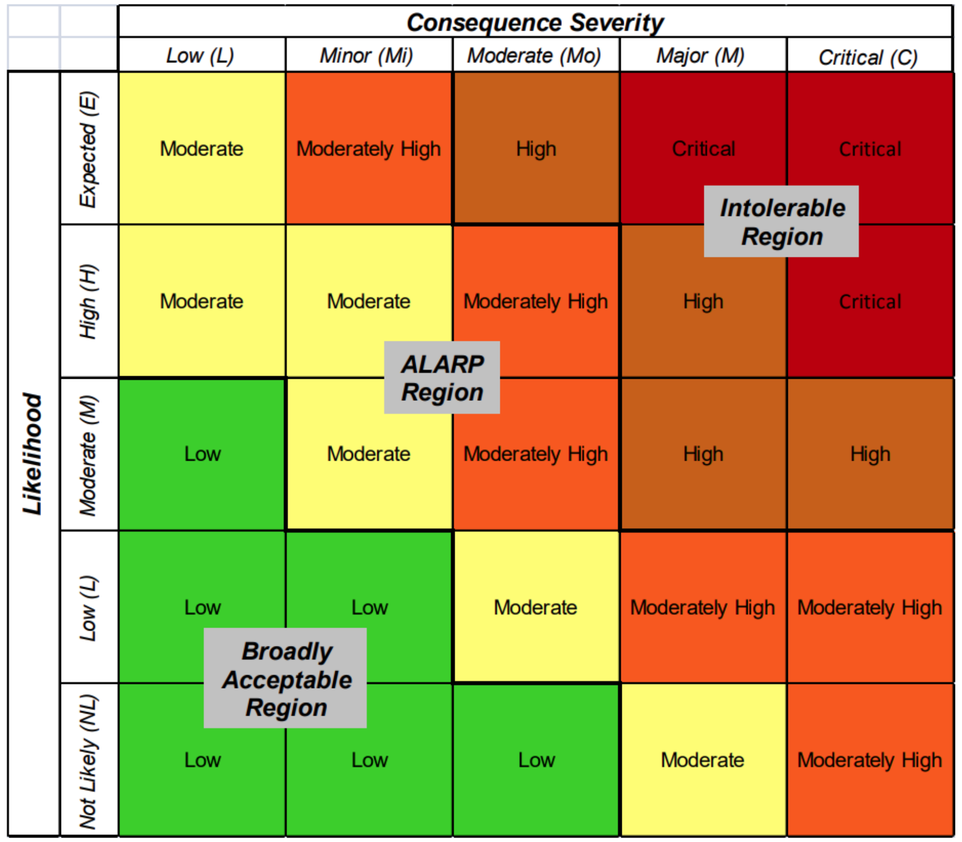
The Cold Regions Cover System Design Technical Guidance Document also provides a risk matrix to evaluate failure modes associated with cover systems as shown in Figure 2-12. This risk matrix provides a comprehensive description of the likelihood and consequence rating and provides a recommended level-of-confidence scale to go along with the risk matrix and selected risk rating. Consequences are assessed in six different categories, including: environmental impact, special considerations, legal and other obligations, consequence costs, community/media/reputation, and human health and safety (MEND 2012). Cover systems are designed to restore the surface of a waste deposit to stable, natural conditions following closure (MEND 2012). Due to this, the risk matrix provided by MEND (2012) provides a useful analogue for development of the risk matrix for the purposes of this research. MEND (2012) recommends a minimum design life of 100-years, noting that the design must be evaluated on a site-specific basis using a risk-based approach. As shown in Figure 2-12, the likelihood should be evaluated over the defined assessment period. It is interesting to note that the assessment period is not specified, which implies that this should be selected on a site-to-site basis despite the design life. This means that it is possible that the assessment period may exceed the design life.

Consequence Categories	Low	Minor	Moderate	Major	Critical
Environmental Impact	No impact.	Minor localized or short-term impacts.	Significant impact on valued ecosystem component.	Significant impact on valued ecosystem component and medium-term impairment of ecosystem function.	Serious long-term impairment of ecosystem function.
Special Considerations	Some disturbance but no impact to traditional land use.	Minor or perceived impact to traditional land use.	Some mitigatable impact to traditional land use.	Significant temporary impact to traditional land use.	Significant permanent impact on traditional land use.
Legal and Other Obligations	No non-compliance but lack of conformance with departmental policy requirement. Informal advice from a regulatory agency. No land claim or other agreement.	Technical/ Administrative non-compliance with permit, approval or regulatory requirement. Warning letter issued. Land claim or other agreement requires the Crown to satisfy administrative obligations (e.g. notification).	Breach of regulations, permits, or approvals (e.g. 1 day violation of discharge limits). Order or direction issued. Land claim or other agreement requires the Crown to respond, but no time frame is specified.	Substantive breach of regulations, permits, or approvals (e.g. multi-day violation of discharge limits). Prosecution. Land claim or other agreement requires the Crown to exercise its obligations within a specified time frame (i.e. 2-5 years).	Major breach of regulation—wilful violation. Court order issued. Land claim or other agreement requires the Crown to exercise its obligations within a specified short time frame (i.e. 1-2 years).
Consequence Costs	<$100,000	$100,000 - $500,000	$500,000 - $2.5 million	$2.5 - $10 million	>$10 million
Community/ Media/ Reputation	Local concerns, but no local complaints or adverse press coverage.	Public concern restricted to local complaints or local adverse press coverage.	Heightened concern by local community, criticism by NGOs or adverse local/ regional media attention.	Significant adverse national public, NGO, or media attention.	Serious public outcry/ demonstrations or adverse international NGO attention or media coverage.
Human Health and Safety	Low-level short-term subjective symptoms. No measurable physical effect. No medical treatment.	Objective but reversible disability/impairment and/or medical treatment. Injuries requiring hospitalization.	Moderate irreversible disability or impairment to one or more people.	Single fatality and/or severe irreversible disability or impairment to one or more people.	Multiple fatalities.

Confidence	Description
Low (L)	Do not have confidence in the estimate or ability to control during implementation
Medium (M)	Have some confidence in the estimate or ability to control during implementation, conceptual level analyses
High (H)	Have lots of confidence in the estimate or ability to control during implementation, detailed analyses following a high standard of care

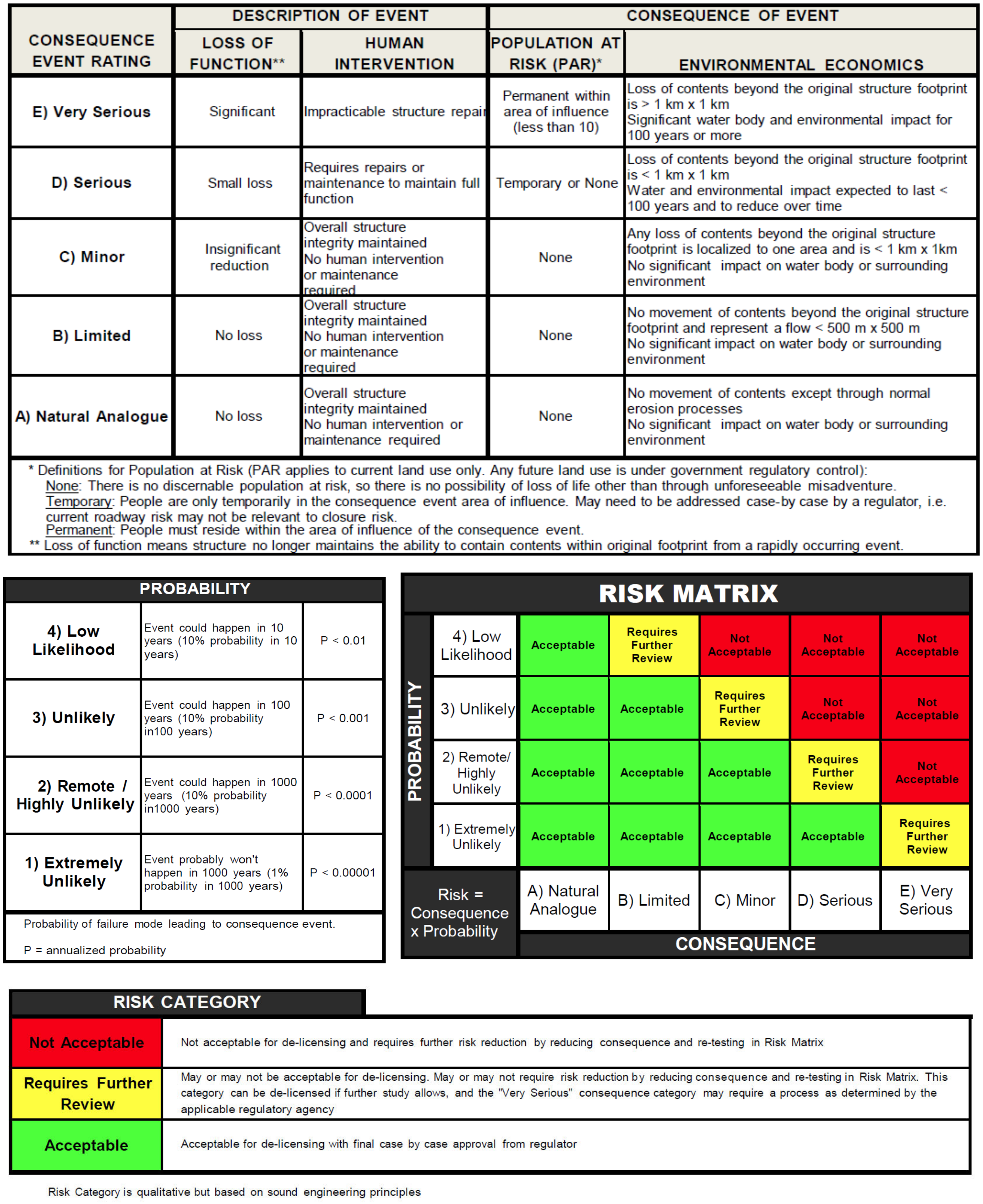
Likelihood Class	Likelihood of Occurrence for Environmental and Public Concern Consequences over the assessment period
Not Likely (NL)	< 0.1% chance of occurrence
Low (L)	0.1 - 1% chance of occurrence
Moderate (M)	1 - 10% chance of occurrence
High (H)	10 - 50% chance of occurrence
Expected (E)	> 50% chance of occurrence



		Consequence Severity				
		Low (L)	Minor (Mi)	Moderate (Mo)	Major (M)	Critical (C)
Likelihood	Expected (E)	Moderate	Moderately High	High	Critical	Critical
	High (H)	Moderate	Moderate	Moderately High	High	Critical
	Moderate (M)	Low	Moderate	Moderately High	High	High
	Low (L)	Low	Low	Moderate	Moderately High	Moderately High
	Not Likely (NL)	Low	Low	Low	Moderate	Moderately High

Figure 2-12: Risk matrix provided by the Cold Regions Cover System Design Technical Guidance Document (from MEND (2012))
Republished with permission of Mine Environment Neutral Drainage, from Cold Regions Cover System Design Technical Guidance Document, Mine Environment Neutral Drainage, 2012.

An example of a risk matrix currently being employed in the mining industry in Alberta is the one developed by OSTDC (2014) for assessing the risk category of various failure modes to aid in assessing the facilities eligibility to be de-licensed from a dam to a solid earthen structure. The relevant charts for determining the risk category using this method are provided in Figure 2-13. It should be noted that the elements used to determine the consequence rating for this method differ from a typical risk matrix used for operations, and includes the loss of function of the structure, degree of human intervention required on the structure after an event occurs, population at risk, and environmental economics. In contrast, a risk matrix designed to assess the risk for an operational facility may consider elements such as health and safety, environment, community, reputation, and legal aspects when assessing the consequences of failure, similar to Figure 2-12. The difference between the two – particularly with regard to human intervention – is due to the difference in application (i.e., assessing closure versus operation). The ultimate goal with tailings dam closure is for the facility to reach a state where minimal or no human intervention is needed (maintenance or in response to a failure). As a result, this should be considered when evaluating the consequences of a failure.



CONSEQUENCE EVENT RATING	DESCRIPTION OF EVENT		CONSEQUENCE OF EVENT	
	LOSS OF FUNCTION**	HUMAN INTERVENTION	POPULATION AT RISK (PAR)*	ENVIRONMENTAL ECONOMICS
E) Very Serious	Significant	Impracticable structure repai	Permanent within area of influence (less than 10)	Loss of contents beyond the original structure footprint is > 1 km x 1 km Significant water body and environmental impact for 100 years or more
D) Serious	Small loss	Requires repairs or maintenance to maintain full function	Temporary or None	Loss of contents beyond the original structure footprint is < 1 km x 1 km Water and environmental impact expected to last < 100 years and to reduce over time
C) Minor	Insignificant reduction	Overall structure integrity maintained No human intervention or maintenance required	None	Any loss of contents beyond the original structure footprint is localized to one area and is < 1 km x 1km No significant impact on water body or surrounding environment
B) Limited	No loss	Overall structure integrity maintained No human intervention or maintenance required	None	No movement of contents beyond the original structure footprint and represent a flow < 500 m x 500 m No significant impact on water body or surrounding environment
A) Natural Analogue	No loss	Overall structure integrity maintained No human intervention or maintenance required	None	No movement of contents except through normal erosion processes No significant impact on water body or surrounding environment

* Definitions for Population at Risk (PAR applies to current land use only. Any future land use is under government regulatory control):
None: There is no discernable population at risk, so there is no possibility of loss of life other than through unforeseeable misadventure.
Temporary: People are only temporarily in the consequence event area of influence. May need to be addressed case-by case by a regulator, i.e. current roadway risk may not be relevant to closure risk.
Permanent: People must reside within the area of influence of the consequence event.
** Loss of function means structure no longer maintains the ability to contain contents within original footprint from a rapidly occurring event.

PROBABILITY		
4) Low Likelihood	Event could happen in 10 years (10% probability in 10 years)	P < 0.01
3) Unlikely	Event could happen in 100 years (10% probability in100 years)	P < 0.001
2) Remote / Highly Unlikely	Event could happen in 1000 years (10% probability in1000 years)	P < 0.0001
1) Extremely Unlikely	Event probably won't happen in 1000 years (1% probability in 1000 years)	P < 0.00001

Probability of failure mode leading to consequence event.

P = annualized probability

RISK MATRIX

PROBABILITY					
4) Low Likelihood	Acceptable	Requires Further Review	Not Acceptable	Not Acceptable	Not Acceptable
3) Unlikely	Acceptable	Acceptable	Requires Further Review	Not Acceptable	Not Acceptable
2) Remote/ Highly Unlikely	Acceptable	Acceptable	Acceptable	Requires Further Review	Not Acceptable
1) Extremely Unlikely	Acceptable	Acceptable	Acceptable	Acceptable	Requires Further Review
Risk = Consequence x Probability	A) Natural Analogue	B) Limited	C) Minor	D) Serious	E) Very Serious
	CONSEQUENCE				

RISK CATEGORY	
Not Acceptable	Not acceptable for de-licensing and requires further risk reduction by reducing consequence and re-testing in Risk Matrix
Requires Further Review	May or may not be acceptable for de-licensing. May or may not require risk reduction by reducing consequence and re-testing in Risk Matrix. This category can be de-licensed if further study allows, and the "Very Serious" consequence category may require a process as determined by the applicable regulatory agency
Acceptable	Acceptable for de-licensing with final case by case approval from regulator

Risk Category is qualitative but based on sound engineering principles

Figure 2-13: Risk assessment matrix (from OSTDC (2014))
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There are many issues associated with risk matrices that risk matrix developers and users must be aware of. Some of these issues can clearly be seen in the example matrices through the lack of clear definitions of consequence and probability categories. The other known issues associated with risk matrices are discussed in Section 4.1.3, which includes: subjective nature, incorrect risk prioritization, ranking reversal, range compression, centering bias, category definition bias, implies risk is categorical rather than a continuum, consequence definition ambiguity, cannot provide aggregate measures of risk, unable to aggregate risk from multiple consequence dimensions, and the use of corporate-wide risk matrices for specific application.

2.6.2 Risk Control

Using the outcomes of the risk assessment process, risk control involves selecting one or more options for modifying risks, and implementing those options (ISO 2009). Various options exist for risk control, including (ISO 2009):

- Risk avoidance;
- Risk acceptance to pursue an opportunity;
- Removal of the risk source;
- Altering the likelihood;
- Altering the consequence;
- Risk pooling where the risk is shared with other parties; and
- Retaining the risk by informed decision.

Selecting appropriate risk control measures is a complex process that involves consideration of the cost and effort for implementation to the overall derived benefit (ISO 2009). Regardless, all risks should be managed to be As Low as Reasonably Practicable (ALARP) whereby all risk control methods are implemented as long as the cost of implementation is reasonably practicable (Lacasse 2016).

2.7 Seepage Modelling

Seepage modelling is used within the geotechnical industry to simulate the flow of water through a particulate medium. Common software used for this purpose includes SoilVision, Rocscience, and GeoStudio. GeoStudio will be used within this research due to its prevalence of use within the oil sands industry and its successful use in other dam applications for modelling the seepage regime. GeoStudio has a seepage modelling component, called SEEP/W, which allows users to conduct three-dimensional (3D), 2-dimensional (2D), or 1-dimensional (1D) numerical models that simulate the physical process of water moving through a particulate medium (GEO-SLOPE International Ltd. 2015). The key components to finite element modelling include creating the numerical domain (geometry, discretization), specification of material properties for each sub-region, and defining the boundary conditions (GEO-SLOPE International Ltd. 2015).

SEEP/W assumes that water flow through saturated and unsaturated soil follows Darcy's Law as shown in Equation 2-1 (GEO-SLOPE International Ltd. 2015).

$$q = ki \tag{2-1}$$

Where: q is the specific discharge, k is the hydraulic conductivity, and i is the gradient of total hydraulic head.

The general governing differential equation for two-dimensional seepage is described as shown in Equation 2-2 (GEO-SLOPE International Ltd. 2015).

$$\frac{\partial}{\partial x}\left(k_x \frac{\partial H}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_y \frac{\partial H}{\partial y}\right) + Q = \frac{\partial \theta}{\partial t} \tag{2-2}$$

Where: H is the total head, k_x is the hydraulic conductivity in the x-direction, k_y is the hydraulic conductivity in the y-direction, Q is the applied boundary flux, θ is the volumetric water content, and t is the time.

A number of studies have been conducted using seepage modelling as a way to improve our understanding of how water moves through a dam (Bussière et al. 2003b, Ferguson et al. 2009, Yasuda et al. 2010, Imran Arshad and Babar 2014, Zhang et al. 2020, Clarkson 2021, Th Al-Hadidi and Hashim 2021). Clarkson (2021) performed 2D steady state and transient numerical modelling using SEEP/W to improve understanding of the phreatic conditions of a tailings dam in response to different external conditions with the goal of supporting the observational approach. Yasuda et al. (2010) used groundwater modelling to assess the effectiveness of the seepage collection ditches of an oil sands tailings dam at Muskeg River Mine. The modelling was used to gain insight into the groundwater flow system using a 2D steady state flow model of a vertical cross section of the dam (Yasuda et al. 2010). Ferguson et al. (2009) conducted 2D transient groundwater modelling at Tar Island Dyke at the Suncor site to assist in quantifying potential long-term environmental impacts by gaining insight into transient flow behaviour. The modelling evaluated the primary flow pathways of process water and assessed how it drained over time, showing that it decreased over time, but remained transient. The authors proposed that the lowering of the porewater pressures in the main dyke increased its strength and long-term stability (Ferguson et al. 2009).

Numerical modelling has also been used in the mining industry for other applications, including cover design (Bussière et al. 2003a, Aubertin et al. 2009, Kalonji Kabambi et al. 2017, Pabst et al. 2017, Lieber et al. 2018, Hotton et al. 2020). Lieber et al. (2018) emphasized the importance of integrating the evolution of the precipitation regime in the design of covers systems to ensure that the cover system operates efficiently in the long term. Numerical modelling was performed using SEEP/W to estimate the impact of climate change on the performance of the cover system at the Doyon-Westwood mine site tailings pond. The land climate interaction boundary condition was employed in a 1D model using climatic conditions. In the initial modelling scenarios, the daily precipitation and summer drought periods were altered with no modifications made to the other climatic parameters (temperature, wind, relative humidity) (Lieber et al. 2018). Hotton et al. (2020) used a 2D numerical model in SEEP/W and the land climate interaction boundary condition to assess the performance of a cover at the Lorraine mine in Quebec due to climate change (precipitation, temperature, relative humidity, wind speed, and solar radiation) and historical and projected extreme drought events.

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3 INTERVIEWS

A series of interviews were conducted with industry professionals. The results were analysed, assessed, and organized into seven themes. Four of the themes were published in CIM Journal and the remaining three themes were published at the 72nd Canadian Geotechnical Conference (GeoSt.John's). Section 3.1 presents the CIM Journal paper in full, which provides a brief summary of the themes presented in the Geo.St.John's paper. Slight modifications were made to align the paper with the thesis structure and format. Section 3.2 expands on the themes presented in the Geo.St.John's paper.

Readers should be aware that the interview questions were specific to the coal and oil sands industries in Alberta. Many interviewees used examples from other industries, but analysis of the results was performed with Alberta in mind. The interviews provide extensive insight into the long-term physical behaviour and challenges associated with tailings dam closure; however, readers are cautioned to remember that tailings dam closure is site specific. This should always be kept at the forefront during the evaluation of the long-term behaviour and risks of a tailings dam.

3.1 Tailings Dam Closure Scenarios, Risk Communication, Monitoring, and Surveillance in Alberta

Abstract

Tailings dams remain as a part of the landscape in perpetuity following mine closure. As many mines approach closure in the province of Alberta, Canada, it is becoming increasingly important to understand the long-term geotechnical behaviour of these facilities and the impact of various loading and environmental scenarios over long time periods. Research surrounding the closure of tailings dams has historically focused on planning for closure, with a limited focus on how the facility may evolve over time. This gap in research has implications for the design and development of policies that adequately account for long-term risk and uncertainty. This paper summarizes key themes identified during interviews conducted with skilled practitioners to leverage their experiences and help fill the knowledge gap surrounding the long-term behaviour and policy-making for tailings dams. These include the impact of recent tailings dam failures, long-term monitoring and surveillance, potential closure scenarios, and risk communication.

3.1.1 Introduction

The mining industry in the province of Alberta, Canada consists primarily of coal and oil sands mines. The mining process typically results in the production of a slurry waste stream referred to as tailings, which consists of varying proportions of fines, sand, and process water. The tailings produced from coal and oil sands mines vary considerably. Regardless of the mine type, tailings may be stored in tailings storage facilities (TSFs) using dams for containment until there is sufficient space in-pit to place the tailings. Tailings dams in the coal industry tend to be much smaller (height and volume contained) with much lower risk classifications compared to the oil sands industry, where tailings dams may exceed 100 m in height and may contain hundreds of millions of cubic meters of fluid (AER 2022). The life cycle differs considerably between a tailings dam and a water dam: construction of a tailings dam is typically staged over the life of the facility, whereas a water dam is constructed to full height prior to operation (Vick 1990). Further, a tailings dam will remain on the landscape in perpetuity following mine closure, whereas a water dam will be removed following cessation of operations. The overall goal of the closure process for a tailings dam is typically for the structure to transition to a solid landform that is “physically, chemically, ecologically, and socially stable” (ICOLD Tailings Dam Committee 2013). Within Alberta, it is expected that tailings dams will be reclaimed to stable, resilient, functional ecosystems with an equivalent land capability to that of the pre-mined land (Government of Alberta 2015). Following closure, the land would be certified and transferred back to the Crown. These conditions are often perceived as a maintenance-free, walk-away closure scenario. This process is far from simple and is relatively new to the industry. In the oil sands region, the only certified area is an overburden dump called Gateway Hill (Morgenstern 2012). As tailings dams in Alberta proceed toward closure, understanding their long-term physical stability is becoming more and more important because it may impact the practicality of achieving the final goal of custodial transfer back to the Crown. To classify and quantify the current state of understanding of these structures, industry professionals with experience with tailings dams and closure were interviewed. The objective of this paper is to present the results of the interview process and discuss the corresponding implications to tailings dam closure in Alberta.

3.1.2 Background

Tailings dams pose a serious risk to the environment and the public. Examples of recent failures include Brumadinho in Brazil (2019), Cadia in Australia (2018), Fundão in Brazil (2015), and Mount Polley in Canada (2014) (WISE Uranium Project 2020). The consequences of these failures vary greatly from significant loss of life, to environmental damage, to containment of the released material within an adjacent dam (WISE Uranium Project 2020). Tailings dam failures are often accompanied by significant financial losses and may affect the social license of the company to operate in that community, where the social license can be defined as an "intangible, informal approval or acceptance by the community" (Garcia 2008). In order to retain a social license, there must be comprehensive closure planning and the mining company (and the regulator for that matter) must demonstrate a commitment to sustainable mining practices. This process must involve the stakeholders, including the surrounding communities, especially given that the community will have to live with the closure landscape long after the mine closes. Further, this process may require a comprehensive risk communication system depending on the tailings dam closure scenario. Because tailings dams do not generate profit, decisions related to construction method and design are often tied to cost considerations. Consequently, tailings dams are often constructed using overburden, tailings sand, or mine waste to reduce the costs associated with fill material (Patnayak and Alam 2016). The construction of a tailings dam generally begins with a starter dyke typically constructed using materials such as overburden mine waste. As the tailings storage requirements increase over time, the dam is raised to accommodate the increasing demand using a variety of materials and methods depending on site and project-specific considerations. These include:

- Upstream construction;
- Downstream construction;
- Centreline construction;
- Modified centreline construction; or
- A combination of the above methods.

A review of public technical documentation by the authors indicates that the construction method or materials used in existing dams may be unknown in some cases, specifically in the coal mining industry, where several structures lack construction records. The construction method, materials, and deposition method employed by a mining operation may change extensively as the design evolves throughout the life of the structure (List 1996, List et al. 1996, Sisson et al. 2012, Pollock et al. 2014). This could be due to several factors including increases in the final design elevation of the dam, changes to the tailings or materials available for construction, changes to best available technology or practice, or changes in nearby ore deposits. This emphasizes the importance of properly documenting the reasons why certain decisions were made, particularly when it comes to assessing the long-term performance of the dam and the potential for the dam to fit into a custodial transfer framework after closure.

The aim of TSFs is generally to maximize tailings storage in a cost-effective manner while maintaining regulatory requirements (Bayliss et al. 2014), a focus that can overlook long-term challenges. This is further complicated by the fact that each dam will have site-specific considerations and circumstances that may not be applicable to other sites. Additionally, there is a lack of willingness among mine owners to share data from their sites. Although this can be understood as a means to minimize exposure to the public, it contributes to a lack of available published information on the long-term physical behaviour of tailings dams.

Often, the literature related to tailings dam closure focuses on planning for closure. Where closure case studies exist, they tend to center on how the tailings dam was reclaimed. Examples include Suncor Pond 1 (or Tar Island Dyke) (Anderson et al. 2010, Russell et al. 2010) and Sullivan Mine (Marsland et al. 2004, Peterson et al. 2015, KCB 2017a). While this is useful, ongoing publication on how tailings dams behave over time would be beneficial to industry. In the case of Sullivan Mine and other closed mines in British Columbia, the public has access to dam safety reports (e.g., British Columbia Ministry of Energy and Mines (2016); Donald et al. (2013); KCB (2014b, 2017b); Piteau Associates Engineering Ltd. (2017)) that can be reviewed in depth to determine how the facilities are aging. However, comprehensive review of these reports demands considerable time and the information has not been collated and synthesized. Further, these reports require the reader to draw conclusions about post-closure behaviour based on performance monitoring information that is not clear in some cases.

A growing body of research evaluates various aspects of the long-term behaviour of tailings dams and how to best design for closure. For example, Slingerland (2019) investigated erosion of a large sand dam in the Alberta oil sands region using a Landscape Evolution Model to aid in assessing the long-term geomorphic stability of the facility. The development and verification of such models would be aided by industry-published information related to facilities that have been closed for a number of years. Currently, TSF closure faces unforeseen challenges, and solutions are often far from optimal (Slingerland et al. 2019). More thorough planning and consideration of the final landscape during the early mine stages would provide more flexibility, a smoother transition to the closure landscape, and better end results (Slingerland et al. 2019). This should be coupled with a sound understanding of the long-term behaviour, risks, and uncertainties of the facility. This paper aims to use industry experience to help fill in the knowledge gap surrounding the long-term behaviour of tailings dams. This will leverage this industry experience into documented guidance that will enhance development and evaluation of tailings dam closure schemes.

3.1.3 Methods

Interviews were conducted to elicit information from industry professionals regarding failure modes following mine closure, potential long-term triggers and indicators of failure, long-term monitoring and surveillance practices, risk communication challenges, and closure and reclamation challenges for coal and oil sands tailings dams in Alberta. The interview methods and the 14 questions were reviewed and approved by the Research Ethics Board at the University of Alberta. The 23 participants (seven consultants, eight world-renowned experts, five mine operators, and three regulators) read and signed an informed consent form. Of the interviewees, 19 were geotechnical engineers. The interviews were 60–90 minutes long and were administered by the first author by telephone or in person. Participants were permitted to skip questions if desired and were able to remove any of their responses for up to eight weeks following the interview. Participant responses were recorded by hand or on a computer and then transcribed following the interview. All of the interview responses were analysed using a staged coding process in NVivo v. 12.2.0.443 (QSR International 2018). Coding allowed for themes to be identified throughout the aggregated data. In the first stage of coding, each interview was assessed individually and then responses within each question were analysed to identify commonalities and develop themes for further investigation. The subsequent stages of coding involved iteration as new themes and patterns were identified.

3.1.4 Results and Discussion

Seven key themes were identified during the interview process (Figure 3-1). This paper presents the results of four out of the seven key themes: impact of recent tailings dam failures, long-term monitoring and surveillance, potential closure scenarios, and risk communication. Although the remaining three themes (changing failure modes, closure challenges, and development of hazards and triggers) were presented in detail in Schafer et al. (2019), the main findings are summarized here as it is important to consider and evaluate all seven themes together. The themes presented in this paper are more holistic in nature whereas the themes presented in Schafer et al. (2019) focused on geotechnical aspects of the closure process. The information presented in this paper is restricted to data collected from the interviews and does not include an assessment of literature related to the key themes. The interview questions were developed to be specific to the coal and oil sands industries in Alberta. While interviewees used examples from other industries, the analysis was performed in the context of the mining industry in Alberta.

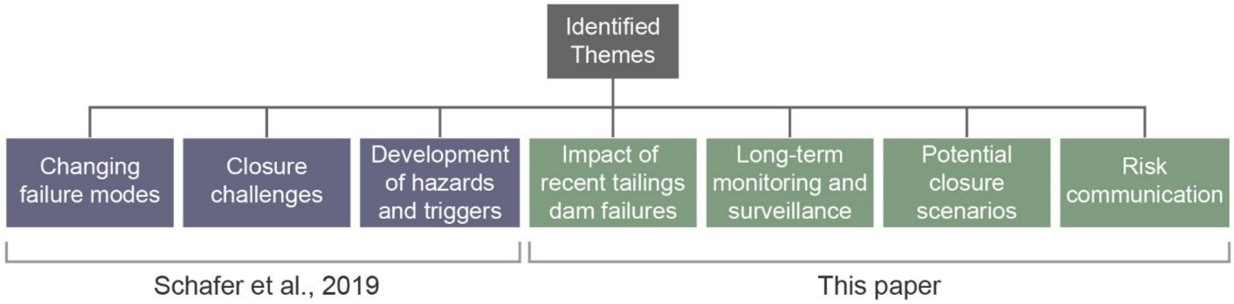


Figure 3-1: Themes identified from interviews with industry professionals

3.1.4.1 Changing Failure Modes

Schafer et al. (2019) discussed the way in which failure modes may change over time with a focus on foundation failure, internal erosion, overtopping, seismic liquefaction, slope instability, spillway failure, and static liquefaction. While it is recognized that failure modes are site-specific, the interview responses showed a higher degree of uncertainty regarding the development of internal erosion and static liquefaction in the long term compared to other failure modes. Overall, this process emphasized the importance of evaluating key assumptions when conducting long-term failure mode analysis.

3.1.4.2 Closure Challenges

The key closure challenge categories identified were cost, human factors, the regulator, risk, technical aspects, and the time frame of closure (Schafer et al. 2019). Of these, the lengthy time frame associated with tailings dam closure was identified as the major barrier to closure. The expectation for closure is that these facilities remain safe in perpetuity. This open-ended time frame introduces a degree of uncertainty that many interviewees were uncomfortable with, especially given the expectation of walk-away closure. It was noted that the time frame is strongly linked to other closure challenges, such as the selection of design criteria and the development of a design basis. The time frame complicates these aspects of closure due to factors like climate change and perpetual degrading forces. Further, lengthy time frames can make it difficult to quantify the risk of a facility in the long term because consequences, the probability of failure, and risk tolerance change over time. Concerns were also expressed regarding the lack of guidance from the regulator on the expectations and requirements for closure, which can make it difficult for operators to invest money into closure without knowing what the regulator will deem acceptable. The closure challenges discussed by interviewees demonstrated a need for further research into the way that tailings dams age and further assessment of the viability of walk-away closure.

3.1.4.3 Development of Hazards and Triggers

Based on the interview results, Schafer et al. (2019) evaluated the development of hazards and triggers as a dam evolves, which is essential to assessing the way that failure modes change over time. This process is site-specific, may be complex, and is difficult to anticipate, especially given the time frames associated with closure noted previously. Interview participants identified several dam evolution processes, many of them are interconnected, which fell into the following categories: changes due to humans, material changes, hydrologic changes, changes due to animals, spillway changes, vegetation, and geometry changes. Interview responses regarding long-term dam evolution, hazards, and triggers varied greatly, with many conflicting opinions on different elements such as the importance of surface erosion and how the phreatic surface will change in the long term.

This process emphasized the uncertainty associated with long-term dam safety. Of concern, some participants noted that there may be processes of which we are simply unaware. This type of uncertainty may be described as ‘unknown-unknowns’: uncertainties that are unforeseeable or uncontrollable (Baecher 2016). The area of unknown-unknowns complicates the process of long-term design as these uncertainties may make it difficult to adequately define all dam evolution processes, hazards, and triggers.

3.1.4.4 Impact of Recent Tailings Dam Failures

Participants were asked to comment on the impact of recent tailings dam failures on the way tailings dams are operated. The January 2019 Brumadinho failure occurred during the interview period. Interviewees commented on four key impacts of the recent tailings dam failures:

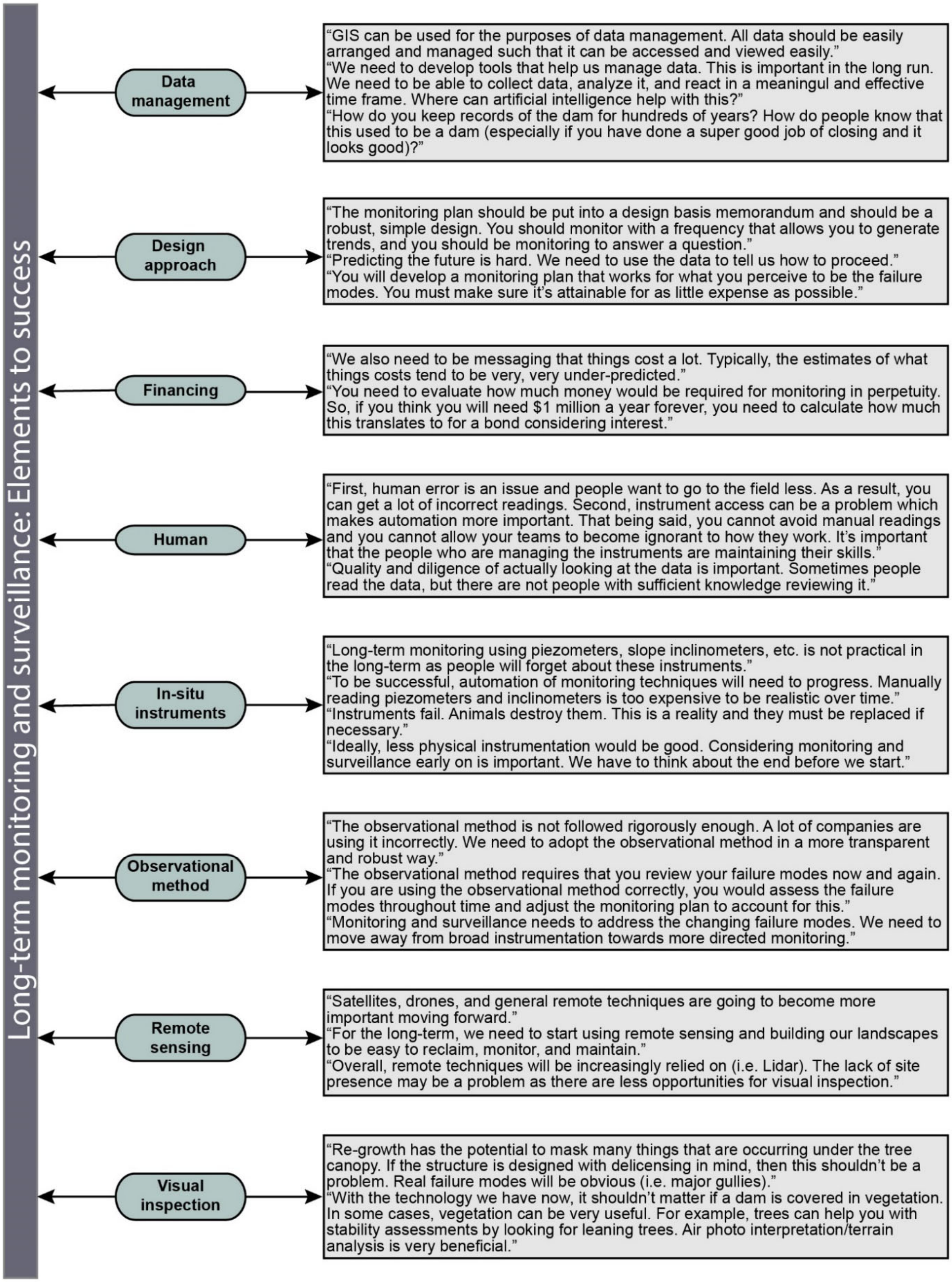
1. The failures resulted in recognition of the risks higher up the corporate ladder, which was beneficial to the front line management.
2. An increase in external oversight resulted, including alterations to the regulatory environment in different areas and an increase in the number of independent review boards. Some of the participants felt that this was a positive outcome of the failures while others viewed it as being negative. Participants that had a negative opinion of the increase in external oversight noted that:
    - Changes to the regulatory environment satisfies the public but may not be successful in creating lasting and impactful change.
    - There are not enough qualified individuals to fill positions on the increasing number of independent review boards.
3. Some participants noted that the failures resulted in an increased effort and level of care for tailings dams as companies sought to update the risk profiles for their mine sites.
4. Some participants indicated that the failures “…haven’t impacted the oil sands very much, except to make people double down and double check what they are doing. We have always done pretty well in this industry and have always had review boards, etc.” Outside of the oil sands, some participants expressed concern that people may become more relaxed in their approaches with time as they forget about the seriousness of these events. As tailings dams proceed to closure, this sentiment is extremely important: the risks associated with

tailings dams should be treated with the same seriousness in the long term as during operations.

3.1.4.5 Long-term Monitoring and Surveillance

A critical component of tailings dam closure is long-term monitoring and surveillance. Following reclamation works on a tailings dam, operators are typically required to monitor the facility for sufficient time to validate performance so the facility can be officially closed, certified, and returned to the Crown. Participants were asked to comment on how the current state of practice for monitoring and surveillance of tailings dams would need to change in the long term to be sufficiently effective. Practices in the oil sands industry were noted to be some of the best in the world. In contrast, coal industry practices were noted to be much less rigorous and unlikely to get better. Participants asserted that there must be commitment to ensure that the structures behave as expected in the long term (i.e., risk is sufficiently low) so that post-closure monitoring is not needed. This must be balanced with cost.

Figure 3-2 shows the eight elements required for long-term monitoring and surveillance identified by participants with supporting original quotes. Many of the elements are connected (e.g., design approach and observational method). Participants noted that all monitoring and surveillance should be done to target a specific failure mode and that we should not 'monitor just to monitor.' This should be combined with the observational method, which should be applied in a transparent and robust manner. One participant noted that the monitoring plan should be put into a design basis memorandum and that we should be able to design to require fewer instruments in the long term (higher factor of safety, no water contained by the dam, lower consequences). The design approach should also outline fundamental shifts that occur throughout monitoring and surveillance (i.e., shifts away from in situ instruments toward remote methods). Having a defined design approach using a design basis memorandum allows for more realistic assessment of the required finances to be developed – another essential element to success. This also requires a realistic view of the closure scenario (walk-away versus perpetual care). Underestimating the monitoring and surveillance requirements may have detrimental impacts from a financial perspective. Some participants noted that monitoring and surveillance in the long term will require a bond with strong oversight from the government.



"GIS can be used for the purposes of data management. All data should be easily arranged and managed such that it can be accessed and viewed easily."
"We need to develop tools that help us manage data. This is important in the long run. We need to be able to collect data, analyze it, and react in a meaningul and effective time frame. Where can artificial intelligence help with this?"
"How do you keep records of the dam for hundreds of years? How do people know that this used to be a dam (especially if you have done a super good job of closing and it looks good)?"

"The monitoring plan should be put into a design basis memorandum and should be a robust, simple design. You should monitor with a frequency that allows you to generate trends, and you should be monitoring to answer a question."
"Predicting the future is hard. We need to use the data to tell us how to proceed."
"You will develop a monitoring plan that works for what you perceive to be the failure modes. You must make sure it's attainable for as little expense as possible."

"We also need to be messaging that things cost a lot. Typically, the estimates of what things costs tend to be very, very under-predicted."
"You need to evaluate how much money would be required for monitoring in perpetuity. So, if you think you will need $1 million a year forever, you need to calculate how much this translates to for a bond considering interest."

"First, human error is an issue and people want to go to the field less. As a result, you can get a lot of incorrect readings. Second, instrument access can be a problem which makes automation more important. That being said, you cannot avoid manual readings and you cannot allow your teams to become ignorant to how they work. It's important that the people who are managing the instruments are maintaining their skills."
"Quality and diligence of actually looking at the data is important. Sometimes people read the data, but there are not people with sufficient knowledge reviewing it."

"Long-term monitoring using piezometers, slope inclinometers, etc. is not practical in the long-term as people will forget about these instruments."
"To be successful, automation of monitoring techniques will need to progress. Manually reading piezometers and inclinometers is too expensive to be realistic over time."
"Instruments fail. Animals destroy them. This is a reality and they must be replaced if necessary."
"Ideally, less physical instrumentation would be good. Considering monitoring and surveillance early on is important. We have to think about the end before we start."

"The observational method is not followed rigorously enough. A lot of companies are using it incorrectly. We need to adopt the observational method in a more transparent and robust way."
"The observational method requires that you review your failure modes now and again. If you are using the observational method correctly, you would assess the failure modes throughout time and adjust the monitoring plan to account for this."
"Monitoring and surveillance needs to address the changing failure modes. We need to move away from broad instrumentation towards more directed monitoring."

"Satellites, drones, and general remote techniques are going to become more important moving forward."
"For the long-term, we need to start using remote sensing and building our landscapes to be easy to reclaim, monitor, and maintain."
"Overall, remote techniques will be increasingly relied on (i.e. Lidar). The lack of site presence may be a problem as there are less opportunities for visual inspection."

"Re-growth has the potential to mask many things that are occurring under the tree canopy. If the structure is designed with delicensing in mind, then this shouldn't be a problem. Real failure modes will be obvious (i.e. major gullies)."
"With the technology we have now, it shouldn't matter if a dam is covered in vegetation. In some cases, vegetation can be very useful. For example, trees can help you with stability assessments by looking for leaning trees. Air photo interpretation/terrain analysis is very beneficial."

Figure 3-2: Elements of monitoring and surveillance identified by interview participants with supporting quotes

Some participants asserted that data management is the most important element to long-term monitoring and surveillance. All data should be easily arranged and managed such that that they can be analysed and evaluated efficiently, and action can be taken if needed. The element of data management becomes increasingly important as we move into longer time frames in excess of 100 years, during which the facility may transfer ownership or there may be the potential for it to be re-mined. In all cases, it is important that we strive to avoid loss of knowledge. Data management is connected to the human element. Participants expressed concern that some places are simply collecting data for the sake of collecting data and that there are often not qualified people evaluating these data. This may become increasingly problematic in the long term and should be addressed in monitoring and surveillance plans.

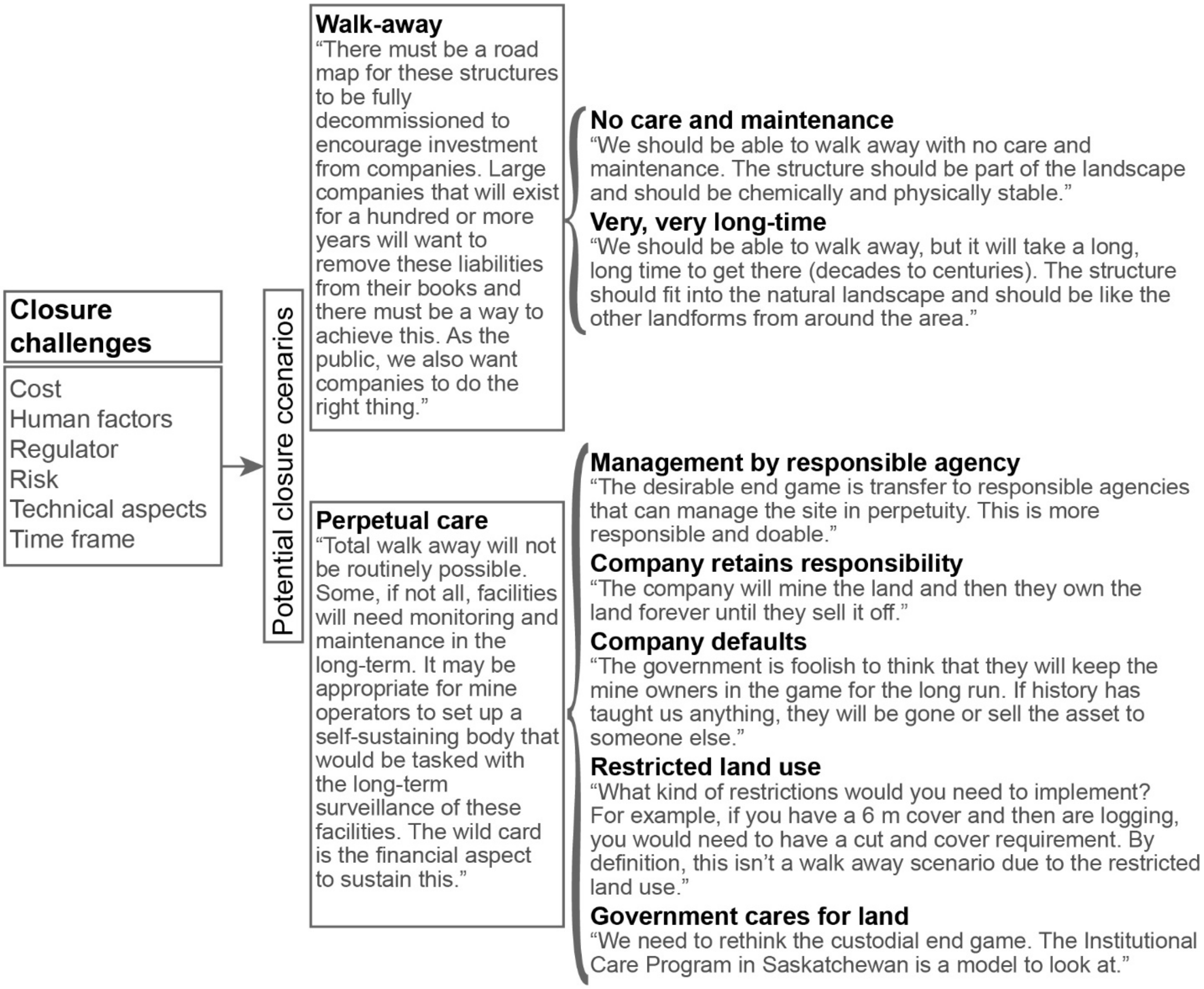
Some participants indicated that in situ instruments are not reliable in the long term as vegetation takes over and people forget about them. There must be alternatives to account for the loss of this instrumentation. Other participants indicated that in order to be effective, automation will need to increase as the number of on-site staff decreases (possibly to zero). Participants also provided broad estimates for the life of instruments installed in the ground (e.g., slope inclinometers, piezometers): from 5 years to decades. Regardless, most people noted that we will need to replace instruments and that this must be considered in cost estimates. Participants noted that satellites, drones, and other general remote techniques will become increasingly important moving forward but that further guidance is needed regarding monitoring frequency. Overall, participants indicated that monitoring and surveillance may be reduced over time, and methods should become simpler and less destructive, if the structure's performance follows an anticipated trajectory and is behaving as expected. One participant felt that all monitoring and surveillance of tailings dams should end at closure based on the idea that decommissioning criteria should be so robust that there is no doubt that these structures will survive severe hydrologic events. This argument is debatable: monitoring and surveillance aims to minimize uncertainties associated with post-closure performance regardless of the robustness of the closure approach and conservativeness of the assumptions for analysis.

3.1.4.6 Potential Closure Scenarios

A theme that developed during the interview analysis was potential closure scenarios for tailings dams in Alberta, given the challenges encountered in the closure process (discussed in Schafer et al. (2019)). This theme investigated the potential for success of the current closure scenario whereby custodial transfer would occur and the land would be certified and transferred back to the Crown. Interviewees associated this scenario with maintenance-free, walk-away closure and thus it is referred to in this manner for the purposes of this discussion. In general, interview responses fell into two general categories (Figure 3-3):

- Walk-away closure is possible; or
- Perpetual care will be required.

Despite a lack of cases of successful tailings dam closure, many participants believed that the end game for tailings dam structures is walk-away closure with no care and maintenance. Participants with responses that fell into this category had a number of different opinions. Some participants responded that walk-away closure with no care and maintenance will be possible. This supports the current regulatory framework within Alberta and may require a transition phase where the end goal is broken down into a series of small, attainable steps as the mine owner builds and demonstrates confidence in the structures through monitoring and surveillance records. Other participants contended that walk-away closure may be possible, but that this will take a very, very long time (decades to centuries). They noted that there is a disconnect between actual and envisioned timelines for closure by senior executives. Regardless, the expectation was that the more expensive active care period is short and the less expensive passive care period is longer. The concern with this type of scenario is that the company will default in the time it takes for the desirable walk-away scenario to be achieved, and systems may not be sufficiently in place to protect the public purse.



Closure challenges

Cost
Human factors
Regulator
Risk
Technical aspects
Time frame

Potential closure ccenarios

Walk-away
"There must be a road map for these structures to be fully decommissioned to encourage investment from companies. Large companies that will exist for a hundred or more years will want to remove these liabilities from their books and there must be a way to achieve this. As the public, we also want companies to do the right thing."

No care and maintenance
"We should be able to walk away with no care and maintenance. The structure should be part of the landscape and should be chemically and physically stable."

Very, very long-time
"We should be able to walk away, but it will take a long, long time to get there (decades to centuries). The structure should fit into the natural landscape and should be like the other landforms from around the area."

Perpetual care
"Total walk away will not be routinely possible. Some, if not all, facilities will need monitoring and maintenance in the long-term. It may be appropriate for mine operators to set up a self-sustaining body that would be tasked with the long-term surveillance of these facilities. The wild card is the financial aspect to sustain this."

Management by responsible agency
"The desirable end game is transfer to responsible agencies that can manage the site in perpetuity. This is more responsible and doable."

Company retains responsibility
"The company will mine the land and then they own the land forever until they sell it off."

Company defaults
"The government is foolish to think that they will keep the mine owners in the game for the long run. If history has taught us anything, they will be gone or sell the asset to someone else."

Restricted land use
"What kind of restrictions would you need to implement? For example, if you have a 6 m cover and then are logging, you would need to have a cut and cover requirement. By definition, this isn't a walk away scenario due to the restricted land use."

Government cares for land
"We need to rethink the custodial end game. The Institutional Care Program in Saskatchewan is a model to look at."

Figure 3-3: Potential closure scenarios for tailings dams in Alberta with supporting interview quotes

In contrast, some participants asserted that walk-away closure is not possible, and management of perpetual care is inevitable. Many noted that the desirable end game is transfer to a responsible agency that can manage the site in perpetuity. Some participants suggested that we should start adopting the concept of an interim landscape following closure where a permanent landscape is implemented once the interim landscape has proven to be stable. Further, it must be understood that the interim landscape could be in place for a few hundred years. An example of an alternative end game was provided whereby the management of the site was transferred to an external company and the mining company will continue to pay for this by yearly endowments. The company identified the need for transition and instigated this themselves (i.e., did not involve the regulator). Participants expressed that a more realistic view of closure must be taken. As Alberta currently requires walk-away closure, closure plans often reflect this sentiment (Slingerland et al. 2019). This may result in critical or fatal flaws being overlooked in the pursuit of attaining walk-away closure.

Participants noted that we must have a comprehensive plan for closure, even if it is perpetual care. If we have planned and stewarded toward it, this is not a problem. The danger lies in situations where the costs and time required for closure are overlooked, a company defaults, and the land and liability revert back to the Crown – and thus the public. These scenarios must be avoided. One participant noted that "We must pursue funding mechanisms for closure now for the future so that the money is there when needed and we don't get into situations like Giant Mine or Faro Mine. The fact is that we may not be using oil in 100 years, so how can we expect a company like Suncor or Syncrude to still be around funding closure?"

The closure scenario will depend on site-specific considerations. It is likely that some structures will be maintenance-free and support a walk-away closure scenario and some structures will require perpetual care. Regardless, the interview responses suggest a serious need for alternatives to walk-away closure to avoid situations where the companies default, and the land reverts to the Crown.

3.1.4.7 Risk Communication

A critical component of planning for tailings dam closure is communicating to stakeholders the long-term physical risks associated with these structures. Interview participants suggested methods that could be employed to facilitate risk communication. Risk communication is an ongoing practice at many mining operations. The challenge with tailings dam closure lies in the associated long-time frames: stakeholders may change over time, including the regulator and the upstream and downstream populations. This is reflected by recent dam failures, such as the Mount Polley tailings dam failure and the Oroville dam spillway incident, where failure to communicate risks related to dam foundation conditions and spillway foundation conditions, respectively, were identified as important contributing factors to failure (Ministry of Energy and Mines 2015, France et al. 2018). Further, the number of staff present at a site may decline as closure proceeds; thus, the facility may begin to resemble crown land and the public could begin accessing the land without permission.

Among the risk communication elements discussed (Figure 3-4), stakeholder engagement was deemed important by several participants. While this typically requires a lot of effort, planning, communication, and money, the importance cannot be overlooked. Many other risk communication elements were seen as key to the success of stakeholder engagement. For example, the communication strategy must be appropriate for the individual stakeholder (i.e., community versus regulator), which requires consultation with professionals who are skilled at risk communication. One participant noted, “engineers are not very good at communicating risk. This should be done by people that are good at communication.” Participants indicated that it may be useful to communicate the risks of these structures using natural analogues (Figure 3-4). However, in order to be effective, the stakeholders must understand the natural analogue.

Figure 3-4: Elements of communication for long-term physical risks of tailings dams according to interview responses

Regardless of method, any effort to communicate physical risks would benefit from the use of visual tools rather than an abundance of data and information (Figure 3-4). Visual tools continue to be developed as technology advances. In some cases, two-dimensional graphics may be sufficient to communicate risk. However, it may be difficult to communicate the scope of some projects, particularly in the case of large tailings dams that evolve over time. In such cases, it may be useful to take advantage of emerging technologies that allow stakeholders to view the project in three-dimensional (3D) space, such as the BGC Engineering Ada Platform, which allows participants to use a HoloLens and view the project using 3D holographic models (BGC Engineering Inc. 2017).

Participants also commented on using signage to communicate risks associated with tailings dams (Figure 3-4). This would be of particular concern in situations where a true walk-away closure scenario has not been attained (i.e., restricted land use). What we communicate today through submissions or distributions to the community may not be reliable for decades or centuries. Based on this, consideration should be given to evaluating how signage could be used in the risk communication process.

Overall, the most discussed element of risk communication was transparency and the need to be open and honest (Figure 3-4). The system used by the British Columbia Ministry of Energy, Mines and Petroleum Resources, where all dam safety reports are required to be public, was commended by some participants as being a step in the right direction. Much of the discussion on transparency focused on the importance of battling untrue information. One participant noted:

> *"The biggest challenge is the perception that we are building these monstrous, toxic, death traps. The longer we hesitate [to talk] about these structures, the harder it's going to be to convince people that they are okay. We have to start embracing more public discussion and start eliminating the untrue facts. We need to be transparent and present the facts and numbers. People are going to demand more 'risk free turn over'. The challenge for the industry is that people believe that you shouldn't be doing this unless you can achieve a risk free environment. This is impractical."*

3.1.5 Summary and Conclusions

During interviews with individuals experienced with tailings dams and dam closure, seven major themes emerged. This paper discussed four themes in detail: the impact of recent tailings dam failures, long-term monitoring and surveillance, potential closure scenarios, and risk communication. It is important that all seven themes are considered together when evaluating the challenges associated with the long-term behaviour and closure of tailings dams.

The conclusions of the work presented in Schafer et al. (2019):

1. Changing failure modes: Failure modes are site specific; however, interview responses showed a higher degree of uncertainty regarding the development of internal erosion and static liquefaction in the long term compared to other failure modes.
2. Closure challenges: Cost, human factors, the regulator, risk, technical aspects, and the time frame of closure were identified as the major barriers to tailings dam closure. The time frame was considered the largest barrier because it introduces uncertainty into the closure process and exacerbates other closure challenges.
3. Development of hazards and triggers: The uncertainty associated with long-term dam safety was highlighted by the broad range of opinions held by participants on different elements, such as the long-term importance of surface erosion.

The conclusions of this paper are:

1. Impact of recent tailings dam failures: Recent tailings dam failures have led to recognition of the risks by corporate management, an increase in external oversight, and increased effort and level of care for tailings dams. As tailings dams proceed toward closure, it is essential that the long-term risks are managed with the same seriousness as during operations.
2. Long-term monitoring and surveillance: Data management, design approach, financing, human factors, in situ instruments, observational method, remote sensing, and visual inspection were identified as critical to the success of long-term monitoring and surveillance. Of these elements, data management was identified as being the most critical to success by a number of participants. It is expected that monitoring and surveillance should decrease over time as confidence in the performance improves. Regardless, a detailed plan for monitoring the facility must be developed, which requires a realistic view of the closure scenario and allows for more accurate assessment of the required finances.
3. Closure scenarios: Identified closure scenarios fell into two broad categories: walk-away closure and management of perpetual care. Interview responses suggest a need to develop alternatives to walk-away closure, especially in light of the closure challenges identified.

4. Risk communication: Participants identified visual tools, transparency, skilled professionals, natural analogues, stakeholder engagement, signage, and visual tools as critical elements to communicate the long-term physical risks associated with tailings dams. Transparency and the need to be open and honest were considered key aspects of risk communication, with a focus on the importance of battling untrue information.

Together, all seven themes reveal the uncertainty/risk associated with the long-time frame of tailings dam closure. This is further complicated by the unique nature of each tailings facility. Some facilities will be easier to close and reclaim, and walk-away closure may be achievable. The question remains: will this be possible for all facilities? The results of the interviews suggest that it is unlikely that walk-away closure will be achievable for all of the facilities in Alberta. In light of this, steps should be taken to comprehensively evaluate the long-term behaviour of each facility and how this can be effectively managed going forward. This should include considerations of long-term monitoring and surveillance and effective risk communication. The results indicate the need for further research into the long-term behaviour of tailings facilities. As a first step, the results from these interviews aggregate industry experience to facilitate development of documented guidance to enhance the design and evaluation for tailings closure schemes.

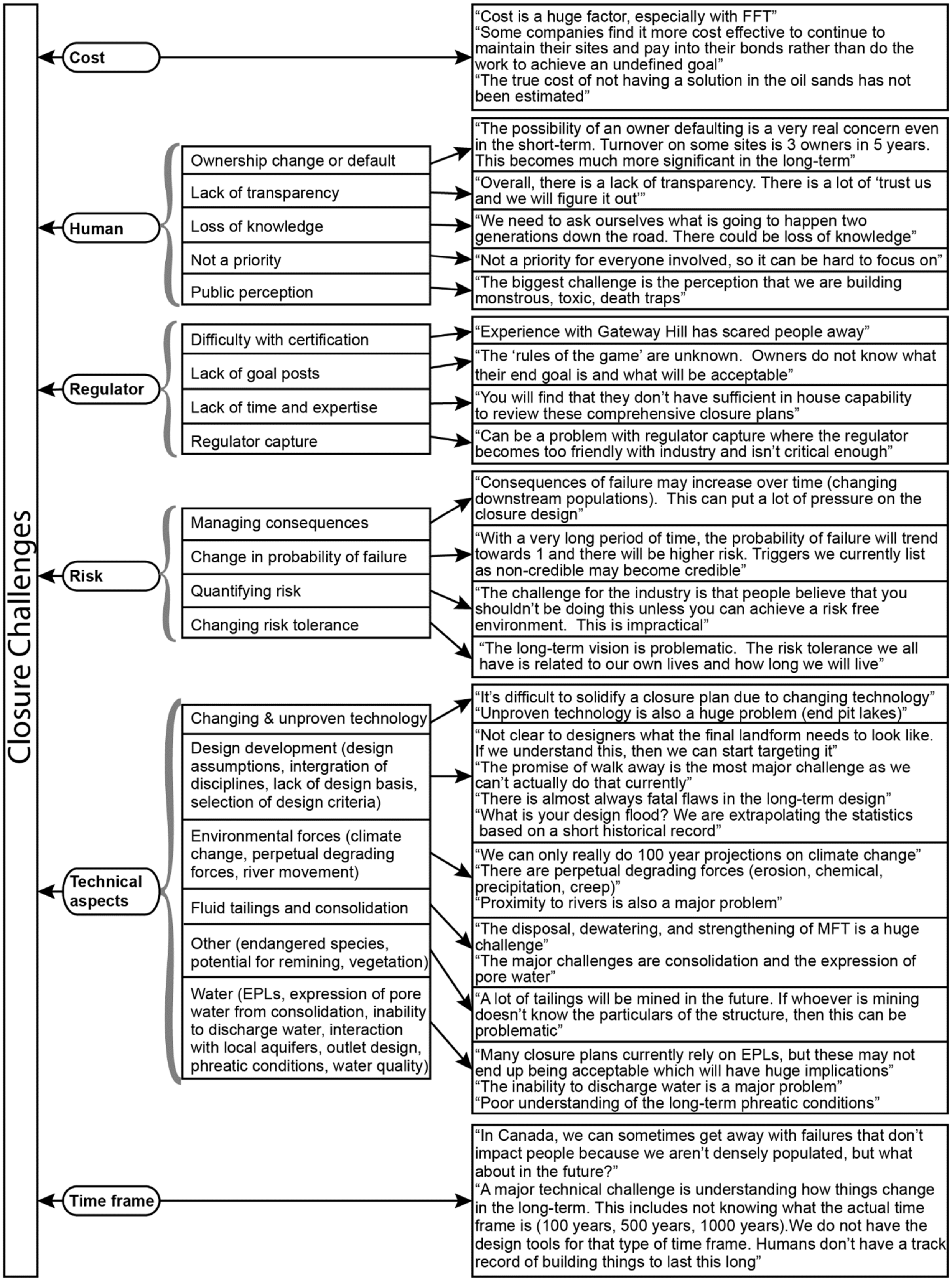
3.2 Expansion on Themes from Schafer et al. (2019)

The Schafer et al. (2019) paper summarized the following themes (which are expanded on here):

- Tailings dam closure challenges;
- Development of hazards and triggers; and
- Changing failure modes

3.2.1 Tailings Dam Closure Challenges

One of the themes discussed were the challenges to tailings dam closure. This theme allowed for identification of areas of potential improvement and areas of uncertainty that contribute to the inability to close a tailings dam. The major challenges identified fell into the following categories: cost, human, regulator, risk, technical aspects, and time frame. All of the identified challenges from the interview analysis with supporting quotes from the interviews are provided in Figure 3-5. Some of the categories have been further discretized. The most common challenges discussed by interviewees were cost, time frame, risk, and the lack of goal posts from the regulator. The remainder of this discussion will focus on these topics. It should also be noted that fluid fine tailings (FFT), mature fine tailings (MFT), consolidation of fluid tailings, and the inability to discharge water were identified as key technical challenges to closure within the oil sands.



Cost

“Cost is a huge factor, especially with FFT”
“Some companies find it more cost effective to continue to maintain their sites and pay into their bonds rather than do the work to achieve an undefined goal”
“The true cost of not having a solution in the oil sands has not been estimated”

Human

- Ownership change or default: “The possibility of an owner defaulting is a very real concern even in the short-term. Turnover on some sites is 3 owners in 5 years. This becomes much more significant in the long-term”
- Lack of transparency: “Overall, there is a lack of transparency. There is a lot of ‘trust us and we will figure it out’”
- Loss of knowledge: “We need to ask ourselves what is going to happen two generations down the road. There could be loss of knowledge”
- Not a priority: “Not a priority for everyone involved, so it can be hard to focus on”
- Public perception: “The biggest challenge is the perception that we are building monstrous, toxic, death traps”

Regulator

- Difficulty with certification: “Experience with Gateway Hill has scared people away”
- Lack of goal posts: “The ‘rules of the game’ are unknown. Owners do not know what their end goal is and what will be acceptable”
- Lack of time and expertise: “You will find that they don’t have sufficient in house capability to review these comprehensive closure plans”
- Regulator capture: “Can be a problem with regulator capture where the regulator becomes too friendly with industry and isn’t critical enough”

Risk

- Managing consequences: “Consequences of failure may increase over time (changing downstream populations). This can put a lot of pressure on the closure design”
- Change in probability of failure: “With a very long period of time, the probability of failure will trend towards 1 and there will be higher risk. Triggers we currently list as non-credible may become credible”
- Quantifying risk: “The challenge for the industry is that people believe that you shouldn’t be doing this unless you can achieve a risk free environment. This is impractical”
- Changing risk tolerance: “The long-term vision is problematic. The risk tolerance we all have is related to our own lives and how long we will live”

Technical aspects

- Changing & unproven technology: “It’s difficult to solidify a closure plan due to changing technology” “Unproven technology is also a huge problem (end pit lakes)”
- Design development (design assumptions, intergration of disciplines, lack of design basis, selection of design criteria): “Not clear to designers what the final landform needs to look like. If we understand this, then we can start targeting it” “The promise of walk away is the most major challenge as we can’t actually do that currently” “There is almost always fatal flaws in the long-term design” “What is your design flood? We are extrapolating the statistics based on a short historical record”
- Environmental forces (climate change, perpetual degrading forces, river movement): “We can only really do 100 year projections on climate change” “There are perpetual degrading forces (erosion, chemical, precipitation, creep)” “Proximity to rivers is also a major problem”
- Fluid tailings and consolidation: “The disposal, dewatering, and strengthening of MFT is a huge challenge” “The major challenges are consolidation and the expression of pore water”
- Other (endangered species, potential for remining, vegetation): “A lot of tailings will be mined in the future. If whoever is mining doesn’t know the particulars of the structure, then this can be problematic”
- Water (EPLs, expression of pore water from consolidation, inability to discharge water, interaction with local aquifers, outlet design, phreatic conditions, water quality): “Many closure plans currently rely on EPLs, but these may not end up being acceptable which will have huge implications” “The inability to discharge water is a major problem” “Poor understanding of the long-term phreatic conditions”

Time frame

“In Canada, we can sometimes get away with failures that don’t impact people because we aren’t densely populated, but what about in the future?”
“A major technical challenge is understanding how things change in the long-term. This includes not knowing what the actual time frame is (100 years, 500 years, 1000 years).We do not have the design tools for that type of time frame. Humans don’t have a track record of building things to last this long”

Figure 3-5: Identified closure challenges based on interview analysis with supporting quotes

Overall, the major restriction to tailings dam closure noted by participants was the lengthy time frames associated with tailings dam closure. The overarching expectation is that the reclaimed facility should be safe in perpetuity. To some in perpetuity means 1000 years and to others it means ‘until the glaciers return’. Regardless, the time associated with tailings dam closure introduces a degree of uncertainty that many are uncomfortable with, especially when combined with the expectations associated with walk-away closure. Interestingly, the time frame challenge is strongly linked to many of the other closure challenges. For example, selection of design criteria and development of a design basis were noted as being closure challenges (Figure 3-5). This is often difficult because of factors like climate change, changing design floods and earthquakes, perpetual degrading forces, and changing downstream populations, which are all linked to the time frame. One participant noted that “it’s not just that we don’t currently know certain things. There are some things that are simply unknowable”.

The regulator was perceived as a challenge to tailings dam closure, specifically with regard to the amount of guidance provided on dam closure and certification. Interview responses related to the regulator primarily expressed a desire for more guidance on the expectations and requirements for closure (or the ‘goal posts’ of closure) and what will be considered acceptable to the regulator. It was noted that this lack of guidance is a deterrent to some mine operators to perform reclamation and close their facilities as they may spend a lot of money without the desired outcome. Some participants went a step further to indicate that the lack of a clear ruling by the regulator on the use of end pit lakes (EPLs) and water discharge criteria is a major challenge to closure in the oil sands.

Another closure challenge tied to the time frame is risk and how difficult it is to quantify in the long term. The risk discussion primarily focused on changing consequences, probability of failure, and risk tolerance over time. Participants noted that over time the probability of failure will trend towards 1 as non-credible triggers become credible. Due to this, they suggested that we should be focusing on minimizing the consequences of failure, which is further complicated by factors like changing land uses and downstream populations over time. It was also noted that quantifying changing risk tolerance over time of relevant stakeholders is difficult.

Cost was identified as a major challenge from two different perspectives: the operator and the public. From the operator perspective, interviewees noted that the cost of closure is rarely estimated correctly resulting in a lack of funding for closure. It can also be difficult for operators to invest money into closure without knowing the regulator goal posts for acceptance. From the public perspective, many participants expressed concern regarding the potential for a company to default leaving the public to pay for the cost of reclamation.

What can industry do to proceed towards closure of these facilities? The lengthy time frame associated with closure will always be a major source of uncertainty. As engineers, scientists, or regulators, we cannot claim to predict the future and must always be aware of our own hubris to avoid complacency. This requires extensive documentation and review – elements that are currently in place in Alberta under the Dam Safety Program. The interviews identified a need for more research into the long-term behaviour of tailings dams and the practicality of designing for in perpetuity such that walk-away closure is feasible (Morgenstern 2012). The interviews also showed a desire from industry for further guidance from the regulator. Some individuals commended the Alberta Energy Regulator (AER) on their commitment to dam safety, noting that their intent and motivation for closure is there, but that they may not yet be capable of walking through the process of tailings dam closure. The regulator's commitment to dam safety and the development of closure practices is evident with the release of the new Alberta Dam and Canal Safety Directive in 2018 and the current collaboration with Dam Integrity Advisory Committee (DIAC). The reality is that regulator processes can often be slow and involve complex policy issues.

3.2.2 Developing Hazards and Triggers

The development of hazards and triggers during dam evolution was a theme that developed during interview analysis. Dam evolution, hazards, and triggers all influence the way in which failure modes will change over time for a specific facility. These processes can be complex and difficult to anticipate, especially when combined with the element of time. This is further complicated when an effort is made to evaluate the compounding effects of various dam changes and the development of hazards and triggers. The hazards and triggers identified by interviewees are provided in Table 3-1, and features of the dam that may evolve over time, as identified by the interviewees, are provided in Figure 3-6.

Table 3-1: Hazards and triggers as identified by interviewees

Category	**Category Description**
Environmental forces	Climate change, erosion, fires, precipitation events, river movement, seismic events (including induced seismicity), thermal effects (freeze-thaw and desiccation)
Excessive cost	Lack of funds for managing closure
Humans	Future activities (change in surrounding land use, land development, recreational activities), reclamation construction, regulatory environment, upstream and downstream populations
Material properties	Change in material properties over time as identified in the dam evolution process (i.e., loss of strength)
Seepage and water movement	Changes to dam structure (cracks, sink holes, slopes), drainage system failure, MFT lens, overland flow via herd pathways or human created paths, changes to the phreatic surface and porewater pressure, pipe failure, pond on reclamation surface, preferential flow paths through burrows
Spillways	Blockage (beaver dams, debris, denning of bears), buoyancy in sand channels, failure of erosion control, icing, sedimentation
Stress changes	Beaver activity, precipitation events, slope changes, toe erosion
Vegetation	Deep root systems, failure of vegetative cover

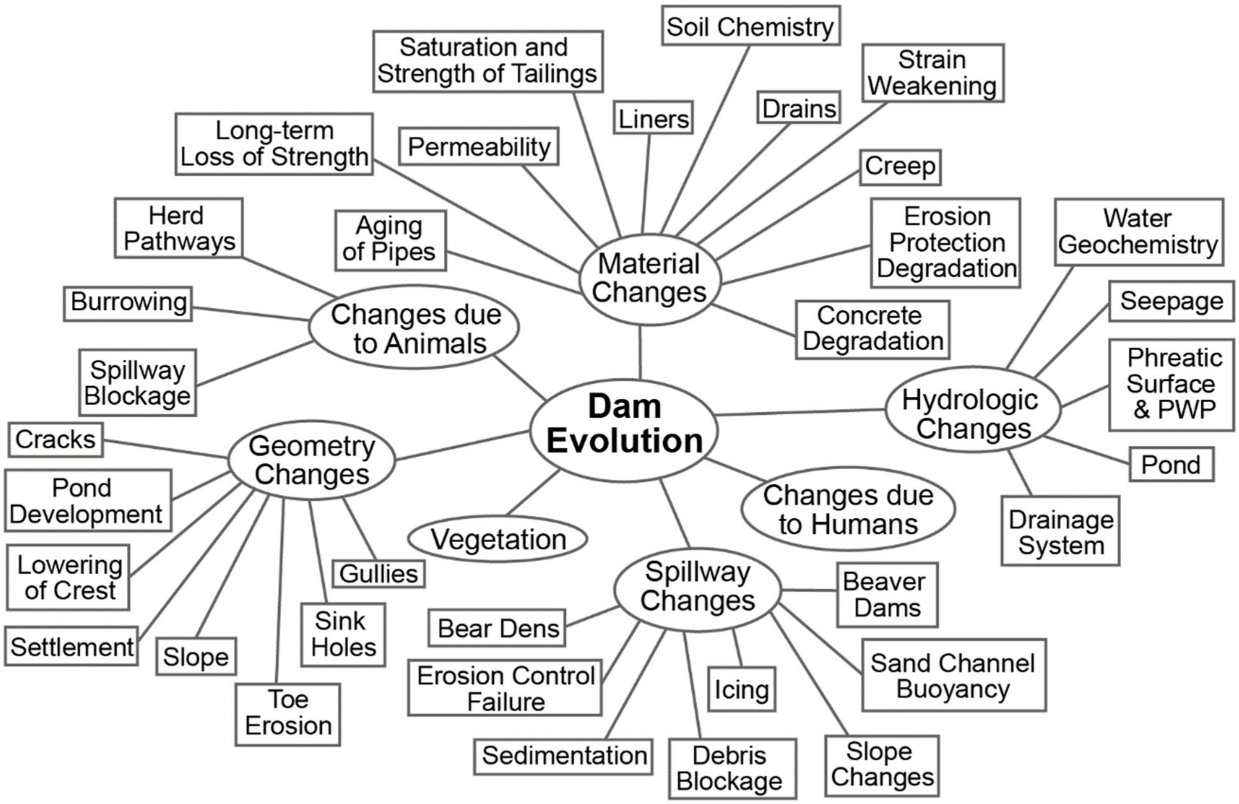


Figure 3-6: Dam evolution over time according to interview responses

These dam evolution processes have the potential to result in the development of a hazard where a hazard is defined as a condition that has the potential to result in an undesirable consequence. Further, many of the features of dam evolution may also form hazards. For example, as the facility evolves, a pond may develop on the reclamation surface. This pond also forms a hazard. Again, it should be noted that the information provided in Table 3-1 and Figure 3-6 are not intended to provide a comprehensive list of all of the hazards, triggers, and dam evolution processes that could occur in the long term. More so, they are intended to provide insight into the complex nature of planning and designing for closure.

It should be noted that individuals varied in their opinions on hazards, triggers, and changes to the dam over time. For example, there were conflicting opinions on the importance of surface erosion in the long term. Most individuals noted that surface erosion is expected to get worse in the long term; however, some participants stated that it is not expected to threaten the integrity of the dam. In contrast, others noted that erosion has the potential to lead to deep gullies that could intersect the crest and cause serious damage to the structure, potentially leading to a failure. While wind and water erosion are easily controlled during operations, this changes in the long term when there is no longer staff present. An additional example is that many people noted that the phreatic surface will decrease in the long term while others stated a number of conditions under which this may not be true (i.e., clogging of drains or aging of sands). Participants noted that there may also be factors that we are simply unaware of. For example, could the sand become clogged or cemented resulting in a decrease in the permeability and a subsequent rise in the phreatic surface? This discrepancy is particularly concerning as the assumption regarding the phreatic surface and porewater pressure (PWP) in the dam influences the assessment of the potential for failure modes to occur in the long term (internal erosion, static liquefaction, etc.).

These discrepancies serve to emphasize the uncertainty associated with long-term dam safety where uncertainty may fall into one of the following three categories (Baecher 2016):

- Known-knowns (often referred to as aleatory uncertainty): uncertainty associated with the randomness of the world where the outcome is in question;
- Known-unknowns (often referred to as epistemic uncertainty): uncertainty associated with limited knowledge or data. This includes parameter and model uncertainty; and
- Unknown-unknowns (deep uncertainty): uncertainties that are unforeseeable or uncontrollable.

From the long-term design perspective, the area of unknown-unknowns poses a significant concern. This category of uncertainty suggests that with significant research and experience it is unlikely that we would be able to comprehensively define all of the evolutionary processes, hazards, and triggers for a dam. While Table 3-1 and Figure 3-6 provide a significant portion of information on these topics, they allow us to identify areas of known known uncertainty and known-unknown uncertainty – not unknown-unknowns. The complexities associated with the time frames required for tailings dam closure is an example of an unknown-unknown uncertainty. In order for closure to proceed towards the desired goal of walk-away closure, the question of unknown-unknowns must be addressed.

3.2.3 Changing Failure Modes

To design for closure, the designers must understand the way in which failure modes change over time. This is not a simple task, especially with consideration of the closure challenges and the development of hazards and triggers over time as the dam evolves. Further, there is little precedent on which to base design assumptions.

Participants noted that failure modes will change drastically between construction, operations, and closure. As a result, it is expected that some failure modes will go away or be reduced in scale. This is expected to be site specific and variable depending on the mine. According to the ICOLD Committee on Tailings Dam and Waste Lagoons (2001), overtopping, slope instability, and earthquakes are the top three causes for active tailings dam incidents. Additional causes include foundation instability, seepage, structural inadequacies, erosion, mine subsidence, and unknown causes (ICOLD Committee on Tailings Dam and Waste Lagoons 2001). During the interview process, the failure modes discussed were:

- Foundation failure;
- Internal erosion;
- Overtopping;
- Seismic liquefaction;
- Slope instability;
- Spillway failure; and
- Static liquefaction.

A general summary from the interviews related to the changing failure modes is provided in Table 3-2.

Table 3-2: Changes to failure modes according to interview responses

Failure Mode	**Changes to Failure Mode According to Interview Reponses**
Foundation failure	The potential for foundation failure is expected to decrease with time.
Internal erosion	The responses varied with regard to the potential for internal erosion in the long term. Some individuals noted that the potential will decrease over time as the expected seepage will reduce over time, especially in cases where the tailings are removed from the pond for closure. However, a number of people noted that this is expected to be a concern in the long term, especially with consideration of evolving seepage systems. It was noted that a lack of warning of failure may be problematic in the long term when there is no one actively caring for the facility.
Overtopping	The potential for overtopping is expected to decrease in the long term in designs with a spillway. The highest risk is when the pond is at full height as closure works begin. Long-term settlement could result in the development of a pond, especially when combined with a large water catchment, which could increase the potential for overtopping. This could be increasingly problematic with the erosion of freeboard. A couple of participants noted that there is a critical point during reclamation works where there is a relatively small area that can handle the probable maximum precipitation before the outlet is constructed, which can increase the risk of overtopping. Overtopping may be critical in scenarios where a dam becomes non-operational and is abandoned without being closed.
Seismic liquefaction	The potential for seismic liquefaction will always be present. It is expected that the response to seismic loading will get better due to consolidation and the lowering of the phreatic surface (assuming this is true). Induced seismicity may become an increasing concern in the long term. Seismicity is not currently considered to be critical in Alberta, but it could become more important in the future.
Slope instability	Slope instability may recede over time, but not always. For example, if there is a progressive failure, this may become more critical over time.
Spillway failure	Spillway failure was noted by some participants as being one of the biggest concerns in closure as a spillway failure may lead to a multitude of other problems with the structure. To attempt to mitigate this, spillways are often designed to be robust and may be large with huge rip rap channels, which can be extremely expensive. This may be problematic in cases where a structure is abandoned prior to reclamation works.
Static liquefaction	The responses varied with regard to the potential for static liquefaction in the long term. Some participants noted that static stability is expected to increase in the long term, assuming that the phreatic surface drops over time and the tailings de-saturate. Other participants noted that static liquefaction can never really be ruled out as a potential failure mode and may be re-invoked in the long term due to stress changes from factors like erosion. Overall, responses indicated that the susceptibility to static liquefaction could get better or worse with time (i.e., consolidation of material versus a rising water table from the re-establishment of natural drainage patterns).

An individual noted that we need to anticipate that failure will occur in the long term, but that we must understand what failure modes are analogous to the natural environment to determine what may be considered acceptable risk. Overall, responses supported the idea that we cannot build a structure, walk away, and expect it to be the same forever. As a result, we must build capacity into our systems to behave naturally in the long term, meaning that we allow them to change, evolve, and mimic the environment. Regardless of this, participants noted that the physical stability should increase in the long term. Participants varied in their opinions on changes to failure modes over time. This was largely based on initial assumptions made regarding dam evolution processes and the potential hazards and triggers that could be present in the long term. The way in which failure modes change is highly site specific. Regardless, the interview results showed a higher degree of ambiguity regarding the importance of internal erosion and static liquefaction in the long term, compared to the other failure modes. This clearly shows the importance of evaluating key assumptions when conducting failure mode analysis for the long term. Further, the uncertainty associated with static liquefaction shows that significant research is needed to support the CDA Mining Dam Committee's requirements for a tailings dam to be classified as a mine waste structure.

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4 GENERALIZED FAILURE MODES EFFECTS ANALYSIS

This research aims to create a risk management tool to be used in industry for managing the risk of external tailings facilities in Alberta following mine closure over time. The risk management tool should be applied at the planning stage and continually throughout the life of the facility. The goal of this process is to help improve the closure plan so that it can be adapted as needed with the goal of achieving effective and efficient closure of the facility that will meet post-closure performance expectations. The developed risk management tool can be viewed as a modified FMEA that incorporates the element of time to account for evolution of the system and will be referred to as the Generalized FMEA.

As noted by the Landform Design Institute (LDI) (2021), there are always residual risks present at reclaimed landforms, including that the reclaimed landscape will not perform as intended, vegetation failing to grow as desired, people not being able to use the land as intended, or performance not meeting regulatory requirements. Managing the long-term residual risks requires a transparent mechanism that includes collaborative design, construction, reclamation, and aftercare (LDI 2021). The risk management tool developed as part of this research aims to aid in identifying the physical residual risks so that they can be managed as needed. Chemical, economic, and social stability is beyond the scope of this research.

While this risk management tool has been developed with Alberta in mind, it does have global significance and could be adapted to fit other jurisdictions. Adaptation of the framework would require considerations of the local context, including any hazards, triggers, or failure modes specific to the geography, climate, or tailings. There is a large global inventory of TSFs with some sources indicating that there are over 3,400 active tailings facilities (Franks et al. 2021). Many of these facilities are old and were designed and constructed with little consideration of closure. This historical approach to mining has resulted in TSFs that are in a poor position for closure or have been abandoned/orphaned all together. In Canada, it is estimated that there are 10,000 abandoned mine sites (Oberle et al. 2020). The goal of this risk assessment tool is for it to be applied early in the mining process to avoid increasing the number of abandoned mine sites globally and in Canada by employing risk informed decision making; however, the risk management tool has also been developed to be applicable to facilities that have already been constructed and facilities present at abandoned or orphaned sites.

This section presents the Minerals journal paper in full, which details the development of the Generalized Failure Modes Effects Analysis (G-FMEA) framework. Slight modifications were made to align the paper with the thesis structure and format. Supplementary material is provided in Appendix A: Supplementary Information for G-FMEA.

4.1 A Failure Modes and Effects Analysis Framework for Assessing Geotechnical Risks of Tailings Dam Closure

Abstract

Tailings dams remain on site following mine closure and must be designed and reclaimed to meet long-term goals, which may include walk-away closure or long-term care and maintenance. The underperformance of these structures can result in significant risks to public and environmental safety, as well as impacts on the future land use and economic activities near the structure. In Alberta, Canada, the expectation is for a tailings dam to be reclaimed and closed so that it can undergo de-registration. To aid in assessing the risks of underperformance during and after closure, a Generalized Failure Modes and Effects Analysis (G-FMEA) framework was developed to assess the long-term geotechnical risks for tailings dams in Alberta, with the goal of assessing the potential success of a tailings dam closure strategy. The G-FMEA is part of an initiative to enhance closure evaluations in Alberta in a collaborative effort between industry, the regulator, and academia. The G-FMEA incorporates the element of time to account for the evolution of the system, which should be applied at the planning stage and updated continually throughout the life of the facility. This paper presents the developed G-FMEA framework for tailings dams in Alberta, including the developed risk matrix framework.

4.1.1 Introduction

Historically, tailings dams were designed with the consideration of geotechnical failure modes that could occur during the active life of the mine. Little consideration was given to closure of the facility and the long period afterwards. This approach has resulted in many tailings dams that are in a poor position for closure or have been orphaned all together. This is problematic as the failure of these structures can still occur after the closure of a mine site, such as at the Matachewan Consolidated Mine in Ontario (Baker et al. 1996); or when the mine is in a period of care and maintenance, such as at Obed Mountain Coal Mine in Alberta (Provincial Court of Alberta 2017b). Regardless of whether the mine is active or not, tailings dams can pose a significant risk to the public and the environment if not properly managed or decommissioned. In the medium-to-long term, after decommissioning, uncertainties associated with the performance of these structures increase, as there is limited information regarding how a tailings dam ages in perpetuity. This knowledge gap poses a significant environmental, public, and financial risk, especially when combined with the serious consequences associated with the failure of tailings dams. As a result, it is vital that risk management practices be developed to assess the risks associated with the long-term behaviour. Mitigation strategies should be adopted early in the life of the structure, or as soon as they are practical for active or closed facilities. There is a transition towards integrating sustainable mining practices at the outset of mining. Of note, the Landform Design Institute (LDI) advocates for mining with an end in mind, noting that there will always be residual risks present following the closure of a mine (LDI 2021). Managing the long-term residual risks requires a transparent mechanism that includes collaborative design, construction, reclamation, and aftercare (LDI 2021).

In Alberta, Canada, the mining industry consists primarily of coal and oil sands extraction. The external tailings facilities (ETFs) at these mines are at various points in their lifecycles. With some facilities reclaimed or in the process of being reclaimed, it is important that systems are in place to aid operators in understanding the regulator's requirements for the process of de-registration. De-registration is the process where the governmental body in charge of regulating these structures (i.e., Alberta Energy Regulator, AER) assesses a dam to determine if it can be removed from the dam and pond registry and no longer be regulated as a dam; Alberta is making ongoing progress towards this goal. This is evident in the release of the Alberta Dam and Canal Safety Directive (the Directive) and Manual 019: Decommissioning, Closure, and Abandonment of Dams at Energy Projects (Manual 019) (Government of Alberta 2018, AER 2020). Manual 019 indicates that "in closure, a dam operator provides active care and may transition to passive care, depending on site-specific circumstances. As a result, the Directive adopts a number of formal risk-management principles to ensure the long-term care and maintenance of tailings dams after the construction and operation phase has ended" (AER 2020).

With the impending closure of a number of external tailings facilities in Alberta, a Generalized Failure Modes Effects and Analysis (G-FMEA) framework was developed to assess the landform design for closure. This assessment should ideally be conducted before mining begins (during permitting) and updated as the project progresses. Ultimately, the goal of the G-FMEA framework is to aid in managing the residual risks associated with ETFs in both a practical and economical way. The residual risks must be acceptable to stakeholders.

In order to complete a comprehensive risk assessment, it may be necessary to conduct various levels of modelling to evaluate the behaviour and/or assess consequences. For example, in operational risk assessments, runout modelling and inundation mapping are important elements of the risk assessment, as noted by Ghahramani et al. (2020). The utility of such assessments for conducting a long-term closure risk assessment for the purposes of de-registration may need to be evaluated in the context of the regulator. For example, the AER (Manual 019) requires flowable tailings to be removed or mitigated for a tailings facility to be de-registered, such that they do not pose an unacceptable risk to dam safety (AER 2020). Similar criteria regarding flowable tailings is outlined by Al-Mamun and Small (2018). While further advancements and an increased confidence in the results of the runout modelling and inundation mapping are useful for understanding the risks associated with flowable tailings, they may not be useful tools within the current de-registration framework. However, they remain useful tools for assessing the long-term risks of tailings facilities where it is not possible to remove the flowable tailings or for orphaned facilities.

The G-FMEA will fit most structures and failure modes but may highlight failure modes that require additional analyses, such as quantitative risk assessments. As such, the G-FMEA is intended to be used as a screening tool for the closure phase of the life cycle of an external tailings facility, where the risks assessed as acceptable require no further analyses and higher risks (or multiplicity of relatively low risk) can trigger more detailed and/or quantitative approaches. The G-FMEA is, therefore, meant to investigate the potential of the facility to be de-registered as a dam by investigating the risk of geotechnical failure. This paper presents the developed G-FMEA framework, including a developed risk matrix framework. The G-FMEA charts developed as part of the framework present the failure modes that are applicable to closure and should not be used to assess dam safety during construction or operation.

4.1.2 FMEA Background

FMEA is a risk assessment tool that allows for the systematic identification and analysis of the different failure modes and their associated consequences (Robertson and Shaw 2006, Ayyub 2014). FMEA aims to identify all potential failure modes, the consequences of these failure modes, the mechanisms of failure, and how the risks associated with the failures can be avoided or controlled (Valis and Koucky 2009). The entire process is based on determining what happens if a specific component or element of the system fails (Hartford and Baecher 2004). When extended and applied to a dam, FMEA focuses on developing a clear picture of the dam, including the various components and how they interact in a systematic way (Hartford and Baecher 2004). Using this basis, FMEA can be used to evaluate how component failures can lead to overall system failures, the consequences of component and system failures, and the criticality of various components for risk control (Hartford and Baecher 2004).

FMEA is generally site-specific and considers the site data, construction method, construction materials, and past behaviour of the structure (Küpper et al. 2013). As a result, it can be a time-consuming, complex process (occasionally even requiring field or laboratory investigations). Despite this, it is proven to be an extremely useful tool as it allows risks to be assessed and managed. As shown by Santos et al. (2012), FMEA is effective in demonstrating the potential failure modes of all components of a tailings dam system, which then allows for the development of a comprehensive dam monitoring and surveillance system. To conduct an FMEA, the following structure can be used (Hartford and Baecher 2004):

1. Define the system, including all components.
2. Based on component interaction, de-aggregate the system into functional sub-systems.
3. Break the sub-systems down into key elements and functions.
4. Analyse the failure modes of the different elements.
5. Assess the failure effects and consequences of the various elements.
6. Summarize the findings.
7. Repeat as necessary.

Steps 4 and 5 involve analyzing the failure mode, effects, and consequences of the different elements. This is an important step as it allows the effect of component failure modes on other components of the sub-system and the overall system to be evaluated.

Applying an FMEA to a tailings dam is not a new or revolutionary task; however, the application of an FMEA to assess the risk of a tailings dam over post-closure time frames is challenging as a major limitation of an FMEA is the inclusion of time dependence and the depreciation of performance of system components (Santos et al. 2012). It is expected that the dam will evolve significantly over time (i.e., clogging of drains, ageing of sands, etc.) (Schafer et al. 2019, 2020). Ultimately, the likelihood and consequences of failure are not static and may increase or decrease over time (Porter et al. 2019, Schafer et al. 2019, 2020). Robertson and Shaw (2006) note that some risks have a different likelihood or consequences if they occur during operations or post closure. Risk matrices aim to include time through defining the time frame in which the probability of failure (PoF) is valid. This is typically set as an annual PoF, for the duration of the life of the structure. This concept is complex for evaluating closure as PoF is expected to change over long periods of time.

Incorporating time into an FMEA requires an evaluation and consideration of how risk profiles may change over time due to system changes, as shown in Figure 4-1. Point A represents the state of a system (dam structure) in terms of its PoF. Point A has an associated probability of failure that is above the acceptable limit at time zero. To move from point A to A' so that the risk meets the acceptable limit would require risk control measures to be implemented. While this satisfies the conditions at time zero, the question remains: What will happen as time progresses and the dam undergoes evolutionary processes? As shown in Figure 4-1, the risk profile may follow several different trajectories that range from decreasing over time to increasing over time.

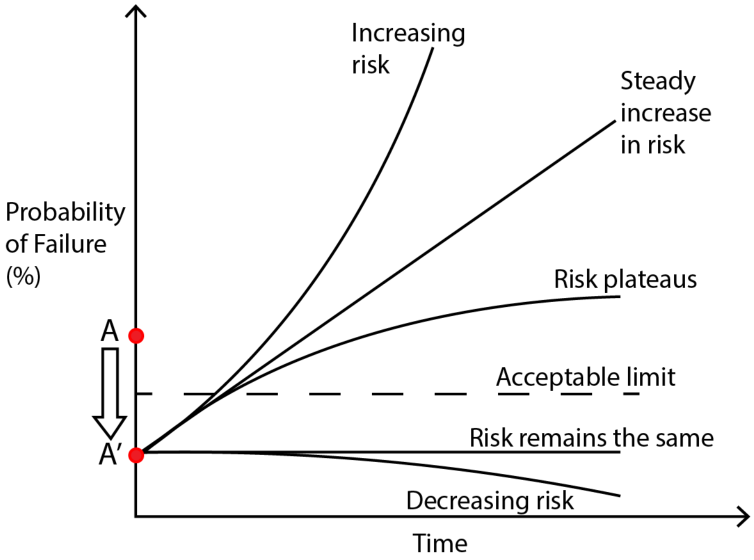


Figure 4-1: Changing probability of failure with time due to system changes

The changing risk profiles over time are influenced by the closure plan and considerations of the custodial transfer scenario of the local jurisdiction. In cases where the closure risks are intended to be managed with long-term maintenance, consideration may be required for scenarios where the maintenance may be disrupted for a period of time (for example, by war or another pandemic). The developed G-FMEA considers different temporal scales as a means of accounting for the time dependence, depreciation of system elements, and the associated changing risk profiles over time, as shown in Figure 4-1.

4.1.3 Risk Matrix Background

FMEAs may be qualitative or quantitative in nature and are commonly combined with qualitative risk matrices to estimate the likelihood and consequences of different failure modes. Risk matrices combine the estimates of the likelihood of a negative outcome with estimates of the magnitude of consequences to determine a risk level (Robertson and Shaw 2006, MEND 2012, Porter et al. 2019). The risk level then determines the level and timing of the required mitigative measures and critical controls to be implemented to reduce the risk level (Brown 2019). Risk matrices are often perceived as being simple to interpret and use. However, according to Porter et al. (2019), "guidance notes that explain the details of how the matrices were developed and how they were meant to be used for risk assessment, risk communication and risk management are often brief and cryptic". Ultimately, this lack of guidance can lead to problems with the application of the risk matrix, which is already commonly criticized for being subjective. Risk matrices have been critiqued by a number of authors, as shown in Table 4-1.

Table 4-1: Risk matrix issues, references, and associated comments related to the G-FMEA

Issue	References	Comments related to the G-FMEA
Subjective nature (not as simple and transparent as it would seem).	(Cox 2008, IEC 2009, Pickering and Cowley 2010, Ball and Watt 2013, Ayyub 2014, Monat and Doremus 2018)	Quantitative data should be used as often as possible with supporting verbal descriptions and quantitative descriptors (ranges or anchor points to the definition of categories). The risk assessment should be accompanied by a description of the risk assessor, including their risk tolerances.
Can lead to incorrect risk prioritization.	(Center for Security Studies 2012, Ball and Watt 2013, Baybutt 2018, Monat and Doremus 2018)	The risk matrix does not focus on risk prioritization, but is intended as a screening tool to assess the closure design.
Can shut down conversations about risk instead of opening them up due to the pre-defined colour coding scheme determining risk prioritization.	(Center for Security Studies 2012)	The risk matrix is designed to determine if a closure design is adequate and is a screening tool. It involves input from stakeholders to determine the consequence ratings and is intended to open up dialogue.
Ranking reversal: where quantitatively smaller risks are assigned qualitatively higher rating levels than some quantitatively larger risks due to incorrect risk prioritization.	(Cox 2008, Pickering and Cowley 2010, Thomas et al. 2014, Baybutt 2016)	The risk matrix does not focus on risk prioritization, but is intended as a screening tool to assess the closure design.
Does not account for different risk tolerances of the individual conducting the risk assessment.	(Oboni and Oboni 2012, Monat and Doremus 2018)	The risk assessor‘s background should be listed with the completed risk assessment.
Range compression where risks with very different likelihoods and consequences are grouped together. Risk matrices with too many categories may give false resolutions.	(Cox 2008, Levine 2012, Oboni and Oboni 2012, Thomas et al. 2014)	The number of risk categories should be developed with consideration of range compression.
Centering bias can be an issue where individuals have the tendency to avoid extreme values or statements when presented with a choice. This can exacerbate range compression.	(Smith et al. 2009, Thomas et al. 2014)	An extra category can be added to both sides of the expected range for the consequences and likelihoods, as suggested by Duijm (2015).
Category definition bias where different definitions exist for a given likelihood or consequence descriptor.	(Thomas et al. 2014, Duijm 2015)	Clear definitions must be provided for the consequences and likelihoods categories.
Risk matrix can be misleading as it implies that risk is categorical as opposed to a position on a risk continuum.	(Pickering and Cowley 2010)	The risk matrix should be accompanied by a clear definition of risk and associated discussion on the risk continuum.
Ambiguity of the consequence definition. There are different definitions used in practice for the consequence that can lead to issues if not clearly	(Duijm 2015)	The consequence category must be clearly defined.

Issue	References	Comments related to the G-FMEA
defined (worst case, most likely, a number of alternate discrete outcomes).		
Risk matrices cannot provide aggregate measures of risk (i.e., total risk).	(IEC 2009, Baybutt 2016, Bao et al. 2018)	The goal of this risk matrix is to serve as a screening tool and is not intended to provide an indication of total risk.
Risk matrices are unable to aggregate risk from multiple consequence dimensions. This means that different types of consequences should not be directly compared (i.e., impact on the environment, human life). In practice, a hazard is often assigned a risk level based on the most severe consequence. This is misleading.	(IEC 2009, Duijm 2015, Oboni and Oboni 2020)	A risk rating should be assigned for each consequence category for a hazard.
Corporate-wide risk matrices are intended to be used as a way of standardizing risk assessment and risk acceptance criteria across a company. This is problematic as risk tolerance may vary throughout a company.	(Duijm 2015)	Corporate-wide risk matrices should not be used with the Generalized FMEA.

To aid in mitigating the known issues with risk matrices, a number of authors have suggested various improvements, including logarithmic scales (Cox 2008, Baybutt 2016); probability-consequence diagrams with continuous scales (Duijm 2015); and following the Cox axioms of weak consistency, betweenness, and consistent colouring (Cox 2008). Despite the issues associated with risk matrices, some authors suggest that an important element of using risk matrices is applying them in the appropriate scenarios. Bao et al. (2018) suggests that subjectivity is a vital characteristic of risk matrices as they are effective for assessments where data are insufficient and quantitative tools cannot be applied. Baybutt (2016) notes that risk matrices should be used to provide "… initial decision guidance, which should be used with caution and the application of common sense. Risk matrices should not be used in isolation to make decisions". Considering all of this, the risk matrix developed as part of this research is intended to be used as a screening tool, where the risks assessed as acceptable require no further analyses and higher risks (or multiplicity of relatively low risk) could inform where/if quantitative risk assessment techniques need to be used in the further decision-making stages for the closure of a facility.

4.1.4 Generalized FMEA Framework

A Generalized FMEA framework was developed, based on the current practice with FMEA, for use by regulators and the industry to assess the long-term risk of the failure of a tailings dam following closure. In order to conduct an FMEA, the definition of tailings dam failure must be clearly laid out. For the purposes of this work, a dual definition will be used for failure, similar to the Ultimate Limit States and Serviceability Limit States used in foundation engineering, as defined in the Canadian Foundation Engineering Manual (Canadian Geotechnical Society 2006). Here, failure is defined as:

- Ultimate failure: the collapse of a tailings dam leading to catastrophic failure as defined by the Global Tailings Review (2020):
  - *"A tailings facility failure that results in material disruption to social, environmental and local economic systems. Such failures are a function of the interaction between hazard exposure, vulnerability, and the capacity of people and systems to respond. Catastrophic events typically involve numerous adverse impacts, at different scales and over different timeframes, including loss of life, damage to physical infrastructure or natural assets, and disruption to lives, livelihoods, and social order. Operators may be affected by damage to assets, disruption to operations, financial loss, or negative impact to reputation. Catastrophic failures exceed the capacity of affected people to cope using their own resources, triggering the need for outside assistance in emergency response, restoration and recovery efforts."*
- Serviceability failure: failure to perform as intended.

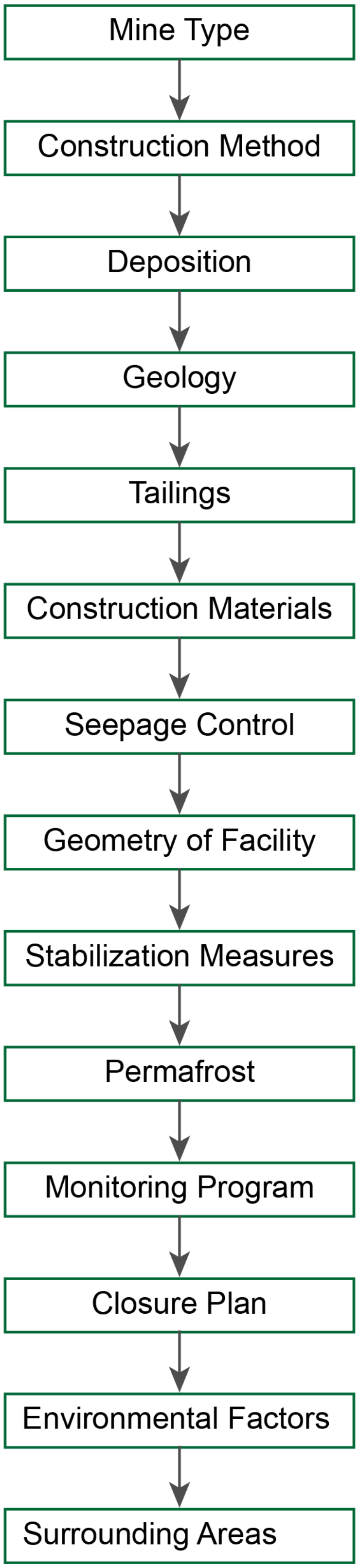
The goal of performing the G-FMEA is to guide practitioners and regulators through the process of continuing to ask questions in a disciplined manner to prevent ultimate failure. The risk management tool is not intended to be a static tool and should be revisited at specific intervals and triggered by changes in the facility or events of underperformance. A clear trigger protocol needs to be developed for revisiting the G-FMEA. The completed G-FMEA should undergo a robust scrutiny, just like the designs, be accompanied by peer reviews, and assessed by external reviewers or review boards, where applicable.

The development of the G-FMEA is assisted by the following:

1. The interviews presented in Section 3.
2. Literature reviews related to:
    a. Tailings dam characteristics in the oil sands and coal industries;
    b. Tailings dam failure modes; and
    c. Risk assessment tools.
3. The input from the regulator and industry stakeholders.

The interviews presented in Section 3 and a detailed literature review were used to develop the overall system definition, which included dam characteristics that impact dam behaviour. The system definition serves as the foundation of the development of the G-FMEA, and Ayyub (2014) notes that the first step to conducting a system definition is to establish the objectives. This step is essential to providing context and ensuring that the users of the risk framework are asking the same questions when applying the G-FMEA to their sites. The objective question of the G-FMEA is: How should geotechnical risks associated with an external tailings facility in Alberta be managed in the long term to achieve an acceptable closure plan, such that the facility is able to be de-registered as a dam? All users of the G-FMEA must understand the objective and intended use of the FMEA.

Following this, the system boundaries can be defined. The system definition is summarized in Figure 4-2 and shows the characteristics of the dam that should be carefully considered and defined prior to starting the FMEA. The general categories are summarized in the flow chart on the left with details on the general categories in the table on the right.



Mine Type	a) Oil sands b) Coal
Construction Method	Starter dyke (Y/N) a) Upstream b) Downstream c) Centreline d) Modified centreline e) Combination f) Unknown
Deposition	a) Hydraulic fill construction i) Spigotting ii) Cycloning with direct deposition iii) Cell construction iv) Combination b) Overburden construction c) Combination d) Unknown
Geology	Assess geology, including determination of liquefiable or brittle behaviour
Tailings	Characterize tailings, including state parameter
Construction Materials	a) Oil Sands i) Tailings ii) Interburden/overburden (i.e. lean oil sand, clay shale, till, etc.) iii) Coke b) Coal i) Interburden/overburden ii) Coarse coal refuse
Seepage Control	a) None b) Seepage reduction measures (low permeability core, grout curtain, upstream impervious blanket) c) Drains (natural materials, tailings, coke, geosynthetic, non-perforated pipe, perforated pipe, etc.) i) Chimney drain ii) Toe drain iii) Strip drain iv) Relief well v) Horizontal blanket drain vi) Seepage collector and outlet pipes
Geometry of Facility	a) Height b) Volume contained c) Slopes
Stabilization Measures	Define stabilization measures (i.e. berms, soil improvement, shear keys etc.)
Permafrost	a) Yes b) No
Monitoring	a) Yes b) No
Closure Plan	a) Plan for tailings (i.e. infilling, dewatering, natural processes, cover, etc.) b) Reclamation surface and cover c) Outlet (Y/N) d) Surface water management
Environmental Factors	a) Determine site climate (consider climate change) b) Precipitation and earthquake events c) Other
Surrounding Areas	Describe upstream/downstream areas (inhabitable/habitable areas, slopes, valleys, water bodies, upstream watershed size, culturally/ecologically significant areas, etc.)

Figure 4-2: System definition of oil sand and coal mines in Alberta, Canada

The system definition serves as the minimum of what should be defined for a tailings dam prior to conducting the FMEA. However, these parameters should be defined comprehensively and may take the form of a fact sheet. This step aids in evaluating and conducting the FMEA.

Following the development of the system definition, a hazard mapping exercise was conducted, which focused on identifying potential failure modes, mechanisms, triggers, and hazards. The hazard mapping is provided in Appendix B: Hazard Mapping. A failure mode is defined as the overarching cause of failure. The failure mechanism is the mechanism by which a hazard leads to a failure mode. This may consist of a series of steps. A trigger is defined as that which initially leads to the failure mechanism. A hazard is defined as a condition with the potential to cause an undesirable consequence. Combined, the system definition and hazard mapping contributes greatly to the development of the G-FMEA. The steps required to use the G-FMEA in practice are outlined in Figure 4-3. If risk mitigation is required, or the closure plan is altered, the process may need to be repeated. This may require the risk assessor to return to Step 1 to update the system definition if substantial changes are made.

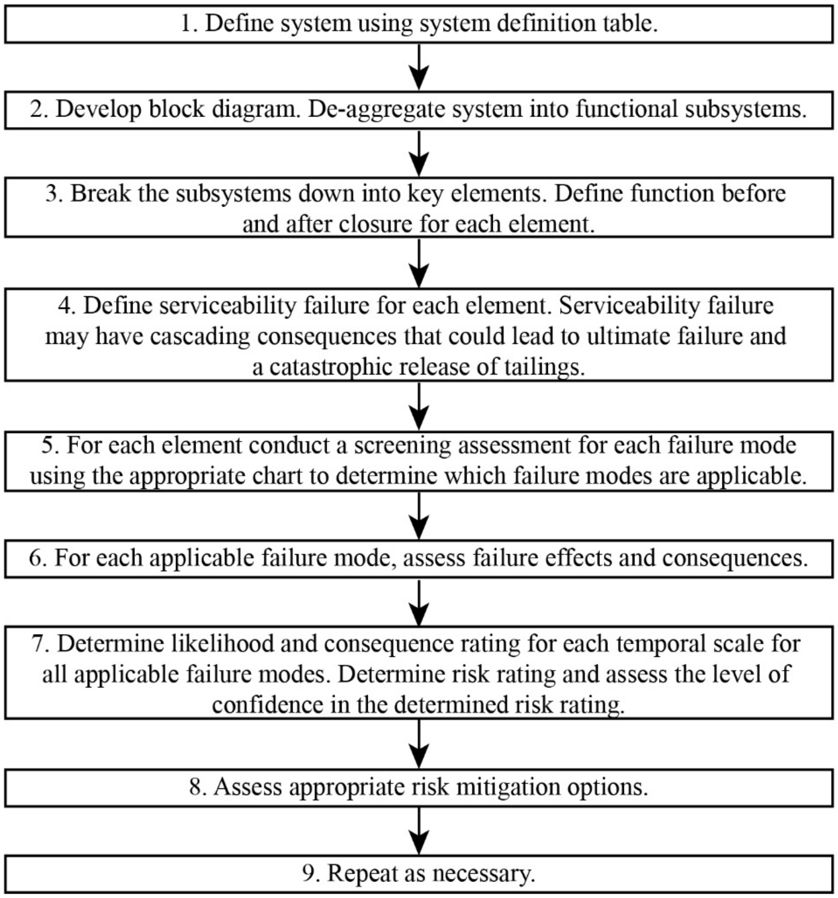


Figure 4-3: G-FMEA steps

The G-FMEA includes four individual charts for the drainage system, foundation, dam body, and landform, which are provided in Section 4.1.6. An excerpt of the drainage system chart is provided in Table 4-2. The drainage system and landform chart consider failure modes for a variety of different elements that could be present within a dam. The foundation chart and dam body chart do not provide failure modes for individual elements, since most failure modes are applicable to multiple elements. Each identified foundation element should be evaluated for every failure mode on the foundation list. Similarly, each dam body element must be evaluated for every failure mode on the dam body list.

Failure modes that are not applicable should be screened out prior to completing the risk assessment, as discussed in Step 5. A justification must be recorded for screening out a failure mode and re-evaluated each time the FMEA is revisited. This may include a justification of whether a failure mode is credible or non-credible as defined by the Global Industry Standard on

Tailings Management (Global Tailings Review 2020). It is important to note that failure modes that may be credible in the short term may not be credible in the long term and vice versa.

While the list of failure modes in Section 4.1.6 for the various elements is extensive and reasonably comprehensive, it is recommended as a pre-list of failure modes as no list can be completely comprehensive as there are always additional site-specific hazards. The G-FMEA charts should be applied to a facility using the complete worksheet provided in Section 4.1.7 (Table 4-12).

Table 4-2: Excerpt from drainage element G-FMEA chart

Element	**Failure Mode Description**	**Potential Trigger/Cause**	**Screening Assessment of Failure Mode**	**Failure Effects**
Perimeter Ditch	Blockage (partial or full)	Sedimentation, sloughing/slope failure of walls, beaver dam, continuous buildup of ice (icing)	Is there erosion protection in place? What is the slope of the ditch? Is it sufficient to keep particles suspended? What is the slope of the side slopes? What is the strength of material? Have there been failures in this material before? Are there beavers in the area? Is the mine located in an area that could experience icing?	Rise in phreatic surface, increase in seepage, pond on reclamation surface, internal erosion, global instability, flooding, blockage of drain outlets, toe erosion, discharge of process affected water to the environment
	Reduction in cross-sectional area	Sloughing/slope failure of walls, excessive vegetation	What is the slope of the side slopes? What is the strength of material? Have there been failures in this material before? Will the ditch regularly have water running through it or will it stay dry for a portion of the year? Are there deterrents in place to prevent the growth of vegetation?	Rise in phreatic surface, increase in seepage, pond on reclamation surface, internal erosion, global instability, reduced capacity, erosion, potential flooding, blockage of drain outlets, toe erosion, discharge of process affected water to the environment
	Change in slope	Erosion, differential settlement	Is there erosion protection in place? Does the material have the potential to consolidate or settle over time? Is it a cut into natural ground or is the material placed?	Change to water discharge velocity, creation of secondary channels, localized areas of erosion, instability of dam

4.1.4.1 Temporal Scales

It is essential that the FMEA for a closed tailings dam considers the element of time (i.e., how the dam evolves). Representing this is not straightforward and can be approached using different methods. The first method would be to complete a series of FMEAs for different points in time considering the different evolutionary processes that may occur. Ultimately, this adds a lot of complexity and may be prohibitively time intensive. Another route, which is adopted here, is to complete immediate-term, short-term, medium-term, and long-term risk assessments using a risk matrix for each. The determination of the time frames requires consideration of what the overall time frame is for closure. An evaluation of this was carried out using the following points: geological context, nuclear repository industry, Uranium Mill Tailings Remedial Action (UMTRA) surface project, the current databases that are relied on in the industry (often for less than 100 years), our ability to forecast the future, and transitions in periods of management. Detailed information on these discussion points is provided in Appendix A: Supplementary Information for G-FMEA.

For the long-term time period, time frames in excess of 10,000 years were deemed to be inappropriate in the mining industry as it is expected that glacial periods in time frames in excess of 10,000 years would change the geology and effectively bury the tailings facilities. The use of these time frames is perhaps better suited for systems such as nuclear waste repositories in tectonically inactive areas. With the consideration of this and the expectation for a tailings dam closure lasting 1000 years (ICOLD 2017, AER 2020), the maximum time frame selected for the G-FMEA is 1000 years. This is also reflected by the UMTRA project where the facilities are designed to be effective for 1000 years where reasonably achievable with a minimum required performance of 200 years (Task Committee on Low-Level Radioactive Waste Management of the Technical Committee on Nuclear Effects 1986, DOE 1991, Mathes 1999, IAEA 2004). All risk assessments conducted for the 1000-year time frame should include a careful consideration of the uncertainties associated with the current databases, climate change predictions, and our ability to forecast the future.

Selection of appropriate time frames for the immediate-term, short-term, and medium-term risk assessment was completed with consideration of the phases of the tailings facility following closure. Initially, consideration was given to aligning the different risk assessments with the ‘active care’ and ‘passive care’ phases commonly used in industry. This was ultimately discarded as different organizations describe these phases in different ways, which may ultimately lead to confusion (ICOLD Tailings Dam Committee 2013, CDA 2014, OSTDC 2014). To mitigate this, the performance monitoring assessment periods recommended by the International Network for Acid Prevention (INAP) were selected. INAP outlines three specific assessment periods, including the adaptive management period, proactive management period, and reactive management period, which are outlined in Table 4-3 (INAP 2017). The primary difference between the assessment periods is the degree of direct management employed (INAP 2017). The focus on management, as opposed to the actions taken during the assessment period, is attractive from a safety management system perspective.

Table 4-3: Assessment periods (INAP 2017)

Assessment Period	Definition
Adaptive Management	Occurs following closure activities when the closed facility may be at its greatest risk of failure prior to reaching equilibrium. The operator has the greatest capacity to respond. This period may be defined explicitly by the regulator, using accumulated knowledge, or using a site-specific scientific basis.
Proactive Management	Occurs as personnel and equipment are reduced. Involves a regular fixed frequency monitoring and maintenance schedule to confirm that the landform is trending along the designed trajectory. It is expected that the frequency will be less than during the adaptive management period.
Reactive Management	Issues are rectified strictly on a reaction basis, once a trigger event occurs. There should be a clear plan in place that outlines what the trigger events are and how they will be managed. Monitoring may occur in response to events such as fires, floods, earthquakes, and other extreme events.

Based on the characteristics associated with the adaptive management period, the immediate-term risk assessment should occur during this phase. The short-term risk assessment may occur during the adaptive management period or the proactive management period, depending on site-specific characteristics.

The selection of a time frame for the medium-term risk assessment involved the consideration of the reactive management period and the time frames outlined by the UMTRA project. The medium-term risk assessment should fall within the reactive management period where direct management efforts (and monitoring) decrease substantially and the facility largely shows that it meets closure objectives. The recommendations for the time frames for the various levels of risk assessment are provided in Table 4-4. The approximate assessment periods provided are intended as a guideline only and should be based on site-specific considerations. It is expected that the immediate-term and short-term risk assessments would have the most active forms of risk mitigation employed with risk measures, slowly transitioning to more passive methods as the risk assessment moves to medium- and long-term temporal scales. It is also expected that the level of confidence will decrease as the risk assessment moves from immediate-term to long-term scales for some failure modes.

Table 4-4: Time frames for various levels for risk assessment

Risk Assessment	Conditions	Approximate Assessment Period [1]
Immediate term	Should fall within the projected adaptive management period	0–10 years
Short term	Should fall within the projected adaptive or proactive management period	10–50 years
Medium term	Should fall within the projected reactive management period	50–200 years
Long term	-	1000 years

[1] Assessment period time frames depend on site-specific considerations. Intended as a guideline.

4.1.4.2 Risk Matrix Framework

The development of the risk matrix for the G-FMEA involves a consideration of the known pitfalls with risk matrices, as outlined in Table 4-1; recommendations for improvement from Baybutt (2018) and Duijm (2015); and the evaluation and consideration of other published risk matrices, including those provided by Brown (2019), Hadjigeorgiou (2019), the Guidelines for Mine Waste Dump and Stockpile Design (Griffin 2017), Mine Environment Neutral Drainage (MEND) (2012), and the Oil Sands Tailings Dam Committee (OSTDC) (2014). A number of key observations can be taken from the reviewed published risk matrices, including:

- Clear descriptions of likelihood and consequence ratings are essential. as provided by Griffin (2017) and MEND (2012). It is common for different risk matrices to use the terms ‘almost certain’, ‘likely’, and ‘possible’ but it is equally common for these to not be accompanied by clear definitions as shown in Brown (2019) and Hadjigeorgiou (2019). This is problematic as terms such as these are not universally understood to have the same meaning amongst practitioners (Reagan et al. 1989). This aligns with the critiques in Table 4-1;
- A level-of-confidence scale (or similar) is recommended to go along with the risk matrix and selected risk rating (MEND 2012);
- MEND (2012) and OSTDC (2014) were both developed for closure scenarios and provide useful analogues for the development of the risk matrix; and
- OSTDC (2014) determines the consequence rating based on the loss of function of the structure, the degree of human intervention required on the structure after an event occurs, population at risk, and environmental economics. In contrast, a risk matrix designed to assess the risk for an operational facility may consider elements such as health and safety,

environment, community, reputation, and legal aspects when assessing the consequences of failure.

While the risk matrix developed by OSTDC (2014) provides the best analogue and a useful basis for this work, it cannot be applied directly to the G-FMEA, for the following reasons:

- The G-FMEA presented in this research assesses the individual elements of a dam, not the dam as a whole, which is what the OSTDC (2014) risk matrix was developed for. The developed risk matrix must be fit for purpose; and
- The OSTDC (2014) risk matrix was developed to assess if a facility could be de-registered as a dam. The consequence and likelihood ratings reflect this. In contrast, the risk matrix is used here to assess the risk of failure over time and if a closure plan is adequate to prevent failure to support a facility being de-registered as a dam.

The risk matrix framework is intended as an example of how a qualitative risk assessment method could be combined with the G-FMEA charts to assess a closure plan and includes a likelihood rating table, consequence rating table, and a risk matrix (including details on how to colour code the risk matrix and an example of a colour-coded matrix). The risk matrix to be used for a site should be defined by the industry, regulators, and other stakeholders with considerations of the technical, social, and economic aspects.

4.1.4.2.1 Likelihood Rating

The developed likelihood rating shown in Table 4-5 has seven different categories for likelihood from ‘Close to non-credible’ to ‘Almost certain’, which are defined with considerations of annual probabilities. Qualitative descriptors were developed to provide further context on the annual probabilities. The inclusion of seven likelihood categories is more extensive than many risk matrices, which commonly have five likelihood ratings. A more extensive likelihood rating list was selected due to the time frames associated with the closure and to aid in mitigating centering bias (Table 4-1). It also serves to cover the full range of likelihoods that may be encountered, which is an essential step to developing a likelihood table (Baybutt 2018). The risk matrix is intended to be applicable from the time that closure works have been completed to 1000 years following the completion of closure works. This means that the risk matrix is not intended to capture failure modes that may occur during the construction of the closure landscape. The risk matrix is also intended to be applied to orphaned facilities, which are defined as facilities with “owners that cannot be found or for which the owner is financially unable or unwilling to carry out the clean up” (NOAMI 2010). These facilities should not be confused with those that undergo abandonment as per the Alberta Dam and Canal Safety Directive (Government of Alberta 2018). It could be argued that the categories of ‘Almost certain’ and ‘Likely’ should not be applied to a closure scenario as the assumption is that the facility is designed to a standard such that the failure of an element will not occur within a year. While this may be true for many facilities, it is unlikely to be true for all facilities (i.e., orphaned facilities). Furthermore, some failure modes may become more likely when conducting a long-term risk assessment as factors such as degradation and climate change occur. The likelihood of occurrence is often described in terms of the probability of failure. While this is an important way of evaluating the likelihood, it is valuable to describe the likelihood categories using qualitative descriptors to anchor the probabilities (Baybutt 2018). Further, humans are notoriously poor at estimating the probability of extreme events (Slovic and Weber 2002). As such, providing qualitative guidance for assessing the likelihood of a failure mode would be useful. Table 4-5 describes the likelihood categories in terms of the annualized probability and provides a qualitative interpretation. The quantitative interpretation guidance for the example risk matrix considers that each rating is a range of probabilities. Anchor values can also be adopted, if preferred, as long as it is clear to the users that the anchor values are a point approximation of this range of probabilities.

Table 4-5: Likelihood rating

Likelihood Rating	Qualitative Interpretation Guidance [1]	Quantitative Interpretation Guidance	Annualized Probability of Occurrence
Almost certain	Almost certain that an incident will occur given the circumstances. Very high probability of one or more occurrences per year.	Higher than 10% probability in a year	$P \geq 0.1$
Likely	High likelihood. Commonly observed at similar facilities.	Higher than 10% probability in 10 years	$P \geq 0.01$
Possible	Has occurred a number of times within the industry and at least once at the site (or similar facilities in the region).	Higher than 1% probability in 10 years	$P \geq 0.001$
Unlikely	Has occurred before within the industry, but not at the site.	Less than a 1% probability in 10 years	$P < 0.001$
Rare	Low likelihood of occurrence, but not impossible. Has not occurred at the site but has occurred in industry.	Less than a 1% probability in 100 years	$P < 0.0001$
Very rare	Very low likelihood of occurrence, but not impossible. Occurrence cannot be deemed non-credible	Less than a 1% probability in 1000 years	$P < 0.00001$
Close to non-credible	Extremely remote likelihood of occurrence. Although the mechanisms are technically plausible for the occurrence, it is seen as near non-credible.	Less than a 1% probability in 10,000 years	$P < 0.000001$

[1] Industry encompasses the mining industry as a whole.

4.1.4.2.2 Consequence Rating

The consequence rating shown in Table 4-6 has five categories that range from 'Slight' to 'Severe'. The consequence rating is selected based on:

- The degree of the consequence of failure of an element on the rest of the system.
  - This involves an assessment regarding if the failure will result in cascading consequences to other elements.
- The degree of human intervention (post failure) required.
  - It is important to note the degree of human intervention required in response to a failure as the ultimate goal is to reach a state of minimal or no human intervention. In cases where this is not possible, this may suggest a careful evaluation of the custodial transfer scenario for that facility.
- Community.
  - The impact on the community should be assessed using input from the relevant stakeholders. This is difficult to evaluate in light of the time frames associated with

closure. Our ability to predict downstream and upstream populations in the future is limited by our short-term knowledge; however, a consideration can be made of the likelihood that the affected area could be inhabited in the future (i.e., is the mine located in inhospitable terrain or in an area that is desirable for development?). This would allow baseline assumptions to be made about the future community impact. A key step to defining the impact on a community is identifying the community. As defined by the Impact and Benefit Agreement (IBA) Community Toolkit (Gibson and O'Faircheallaigh 2015), this involves answering the questions: "Who is the community? How is the geographic, ethnic, or scope of community defined? Who legitimately represents the community? Is it simply representatives from local community organizations, or is it necessary to reach out to more diverse groups to ensure all elements are consulted? The definition of 'community' should be inclusive enough to promote equity and avoid future conflict resulting from lack of inclusion" (Gibson and O'Faircheallaigh 2015). The community consequence rating provided in Table 4-6 is provided as a guideline only and requires input from the relevant stakeholders to explicitly define the community impact. This should be accomplished using meaningful engagement as defined by the Global Tailings Review (2020). Defining the consequence rating for the community may involve a consideration of health (including fatalities), loss of access/destruction of traditional lands, housing, destruction/damage of farmland, harm to livestock, damage to water or soil resources, impacts to trapping and fishing, the loss of animals, overall cultural impact, and employment. It is critical that the impact on all valued components (and their condition following a failure) to the relevant stakeholders are considered. A valued component is that which is considered important by the community (Gibson and O'Faircheallaigh 2015). It should be noted that Impact and Benefit Agreements developed between the mining companies and Aboriginal communities may include agreement provisions to account for catastrophic failures and losses and should be consulted when assessing the consequences of a dam failure to the community (Gibson and O'Faircheallaigh 2015).

- Environment.
    - The environmental impact must be assessed with a consideration of the impacted land (both surrounding the facility and in the facility itself, with respect to its post mining land use) and waterbodies and the toxicity of the tailings. The Canadian Dam Association (CDA) developed a Working Group to revamp their environmental classification system, noting that the existing system lacked a clear scientific basis and used vague criteria that was open to interpretation based on personal beliefs and principles (Nikl et al. 2018). Nikl et al. (2018) provides a summary of the draft environmental consequence classification system. The framework considers three variables: ecological impact, the intrinsic hazards of contents, and the duration of the impact, to determine the consequence category (low, significant, high, and very high) using a matrix and dial combination method approach (Nikl et al. 2018). The consequence classification is intended to assess the environmental consequences from a global tailings dam failure (i.e., ultimate failure in this case). In contrast, the risk matrix and G-FMEA is intended to assess the failure modes of individual elements; however, the principles and concepts from Nikl et al. (2018) can still be used to support the environmental consequence category. As such, the methodology used by Nikl et al. (2018) is adapted to fit within the consequence rating framework. The goal of a closure plan is for the facility to remain safe and sustain a particular land use. Consequently, the environment category should be assessed with a consideration of the impact on the post mining land use, in addition to the surrounding environment. It is recognized that post mining land uses may change over time as the closure plan develops (Department of Mines and Petroleum and Environmental Protection Authority 2015). As the agreed post mining land use changes, hazards should be re-evaluated. The most serious consequence associated with the post mining land use is when the promised land use is destroyed leaving the land sterilized. In such a situation, the facility may be fenced off to prevent all access to the site. This situation may also lead to downstream effects where additional land is sterilized. Ultimately, this would yield a severe consequence rating.

Fatalities were included in the consequence rating table in the ‘Severe’ consequence rating in the community column. The inclusion of fatalities in risk decisions can be a contentious issue as various stakeholders may have different risk tolerances for fatalities, especially with regard to voluntary versus involuntary risks. It could be argued that fatalities should be included throughout the risk matrix. For example, one fatality could classify a moderate risk rating, 10–100 fatalities could classify a major risk rating, and greater than 100 fatalities could classify a severe risk rating. Including fatalities only in the ‘Severe’ consequence rating is out of step with the risk tolerances for other industries and fails to reflect the reality that multiple-fatality events are more consequential than single-fatality events (e.g., road vs. air accidents). However, this goes against the Global Industry Standard on Tailings Management, which has a goal of zero harm to people and the environment with zero tolerance for human fatalities (Global Tailings Review 2020). Considering this and the overall goals of the closure design, the current consequence rating table classifies one fatality as ‘Severe’. This may be adapted through meaningful engagement with stakeholders, if appropriate.

The approximate time frames for the environment and community categories are provided: short term (<5 years), medium term (5–25 years), and long term (>25 years). These time frames are intended as guidance and may be amended with the input of stakeholders. Depending on the risk tolerance of the stakeholders, it may be necessary to reduce these time frames.

Table 4-6: Consequence rating

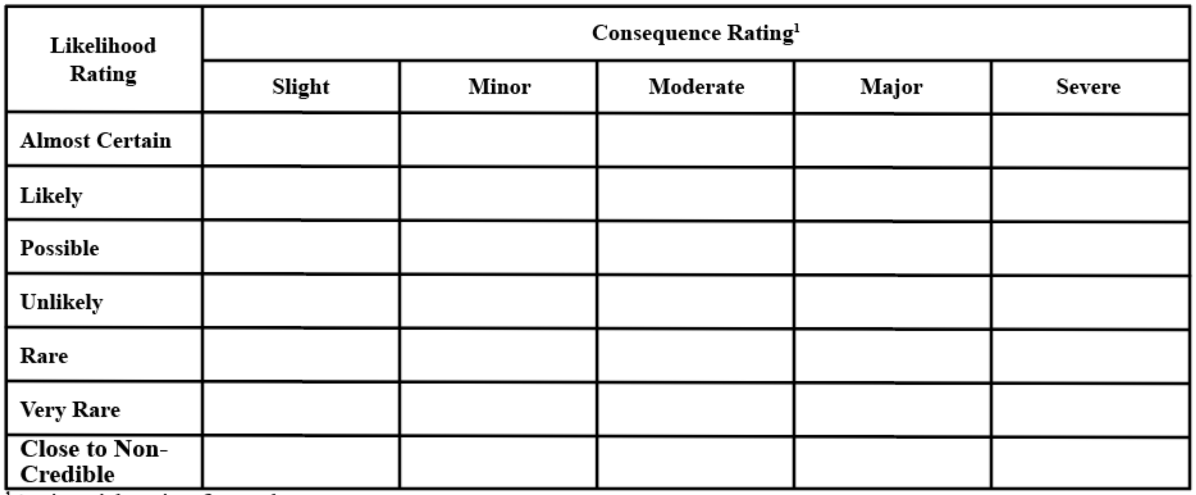
Consequence Rating [1]	Consequence of Failure of Element on the Rest of the System	Degree of Human Intervention Required	Environment	Community
Slight	Failure of element does not have cascading consequences.	Structural integrity maintained. No intervention or maintenance required.	No movement of tailings beyond the structure footprint.	No impact on local community.
Minor	Failure of element may have cascading consequences that do not result in global failure.	Structural integrity maintained. Minor or localized intervention or maintenance required.	Released tailings are not toxic [2], and/or minimal loss of habitat (<5%) of species of special interest [3], and/or acceptable restoration of water bodies and environment feasible in a short time frame (<5 years).	Impact [4] on local community for less than 1 year.
Moderate	Failure of element has cascading consequences that do not result in global failure.	Intervention or maintenance required to limit impact of cascading consequences.	Released tailings are not toxic [2], and/or moderate loss of habitat (5–20%) of species of special interest [3], and/or acceptable restoration of water bodies and environment feasible in a short time frame (<5 years).	Short-term (<5 years) impact[4] on local community.
Major	Global failure of tailings dam with minor release of tailings.	Intervention or maintenance required to maintain function of structure as a whole.	Released tailings are toxic [2], and/or significant loss of habitat (20–50%) of species of special interest [3], and/or acceptable restoration of water bodies and environment feasible in a moderate time frame (5–25 years).	Medium-term (5–25 years) impact [4] on local community.
Severe	Global failure of tailings dam with catastrophic release of tailings.	Structural repair not possible.	Released tailings are toxic [2], and/or very significant loss of habitat (>50%) of species of special interest[3], and/or acceptable restoration of water bodies and environment unlikely within an extended time frame (>25 years).	Long-term (>25 years) impact [4] on local community. Fatalities.

Notes: [1] Assigned consequence should reflect the most likely outcome. If assigning consequence with consideration of the worst case or a combination of discrete outcomes, this must be declared. [2] Toxicity assessment of tailings should consider an assessment of the fluids and solids (leaching potential, acidity, radioactivity). [3] Species of special interest is defined as a species that lives in the inundation area that would be greatly impacted by habitat loss (preferable to select a species that is provincially or federally listed). [4] Community impacts must be determined through meaningful engagement with stakeholders and may include a consideration of health, loss of access/destruction of traditional lands, housing, destruction/damage of farmland, harm to livestock, damage to water or soil resources, impacts to trapping and fishing, loss of animals, overall cultural impact, and employment. [5] Reputation, legal aspects, and economics are not considered in this consequence table as they are considered site- and corporation-specific. It may be necessary to assess these aspects on a site-specific basis.

4.1.4.2.3 Risk Matrix and Rating

The seven likelihood ratings and five consequence ratings can be combined to form a risk matrix, as shown in Figure 4-4. The challenging part of finalizing the risk matrix lies in determining the assigned risk category for a given likelihood and consequence rating. The risk categories for the G-FMEA are presented in Table 4-7. The risk categories were developed with the consideration of the suitability of the closure design to prevent failure such that a facility could be de-registered as a dam. This resulted in four risk categories from ‘Low’ to ‘Extreme’. As the risk category increases, the level of the required risk mitigation increases as the closure plan is assessed as being inappropriate in preventing serviceability failure of a particular element.

It is common practice for risks to be managed using the ALARP principle: As Low As Reasonably Practicable (ALARP). In ALARP, all risk reduction measures should be employed as long as the cost of implementing them is reasonably practicable with a consideration of cost effectiveness (Aven 2016). In Table 4-7, the high-risk category is defined with consideration of the principle of ALARP. In the high-risk category, the risks are undesirable and must be reduced using ALARP. If the risk category cannot be reduced using ALARP, the closure plan should be altered to accommodate risk mitigation.



Likelihood Rating	Consequence Rating[1]				
	Slight	Minor	Moderate	Major	Severe
Almost Certain					
Likely					
Possible					
Unlikely					
Rare					
Very Rare					
Close to Non-Credible					

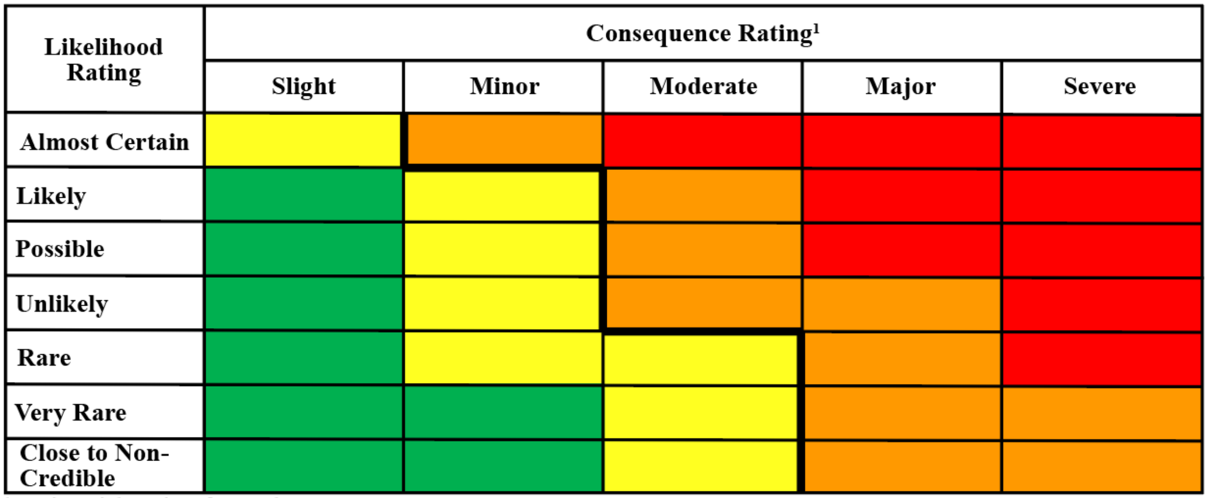
[1] Assign risk rating for each consequence category.

Figure 4-4: Risk matrix

Table 4-7: Risk category

Risk Category	Description of Risk Category
Low	Risk minimal. Monitor risks. Acceptable closure plan.
Moderate	Risk tolerable with controls. Assess risk mitigation options and monitor these risks. Minor re-design of closure plan may be required to accommodate risk mitigation.
High	Risk undesirable. Risk mitigation should be employed to ALARP to reduce risk category. Closure plan may require alteration to accommodate risk mitigation.
Extreme	Risk intolerable. Risk mitigation required immediately to reduce risk category. Requires more detailed risk analysis. Closure plan requires alteration.

Once the risk categories are developed, they can be applied to the risk matrix to develop a colour-coded ‘heat map’ based on the combination of the likelihood rating and consequence rating. The risk matrix is not colour-coded or populated with risk ratings as this defines risk tolerance. This step should be completed with the input of all relevant stakeholders (i.e., industry, regulator, the public). However, an example of a colour-coded risk matrix is provided in Figure 4-5. The colour-coded matrix presented in Figure 4-5 demonstrates major hazard aversion and presents a threshold line that is suggested to be used to trigger a more detailed quantitative analysis. The framework for attaining the colour-coded matrix is provided in this section.



Likelihood Rating	**Consequence Rating**[1]				
	Slight	**Minor**	**Moderate**	**Major**	**Severe**
Almost Certain	🟨	🟧	🟥	🟥	🟥
Likely	🟩	🟨	🟧	🟥	🟥
Possible	🟩	🟨	🟧	🟥	🟥
Unlikely	🟩	🟨	🟧	🟧	🟥
Rare	🟩	🟨	🟨	🟧	🟥
Very Rare	🟩	🟩	🟨	🟧	🟧
Close to Non-Credible	🟩	🟩	🟨	🟧	🟧

[1] Assign risk rating for each consequence category.

[2] This matrix is provided for illustration purposes. Site specific risk matrices should be developed using Steps 1-7 and include meaningful engagement with stakeholders to ensure that risk tolerance of these stakeholders is represented.

Figure 4-5: Example risk matrix considering major hazard aversion and threshold for quantitative analysis

Minimal guidance is provided in the literature on how to colour code a risk matrix. Ayyub (2014) indicates that colour coding a risk matrix involves shading each box depending on a "subjectively assessed risk level". IEC (2009) provides more guidance on assigning risk categories to the risk matrix, indicating that assigning risk categories should depend on the definitions of the likelihood and consequence tables. Using these definitions, the risk matrix can have risk categories assigned to provide extra weight to the consequences or likelihoods, or it may be symmetrical (IEC 2009). Oboni (2016) suggests that a risk matrix cannot be symmetrical as this typically indicates an incorrect prioritization of risks. Risk matrices should be coloured with consideration of what the cells tell the user.

The developed risk matrix for this research helps to assess if the risks associated with decommissioning an ETF are acceptable or where/if a more detailed analysis is required, and could be applied throughout a tailings facility's life. In light of this, an alternative way to use the developed risk matrix is to work with a 'threshold'. Any hazard categorized with a risk higher than the defined threshold (orange in Figure 4-5) requires a more detailed quantitative risk assessment method, which may require a more in-depth investigation, design, or modelling to be completed. This is an important step to aid in mitigating issues associated with upper severity limits (Baybutt 2018).

The framework for developing the example risk matrix was developed with a consideration of the tool being used as a screening method; guidance provided by Baybutt (2018), Duijm (2015), and Levine (2012); and a consideration of the known pitfalls that can be associated with risk matrices, as discussed in Table 4-1. The development of the example risk matrix in Figure 4-5 was accomplished using the following steps, and may be used as guidance for colour coding the risk matrix for a specific site (see Figure 4-4). Section 4.1.8 shows how Figure 4-5 was developed using the following steps.

1. Evaluate the likelihood ratings (Table 4-5), consequence ratings (Table 4-6), and risk ratings (Table 4-7).
2. Develop iso-contours of equal risk based on the estimated quantitative consequence measure and the provided likelihoods (Likelihood = Risk/Consequence). Assuming that the consequence quantitative measure is an order of magnitude between categories, the consequence and likelihood iso-contours should be plotted in log-log space. Plot the iso-contours on the risk matrix. Assign the risk categories to the iso-contours of equal risk and use these to develop an initial colour-coded risk matrix. This step serves as a starting point for colour coding the risk matrix. Any available known acceptance criteria can be used as an initial starting point for this exercise. Decisions will need to be made about the cells that have an iso-contour cutting through them (i.e., do you assign the higher or lower risk category?). This exercise demonstrates a known issue with risk matrices where risk is represented as categorical, rather than on a continuum, and hazards are binned into these categories.
    a. A note from Baybutt (2018): When consequences and likelihood categories differ by orders of magnitude, they are represented in log-log space. Practically, this means that high consequence-low likelihood events (negatively correlated) have

the most uncertain risks in these type of rating schemes. This is especially problematic as these events already have a lot of inherent uncertainty. Ultimately, it is not possible to increase the precision of these events on a risk matrix. This concept of uncertainty related to these types of events supports the idea of using a threshold value on the risk matrix to trigger more extensive risk analysis.

3. Assess the initial colour-coded risk matrix against the Cox (2008) axioms for a well-defined risk matrix. This step is simply a logical 'check'. Duijm (2015) recommends that a key to using the risk matrix is to recognize that the colouring of the risk matrix is a risk definition in its own right (and cannot be separately and stringently defined as Risk = probability × consequence) as it expresses a subjective risk perception (i.e., major hazard aversion), which is an important element of risk decisions. Duijm (2015) notes that, when no reference is made to an external risk definition, then "the colouring of the matrix itself is the only relevant risk definition, then the axioms of weak consistency and consistent colouring are trivial". If a quantitative definition of risk is desired by stakeholders, then the Cox (2008) axioms should be satisfied. Cox (2008) axioms can be summarized as:
    a. Weak consistency, where each hazard in the red category represents a higher risk than the hazards in the green category.
    b. Betweenness, where every positively sloped line segment that starts in a green cell and ends in a red cell must pass through an intermediate risk category.
    c. Consistent colouring, where hazards with an approximately equal risk have the same colour.
4. Assess if the Levine (2012) lettering scheme is more appropriate for your risk analysis goals. In the study by Levine (2012), logarithmic axes are used for the consequence and likelihood axes. Straight line iso-contours of equal risk are drawn. Instead of using colours, the different areas are labelled A, B, C, D, E, F, and G (each line represents a new letter). This method results in a matrix that is somewhat unintuitive, but this prevents risk matrix users from making assumptions about the risks based on the colouring scheme. When a risk matrix is constructed in this manner, the following conclusions can be drawn:

    a. Risks in one letter category can only be distinguished from risks in another category if they are more than one letter apart (i.e., C > A, D > B).
    b. Risks in categories that are zero or one letter apart are not able to be distinguished from one another (i.e., it is not known if C > B or B > C).
5. As noted by Duijm (2015), another way to develop risk scores and colouring is by using basic arithmetic (multiplication and addition) based on ordinal numbers assigned to each consequence and probability category. When the categories are essentially linearly spaced, then the multiplication of the ordinal numbers is an appropriate way of defining the risk score. When the categories are essentially logarithmically spaced, the addition of the ordinal numbers is desired. Apply the appropriate mathematical operations and compare to the risk matrix developed in Step 3.
6. Assess if major hazard aversion is required and apply as necessary. Hazard aversion is the concept of low-probability–high-consequence events being assigned a higher risk than a high-probability–low-consequence event, even if the expected loss is mathematically the same (Duijm 2015). This concept is used in scenarios where low-probability–high-consequence events are of greater concern and may require different decisions (Baybutt 2018).
7. Conduct 'logic checks' by stress testing the risk matrix with different scenarios. Focus on what the risk matrix is telling the user. Adjust the colour scheme as needed and repeat. This is an important step as the risk matrix may be developed using one quantitative measure. As such, it must be assessed to determine if it is applicable across the different consequence categories.

4.1.4.2.4 Limitations of the Risk Matrix Framework

As noted in Table 4-1, a common issue related to risk matrices is their inability to aggregate risks, both in general and from multiple consequence categories. With regard to aggregating risks, as noted by IEC (2009) "one cannot define that a particular number of low risks or a low risk identified a particular number of times is equivalent to a medium risk". This is an important limitation of risk matrices, and one that risk matrix users must be cognizant of. Therefore, sound engineering judgement is required for evaluating the results of the matrix where multiple low-risk failure modes are present. Once the assessment is complete, a careful evaluation of the results must be completed. All hazards that receive a risk rating of red or orange need to undergo further analyses and may need additional controls. If a scenario occurs where all the hazards are green (or green and yellow), the organization should evaluate if the aggregation of them represents an intolerable risk. In that case, the quantified descriptions in the likelihood matrix can help with the aggregation of likelihood.

Next, it is common practice for a hazard to be assigned a risk level based on the most severe consequence. Caution should be employed with this practice, and if practitioners choose to use this methodology, it must be clearly declared. Instead, it is recommended that risk ratings are assigned for each consequence category (i.e., consequence of failure of an element on the rest of the system, degree of human intervention required, environment, and community). This is largely due to the inability of risk matrices to aggregate the risk from multiple consequence dimensions, meaning that the consequences should not be directly compared (as noted in Table 4-1). Therefore, a careful consideration is needed when determining a final risk rating for the hazard.

One final issue that must be addressed is related to the correlated risk. The G-FMEA involves breaking the system down into its individual components. It is possible that one hazard may become a trigger for another hazard. Risk matrix users must be aware of the correlated risks and note them explicitly in the reporting of results, along with how they were considered in the study.

Given the time frames associated with closure, it is recommended that a level of confidence regarding the risk estimates is provided. There are uncertainties associated with assessing the likelihood and consequence ratings, which may be associated with a lack of data, lack of system understanding, uncertain future operating conditions or uncertain maintenance, and regional development post closure (Robertson and Shaw 2006). As the time frames associated with the G-FMEA may extend to 1000 years, it is expected that the level of confidence may decrease as the temporal scale increases. A level-of-confidence framework is currently being developed at the University of Alberta to accompany the G-FMEA.

4.1.5 Summary and Conclusions

Tailings dams can pose a significant risk to the public and the environment following closure. To prevent the failure of these large structures after mining, their long-term behaviour must be understood and incorporated into the closure design, ideally from the conception of the project and initial design. Challenges lie in the limited information available regarding how these structures age over time and forecasting loading and environmental scenarios over long-term periods (weather events, seismicity, human activity, etc.). A G-FMEA framework was developed to aid in assessing the potential success of a tailings dam closure strategy for external tailings facilities in Alberta, Canada. The goal of the G-FMEA was to reduce the future risk of geotechnical failure on the environment and the public to a degree that is both practical and economical. The G-FMEA can be used to assess the closure risks at the onset of mining if adopted early in the design process, which allows meaningful changes to be made to reduce the long-term risks from operational design decisions and ultimately support the goal of de-registration. In many cases, this is not possible as the tailings facility may be further into its life cycle (as is the case at many Alberta tailings facilities).

While this geotechnical risk management tool was developed with Alberta in mind, it does have global significance and could be easily adapted to other jurisdictions or organizations (i.e., to account for the different types of mines present in other parts of Canada or the world). Furthermore, the G-FMEA may be adapted for in-pit facilities with perimeter dykes (as desired) by updating the G-FMEA tables to account for failure modes applicable to these types of facilities. The current G-FMEA tables were developed with a consideration of external tailings facilities at oil sands and coal mines in Alberta. Differences in physiographic regions, seismic regions, expected climate change, etc., could lead to other failure modes that should be included in the G-FMEA tables.

The G-FMEA requires that the dam be broken down into the individual elements. Each element should be analysed using the G-FMEA framework, which includes four individual charts for the drainage system, foundation, dam body, and landform. The G-FMEA is accompanied by a developed risk matrix, including a likelihood rating table, consequence rating table, and final risk matrix. The risk matrix framework is intended as an example of how a qualitative risk assessment method could be combined with the G-FMEA charts to assess a closure plan. It is recommended that the risk matrix to be used for a site should be defined by industry and regulators with considerations of technical, social, and economic aspects. Guidelines are provided on how to colour code the risk matrix. It is recommended that the risk matrix be accompanied by a level-of-confidence rating, which is currently being developed at the University of Alberta.

This risk management tool is timely and necessary in Alberta as many tailings facilities approach closure. It provides a systematic method for assessing the post-closure risks associated with tailings facilities, so that they can be managed, and, ultimately, aims to develop actionable tools consistent with the Global Industry Standard on Tailings Management. The G-FMEA framework aids in satisfying the risk management requirements required by the Alberta Energy Regulator for the closure of a tailings dam to support these facilities being de-registered as dams.

4.1.6 Appendix A: G-FMEA Charts

This sections summarizes the Generalized-FMEA Charts for different dam elements, including: drains (Table 4-8), foundation (Table 4-9), dam body (Table 4-10), and landform (Table 4-11).

Table 4-8: Drain FMEA

Element	Failure Mode Description	Potential Trigger/Cause	Screening Assessment of Failure Mode	Failure Effects
Perimeter ditch	Blockage (partial or full)	Sedimentation, sloughing/slope failure of walls, beaver dam, continuous build up of ice (icing)	Is there erosion protection in place? What is the slope of the ditch? Is it sufficient to keep particles suspended? What is the slope of the side slopes? What is the strength of the material? Have there been failures in this material before? Are there beavers in the area? Is the mine located in an area that could experience icing?	Rise in phreatic surface, increase in seepage, pond on reclamation surface, internal erosion, global instability, flooding, blockage of drain outlets, toe erosion, discharge of process affected water to the environment
	Reduction in cross-sectional area	Sloughing/slope failure of walls, excessive vegetation	What is the slope of the side slopes? What is the strength of the material? Have there been failures in this material before? Will the ditch regularly have water running through it or will it stay dry for a portion of the year? Are there deterrents in place to prevent the growth of vegetation?	Rise in phreatic surface, increase in seepage, pond on reclamation surface, internal erosion, global instability, reduced capacity, erosion, potential flooding, blockage of drain outlets, toe erosion, discharge of process affected water to the environment
	Change in slope	Erosion, differential settlement	Is there erosion protection in place? Does the material have the potential to consolidate or settle over time? Is it a cut into natural ground or is the material placed?	Change to water discharge velocity, creation of secondary channels, localized areas of erosion, instability of dam
	Sand channel buoyancy	Freezing conditions in channels composed of sand	Are the drainage channels constructed of sand? Could the channel experience freezing?	Rise in phreatic surface, increase in seepage, pond on reclamation surface, internal erosion, global instability, reduced capacity, erosion, potential flooding, blockage of drain outlets, toe erosion, discharge of process affected water to the environment
Pipes (perforated and non perforated)	Breakage of pipe	Break in pipe, buckling, physical degradation	Is the pipe capable of breaking, buckling, and/or physically degrading over time?	Lack of control of phreatic surface (potential rise in phreatic surface), increase in seepage, pond on reclamation surface, internal erosion, global instability, release of water into downstream shell, erosion on downstream slope
	Pipe clogging	Biological, chemical, particulate clogging	Is chemical, biological, or sediment clogging possible?	Lack of control of phreatic surface (potential rise in phreatic surface), increase in seepage, pond on reclamation surface, internal erosion, global instability, release of water into downstream shell, erosion on downstream slope
	Clogging surround (woven sock or sand and gravel bed)	Biological, chemical, or particulate clogging	Is it possible for the material surrounding the pipe to become clogged?	Lack of control of phreatic surface (potential rise in phreatic surface), increase in seepage, pond on reclamation surface, internal erosion, global instability, release of water into downstream shell, erosion on downstream slope
	Blockage at outlet	Blockage from perimeter channel or other (snow, debris, etc.)	Is the pipe outlet close enough to the base of the perimeter channel that it could become blocked?	Lack of control of phreatic surface (potential rise in phreatic surface), increase in seepage, pond on reclamation surface, internal erosion, global instability
	Breakage of connection between a drain and outlet pipe	Overloading, degradation of connection, poor installation	How are the drain and outtake connected?	Lack of control of phreatic surface (potential rise in phreatic surface), increase in seepage, pond on reclamation surface, internal erosion, global instability, release of water into downstream shell, erosion on downstream slope
Granular materials	Erosion from flowing water	Increase in seepage gradients, development of preferential flow paths adjacent to drain (i.e., burrowing from animals, cracks)	Could cracks develop along drains? Is the site known for having issues with burrowing animals? Is the material erodible?	Decreased capacity of drain resulting in failure, lack of control of phreatic surface (potential rise in phreatic surface), increase in seepage, pond on reclamation surface, internal erosion, global instability, erosion on downstream slope
	Clogging	Biological, chemical, particulate clogging	Is chemical, biological, or sediment clogging possible? What is the grain size distribution?	Lack of control of phreatic surface (potential rise in phreatic surface), increase in seepage, pond on reclamation surface, internal erosion, global instability, release of water into downstream shell, erosion on downstream slope
	Failure to meet drain criteria	Change in material properties, including permeability due to aging, change in gradation due to movement with seepage, weathering/degradation	To what extent is aging and weathering/degradation of the material possible?	Lack of control of phreatic surface (potential rise in phreatic surface), increase in seepage, pond on reclamation surface, internal erosion, global instability, release of water into downstream shell, erosion on downstream slope
	Obstruction of drainage at outlet	Snow and ice blocking outlet	Will an obstruction prevent the drain from performing as intended? Is the outlet protected from a blockage?	Lack of control of phreatic surface (potential rise in phreatic surface), increase in seepage, pond on reclamation surface, internal erosion, global instability, release of water into downstream shell, erosion on downstream slope
	Deformation leading to reduction in drain capacity	Slow and continuous deformation under long-lasting shear and pressure forces from consolidation of overlying material	How much deformation is expected over time as the materials above the drain consolidate and settle? Has the impact on the drain been considered?	Lack of control of phreatic surface (potential rise in phreatic surface), increase in seepage, pond on reclamation surface, internal erosion, global instability, release of water into downstream shell, erosion on downstream slope
	Crushing/breakage of granular drain	Overloading drain, settlement of the dam	How much settlement is expected to occur over time? Was settlement accounted for in the design? Will the drain continued to be loaded?	Lack of control of phreatic surface (potential rise in phreatic surface), increase in seepage, pond on reclamation surface, internal erosion, global instability, release of water into downstream shell, erosion on downstream slope

Element	Failure Mode Description	Potential Trigger/Cause	Screening Assessment of Failure Mode	Failure Effects
Geosynthetics	Aging	Degradation of geosynthetic over time (temperature, oxidation, hydrolytic, chemical, biological, radioactive, etc.)	Is the geosynthetic capable of aging in the given time frame? Have sufficient tests been performed to investigate this?	Brittle rupture of geosynthetic, lack of control of phreatic surface (potential rise in phreatic surface), increase in seepage, pond on reclamation surface, internal erosion, global instability, release of water into downstream shell, erosion on downstream slope
	Creep deformation	Slow and continuous deformation under long-lasting shear and pressure forces from consolidation of overlying material	How much deformation is expected over time as the materials above the geotextile consolidate and settle? Has the impact on the geosynthetic been considered?	Reduction in thickness leading to reduction in drain capacity or shear failure of drain if in-place deformation reaches a critical value, lack of control of phreatic surface (potential rise in phreatic surface), increase in seepage, pond on reclamation surface, internal erosion, global instability, release of water into downstream shell, erosion on downstream slope
	Clogging	Biological, chemical, particulate clogging	Are there dispersive soils present? Are there ferrous soils? Does the permeant contain oily waters or sludge? Is there turbid water with high suspended solids? Is there potential for chemical precipitation or biological growth? What is the end land use (does it involve agriculture or sewage systems that could result in clogging)? Is sediment capable of clogging the drain? What is the grain size distribution?	Lack of control of phreatic surface (potential rise in phreatic surface), increase in seepage, pond on reclamation surface, internal erosion, global instability, release of water into downstream shell, erosion on downstream slope
	Blockage	Intrusion of adjacent materials (i.e., geotextile), blockage of downstream or exit surface caused by sedimentation, vegetation, etc.	Does the downstream or exit surface of the geosynthetic have the potential to be blocked and prevent drainage from sediment, vegetation, ice, snow, etc.? Could adjacent materials impede movement of water to the geosynthetic?	Lack of control of phreatic surface (potential rise in phreatic surface), increase in seepage, pond on reclamation surface, internal erosion, global instability, release of water into downstream shell, erosion on downstream slope
	Blinding where fine-grained soils are prevented from entering the geotextile, which creates a filter cake	Formation of a filter cake at the interface of the geosynthetic from coarse particles being retained by the geotextile and intercepting fine particles migrating from the soil	Is the geosynthetic in intimate contact with the soil? Have all appropriate filter criterion been followed during design?	Lack of control of phreatic surface (potential rise in phreatic surface), increase in seepage, pond on reclamation surface, internal erosion, global instability, release of water into downstream shell, erosion on downstream slope
Low permeability cores	Hydraulic fracture	Decrease in total stress (i.e., differential settlement, arching in narrow cores), increase in porewater pressure	Is there a narrow core? Is there the potential for excessive differential settlement that could lead to a decrease in total stress? Is there the potential for an increase in porewater pressure? Is there an effective downstream filter to prevent internal erosion of the core?	Cracking, internal erosion, global instability
	Internal erosion in dam from suffusion	High hydraulic gradients, design/construction defect, presence of widely gap-graded or non-plastic gap-graded soils	Is the material widely gap-graded or gap-graded non plastic? Is there an effective downstream filter to prevent internal erosion of the core?	Global instability, seepage on the downstream slope, settlement of the crest, permeability may increase as erosion progresses or decrease if clogging occurs
	Internal erosion in dam from concentrated leak	Cracks from vertical deformation in foundation, starter dyke, or other tailings materials or differential settlement; tunnels created by burrowing animals; hydraulic fracture; high hydraulic gradient; design/construction defects	Is there a crack or gap that could allow for a concentrated leak to develop? Is there an effective downstream filter to prevent internal erosion of the core?	Global instability, development of a pipe
	Internal erosion in dam from contact erosion	Parallel flow in coarser layer to the interface between the coarse-grained and fine-grained soil, high hydraulic gradients, design/construction defects	Is there a contact between a coarse and fine-grained soil? Is there a filter in place? Is there an effective downstream filter to prevent internal erosion of the core? Is there an effective downstream filter to prevent internal erosion of the core?	Global instability, static liquefaction, settlement of the crest, loss of stability or unravelling, eroded material can clog the permeable layer and increase the porewater pressure (could result in hydraulic fracture and uplift of the downstream toe or a rise in the phreatic surface), development of a pipe
	Shear failure from changing shear strength	Degradation/weathering, porewater pressure change, change in permeability over time, failure of drains, progressive failure of strain softening materials, brittle failure of contractive materials	Is there potential for weathering or degradation of materials? Does the porewater pressure rely on drain performance? Could drains fail over time? Are the materials strain softening or brittle? Is there an effective downstream filter to prevent internal erosion of the core?	Slumping of downstream slope, translational slide, rotational slide
	Shear failure from changing shear stress	Loading/unloading crest, toe, upstream, or downstream; surface erosion of downstream slope; excessive and uncontrolled seepage through foundation resulting in erosion of toe; subsurface stress changes (geothermal development, in situ oil or gas production, wastewater injection, etc.)	Is there potential for anthropogenic contributions (i.e., excavations or construction)? Erodibility of material? Is there an effective downstream filter to prevent internal erosion of the core?	Slumping of downstream slope, translational slide, rotational slide
	Vertical deformation (differential or otherwise) from consolidation	Consolidation/settlement	Does the material have the potential to consolidate? How much consolidation has occurred already? How much is expected to occur? Is there an effective downstream filter to prevent internal erosion of the core?	Release of pore water and loss of height (potential for pond to develop on reclamation surface), development of cracks above starter dyke, internal erosion, overtopping

Table 4-9: Foundation FMEA

Failure Mode Description	Potential Trigger/Cause	Screening Assessment of Failure Mode	Failure Effects
Heave (seepage forces create zero effective stress condition)	Embankment loading, excessive rainfall, embankment seepage	What are the current hydraulic gradients and maximum possible due to geometry? What are the materials present? Are there cohesionless soils confined by an overlying lower permeability layer?	Global instability
Vertical deformation from collapse of karst formation	Collapse of karst formation	Is there karst present in the foundation?	Cracking (transverse cracks - perpendicular to dam crest are larger problems than longitudinal cracks) in dam, internal erosion in dam, crest subsidence
Vertical deformation caused by settlement of material	Consolidation	Will the materials in the foundation consolidate over time? How much consolidation has already occurred? Does the material have the potential to collapse?	Cracking (transverse cracks - perpendicular to dam crest are larger problems than longitudinal cracks) in dam, internal erosion in dam, crest subsidence
Excessive/uncontrolled seepage through foundation or foundation/dam contact	Excessive rainfall	Is there potential for seepage through the foundation? What is the permeability of the materials?	Erosion of downstream toe, increase in porewater pressure in dam, global instability
Shear failure along pre-existing shear plane from changing shear stress	Loading/unloading of foundation, earthquake, subsurface stress changes (geothermal development, in situ oil or gas production, wastewater injection, etc.)	Are there pre-existing shear planes? Is there the potential for anthropogenic loading or unloading events? Is the material erodible?	Slumping of downstream slope, translational slide, rotational slide, static liquefaction
Shear failure along new shear plane from changing shear stress	Loading/unloading of foundation, earthquake, subsurface stress changes (geothermal development, in situ oil or gas production, wastewater injection, etc.)	Is there the potential for anthropogenic loading or unloading events? Is the material erodible?	Slumping of downstream slope, translational slide, rotational slide, static liquefaction
Shear failure along pre-existing shear plane from changing shear strength	Degradation/weathering, porewater pressure change, progressive failure of strain softening materials, brittle failure of contractive materials	Are there pre-existing shear planes? Is there the potential for degradation or weathering of the material? Is the material strain softening or brittle?	Slumping of downstream slope, translational slide, rotational slide, static liquefaction
Shear failure along new shear plane from changing shear strength	Degradation/weathering, porewater pressure change, progressive failure of strain softening materials, brittle failure of contractive materials	Is there the potential for degradation or weathering of the material? Is the material strain softening or brittle?	Slumping of downstream slope, translational slide, rotational slide, static liquefaction
Internal erosion in foundation or dam/foundation contact from global backward erosion	Failure of soil above or around a backward erosion pipe to hold a roof, heave, high hydraulic gradients, design/construction defect, presence of non-plastic soils in the foundation	Are there non-plastic soils in the foundation?	Static liquefaction, global instability, unravelling/sloughing of downstream face, sub vertical cavities
Internal erosion in foundation or dam/foundation contact from backward erosion piping	Heave, high hydraulic gradients, design/construction defect, presence of non-plastic soils that are capable of holding a roof	Are there non-plastic soils in the foundation and soils capable of 'holding a roof'?	Enlargement of pipe, global instability, static liquefaction
Internal erosion in foundation or dam/foundation contact from contact erosion	Parallel flow in coarser layer to the interface between the coarse-grained and fine-grained soil, high hydraulic gradients, design/construction defect	Is there a contact between a coarse-grained and a fine-grained soil? Is the geometrical and hydraulic condition for contact erosion met?	Global instability, static liquefaction, settlement of the crest, loss of stability or unravelling, eroded material can clog the permeable layer and increase the porewater pressure (could result in hydraulic fracture and uplift of the downstream toe or a rise in the phreatic surface), development of a pipe
Internal erosion in foundation or dam/foundation contact from suffusion	High hydraulic gradients, design/construction defect, presence of widely gap-graded or non-plastic gap-graded soils	Is the material widely gap-graded or gap-graded non plastic?	Global instability, seepage on the downstream slope, settlement of the crest, permeability may increase as erosion progresses or decrease if clogging occurs
Internal erosion in foundation or dam/foundation contact from concentrated leak	Fracture in foundation soil, hydraulic fracture, high hydraulic gradient, cracks at dam/foundation contact from vertical deformation in foundation or poor construction practices or differential settlement, design/construction defects	Is there a crack or gap that could allow for a concentrated leak to develop?	Global instability, development of a pipe
Thawing of foundation permafrost	Climate change	Is there permafrost in the foundation?	Cracking (transverse cracks - perpendicular to dam crest are larger problems than longitudinal cracks) in dam, piping in dam, crest subsidence

Table 4-10: Dam body FMEA

Failure Mode Description	**Potential Trigger/Cause**	**Screening Assessment of Failure Mode**	**Failure Effects**
Destruction of vegetation	Suffocation by eroded material, forest fires, pests and disease, climate change, large storm event, anthropogenic contributions, surface erosion on downstream slope, evolution of vegetation over time due to climate change	Does the resistance to erosion rely on the vegetation? Is the area susceptible to forest fires? Are there pests/disease that could lead to vegetation destruction? What is the downstream slope? Is the area remote? Are there surrounding communities that could lead to destruction of vegetation (i.e., recreational vehicles)?	Increase in surface erosion, instability of downstream slope, global instability, change in overall evapotranspiration and water balance impacts (infiltration versus runoff)
Internal erosion in dam from suffusion	High hydraulic gradients, design/construction defect, presence of widely gap-graded or non-plastic, gap-graded soils	Is the material widely gap-graded or gap-graded non plastic?	Global instability, seepage on the downstream slope, settlement of the crest, permeability may increase as erosion progresses or decrease if clogging occurs
Internal erosion in dam from concentrated leak	Cracks from vertical deformation in foundation, starter dyke, or other tailings materials or differential settlement; tunnels created by burrowing animals; hydraulic fracture; high hydraulic gradient; design/construction defects	Is there a crack or gap that could allow for a concentrated leak to develop?	Global instability, development of a pipe
Internal erosion in dam from contact erosion	Parallel flow in coarser layer to the interface between the coarse-grained and fine-grained soil, high hydraulic gradients, design/construction defects	Is there a contact between a coarse and fine-grained soil? Is there a filter in place?	Global instability, static liquefaction, settlement of the crest, loss of stability or unravelling, eroded material can clog the permeable layer and increase the porewater pressure (could result in hydraulic fracture and uplift of the downstream toe or a rise in the phreatic surface), development of a pipe
Dynamic liquefaction	Earthquakes, induced seismicity, construction traffic, blasting	Seismic events in area? Induced seismicity? Density of material (contractive or dilative)? Saturated or unsaturated? Hydraulically placed or compacted?	Global instability, local slumps, crest drops
Shear failure from changing shear strength	Degradation/weathering, porewater pressure change, change in permeability over time, failure of drains, progressive failure of strain softening materials, brittle failure of contractive materials	Is there potential for weathering or degradation of materials? Does the porewater pressure rely on drain performance? Could drains fail over time? Are the materials strain softening or brittle?	Slumping of downstream slope, translational slide, rotational slide
Shear failure from changing shear stress	Loading/unloading crest, toe, upstream, or downstream; surface erosion of downstream slope; excessive and uncontrolled seepage through foundation resulting in erosion of toe; earthquake; subsurface stress changes (geothermal development, in situ oil or gas production, wastewater injection, etc.)	Is there potential for anthropogenic contributions (i.e. excavations or construction)? Erodibility of material?	Slumping of downstream slope, translational slide, rotational slide
Static liquefaction from changing mean effective stress	Change in pore pressures caused by a phreatic surface change (i.e., failure of drainage system)	Density of material (contractive or dilative)? Saturated or unsaturated? Hydraulically placed or compacted? Does control of the phreatic surface rely on drain function? Could drains become clogged or fail in the future?	Global instability
Static liquefaction from changing shear stress	Loading/unloading; overloading, including increasing the load, construction activities at the crest, fill placement at toe; over steepening of downstream slope or toe (slumping of downstream slope from shear failure), including erosion or excavation of toe; foundation shear; shear in starter dyke; shear in other tailings materials; excessive and uncontrolled seepage through foundation resulting in erosion of toe; subsurface stress changes (geothermal development, in situ oil or gas production, wastewater injection, etc.)	Density of material (contractive or dilative)? Hydraulically placed or compacted? Saturated or unsaturated? Is there a likelihood for anthropogenic contributions in the future (i.e., unexpected construction)? Is the site remote? What is the material of the downstream slope? Is there a nearby river?	Global instability
Static liquefaction from changing shear stress and mean effective stress	Lateral extrusion	Density of material (contractive or dilative)? Hydraulically placed or compacted? Saturated or unsaturated? Weak layers interbedded in tailings? Could the tailings 'squish' out like toothpaste during loading?	Global instability
Static liquefaction from long-term change in material properties resulting in changing shear strength	Changing shear strength caused by degradation/weathering, progressive failure, porewater pressure change, failure of drains	Density of material (contractive or dilative)? Hydraulically placed or compacted? Saturated or unsaturated? To what extent could weathering or degradation of the material occur? Will it result in an increase or decrease in strength? Will a change in the phreatic surface impact the strength of the material?	Global instability
Surface erosion from spring sapping (headward erosion of gullies due to concentration of seepage forces at the locus of the gully, which accentuates erosion)	Destruction of vegetation, increased seepage on downstream slope from failure of drainage system, increased seepage from internal erosion of starter dyke or tailings deposits)	Is the material susceptible to erosion? Is there a vegetative cover or erosion protection? Will seepage daylight on the downstream slope?	Slope failures (shallow surficial movement, slumps), change in downstream slope angle, blockage in perimeter channel with sediment, development of negative drainage, development of large erosion scarps
Surface erosion from wind and overland flow resulting in rills, gullies, or sheet erosion	Destruction of vegetation, rainfall, melting of snow, wind, increased seepage on downstream slope from failure of drainage system, increased seepage from internal erosion in embankment	Is the material susceptible to erosion? Is there a vegetative cover or erosion protection?	Slope failures (shallow surficial movement, slumps), change in downstream slope angle, blockage in perimeter channel with sediment, development of negative drainage, development of large erosion scarps
Toe erosion	Flow action from perimeter ditch or nearby river, release of a dam from a beaver, flood event, river changing course over time, destruction of vegetation, excessive and uncontrolled seepage through foundation, excessive erosion from internal erosion	Is the material susceptible to erosion? Is there a vegetative cover or erosion protection? Is there a nearby perimeter ditch or river? Is there known animal activity in the area?	Slope failures (shallow surficial movement, slumps), change in downstream slope angle, blockage in perimeter channel with sediment, development of negative drainage, development of large erosion scarps, beaver bafflers
Vertical deformation (differential or otherwise) from consolidation	Consolidation/settlement	Does the material have the potential to consolidate? How much consolidation has occurred already? How much is expected to occur?	Release of pore water and loss of height (potential for pond to develop on reclamation surface), development of cracks above starter dyke, internal erosion, overtopping

Table 4-11: Landform FMEA

Item/Functional Identification	Failure Mode Description	Potential Trigger/Cause	Screening Assessment of Failure Mode	Failure Effects - End Effects
Cap	Excessive settlement	Consolidation	Does the material have the potential to settle over time?	Formation of ponds on reclamation surface, overtopping, piping (increase in seepage forces and gradients), infiltration of previously unsaturated tailings that could increase vulnerability to liquefaction for materials previously considered 'not flowable'
	Differential settlement	Consolidation, poor construction practices	Does the material have the potential to settle over time? Are there areas that have the potential to settle more that others?	Formation of ponds on reclamation surface, failure to direct surface water runoff towards drainage channels, development of cracks, formation of preferential flow paths, localized depressions, infiltration of previously unsaturated tailings that could increase vulnerability to liquefaction for materials previously considered 'not flowable'
Infilled material	Excessive settlement	Consolidation	Does the material have the potential to settle over time?	Formation of ponds on reclamation surface, overtopping, piping (increase in seepage forces and gradients)
	Differential settlement	Consolidation, poor construction practices	Are there areas that have the potential to settle more than others?	Formation of ponds on reclamation surface, overtopping, piping (increase in seepage forces and gradients), failure of drainage channels to behave as intended, localized depressions
Hummocks	Shear failure from changing shear stress	Loading/unloading crest, toe, slopes; surface erosion; failure of underlying material to support hummock	Is there potential for anthropogenic contributions (i.e., excavations or construction)? Erodibility of material?	Slumping, translational slide, rotational slide, blockage of drainage channels
	Shear failure from changing shear strength	Degradation/weathering, porewater pressure change, change in permeability over time, failure of drains, progressive failure of strain softening materials, brittle failure of contractive materials	Is there potential for weathering or degradation of materials? Are the materials strain softening or brittle?	Slumping of slopes, translational slide, rotational slide, blockage of drainage channels
	Surface erosion from wind and overland flow resulting in rills, gullies, or sheet erosion	Destruction of vegetation, rainfall, melting of snow, wind	Is the material susceptible to erosion? Is there a vegetative cover or erosion protection?	Slope failures (shallow surficial movement, slumps), change in downstream slope angle, blockage in drainage channel with sediment, development of negative drainage, development of large erosion scarps
Drainage channels	Washout of erosion protection (riprap)	Precipitation event larger than design events (including extreme or repeat events)	What precipitation event are the channels designed for? What is the chance of exceedance over 1000 years? How susceptible are the underlying materials to erosion? Was the erosion protection properly designed and constructed?	Excessive erosion (erosion gullies, etc.), change in slope of drainage channels, erosion and release of materials underlying drainage channels
	Blockage (complete or partial)	Debris, beaver dam, icing, sedimentation, slumping from slope failure, ingress of vegetation, slope failure/excessive erosion from nearby hummock	Are there beavers in the area? Is there a chance for a slope failure? Could debris be carried downstream and deposited in the channels resulting in a complete or partial blockage? Is the mine located in an area that could experience icing?	Formation of a pond upstream of the drainage channel, blockage breakthrough resulting in flooding, overtopping from pond formation, revert back to a pond, piping through dam (increase in seepage forces and gradient)
	Sand channel buoyancy	Freezing conditions in channels composed of sand	Are the drainage channels constructed of sand? Could the channel experience freezing?	Flooding
	Erosion control failure	Improper design/construction, differential settlement	Do the drainage channels rely on erosion control for stability? Is there the chance for differential settlement of the channel?	Excessive erosion (erosion gullies, etc.), change in slope of drainage channel, erosion and release of materials underlying drainage channel, formation of secondary channel
Outlet	Washout of erosion protection (riprap)	Precipitation event larger than design event (including extreme or repeat events), flood following sand channel buoyancy event in drainage channel	What precipitation event is the outlet designed for? What is the chance of exceedance over 1000 years? How susceptible are the underlying materials to erosion? Was the erosion protection properly designed and constructed?	Excessive erosion (erosion gullies, etc.), change in slope of outlet, erosion and release of materials underlying outlet
	Blockage (complete or partial)	Debris, beaver dam, icing, sedimentation, slumping from slope failure, ingress of vegetation, increase in depositional material due to failure of erosion protection in drainage channels upstream	Are there beavers in the area? Is there a chance for a slope failure? Could debris be carried downstream and deposited in the outlet resulting in a complete or partial blockage? Is the mine located in an area that could experience icing?	Formation of a pond upstream of the outlet, blockage breakthrough resulting in flooding, overtopping from pond formation, revert back to a pond, piping through dam (increase in seepage forces and gradient)
	Sand channel buoyancy	Freezing conditions in channels composed of sand	Is the outlet constructed of sand? Could the channel experience freezing?	Flooding
	Erosion control failure	Improper design/construction, differential settlement	Does the outlet rely on erosion control for stability? Is there the chance for differential settlement of the channel?	Excessive erosion (erosion gullies, etc.), change in slope of outlet, erosion and release of materials underlying outlet, formation of secondary channel
Vegetative cover	Destruction of vegetation	Suffocation by eroded material, forest fires, pests and disease, climate change, large storm event, anthropogenic contributions	Does the resistance to erosion rely on the vegetation? Is the area susceptible to forest fires? Are there pests/disease that could lead to vegetation destruction? Is the area remote? Are there surrounding communities that could lead to destruction of vegetation (i.e., recreational vehicles)?	Increase in surface erosion, deposition of material in drainage channels that could lead to a blockage via sedimentation, development of negative drainage on reclamation surface, ponding of water near dam crest, internal erosion (increase in seepage forces and hydraulic gradient)
Tailings	Excessive settlement	Consolidation	Does the material have the potential to settle over time?	Formation of ponds on reclamation surface, overtopping, piping (increase in seepage forces and gradients)
	Differential settlement	Consolidation, different material properties/infilling techniques, etc.	Are there areas that have the potential to settle more than others?	Formation of ponds on reclamation surface, overtopping, piping (increase in seepage forces and gradients), failure of drainage channels to behave as intended, localized depressions

4.1.7 Appendix B: FMEA Worksheet

This section provides the worksheet that should be used with the G-FMEA charts, as shown in Table 4-12.

Table 4-12: G-FMEA worksheet

Element	Failure mode identification	Failure mode description	Potential trigger/cause	Screening assessment of failure mode	Is this failure mode applicable?	If yes, is there sufficient data to evaluate the risk? List any resource gaps.	Failure effects	**Immediate-term/Short-term/Medium-term/Long-term Assessment ***														
								Likelihood	**Consequences**				**Risk Rating**				**Level of Confidence**				Controls	Remarks
									Element failure consequence	Human intervention	Environment	Community	Element failure consequence	Human intervention	Environment	Community	Element failure consequence	Human intervention	Environment	Community		

* Likelihood rating, consequence rating, risk rating, level of confidence, and controls must be determined for each failure mode for the short-term assessment, medium-term assessment, and long-term assessment.

4.1.8 Appendix C: Risk Matrix Development

The steps to colour code the risk matrix outlined in Section 4.1.4.2.3 are described here with the associated development of the example risk matrix in Figure 4-5 used for illustration purposes.

1. The likelihood ratings (Table 4-5), consequence ratings (Table 4-6), and risk ratings (Table 4-7) were evaluated.
2. In order to develop the iso-contours of equal risk, quantitative values from 0.01 to 10,000 were assigned to the consequence categories and assumed to have an order of magnitude increase between the categories. For individual projects, site-specific consequences could be considered here where there are known magnitudes of the consequences (i.e., financial impacts of environmental consequences). Iso-contours of equal risk were developed based on the estimated quantitative consequence measure and the provided likelihoods using the definition (Likelihood = Risk/Consequence). The iso-contours are shown in Figure 4-6, which show the annualized probability plotted against the consequences. It is important to remember that this is an estimation technique only and serves as a first-order step for colour coding the matrix. It is desirable to use quantitative measures of the consequences that extend across the full range of categories. Risk categories were then assigned to the iso-contours of equal risk (Table 4-13). This was used to colour code the initial risk matrix shown in Figure 4-7. Cells that had an iso-contour cutting through them were assigned to the higher risk category

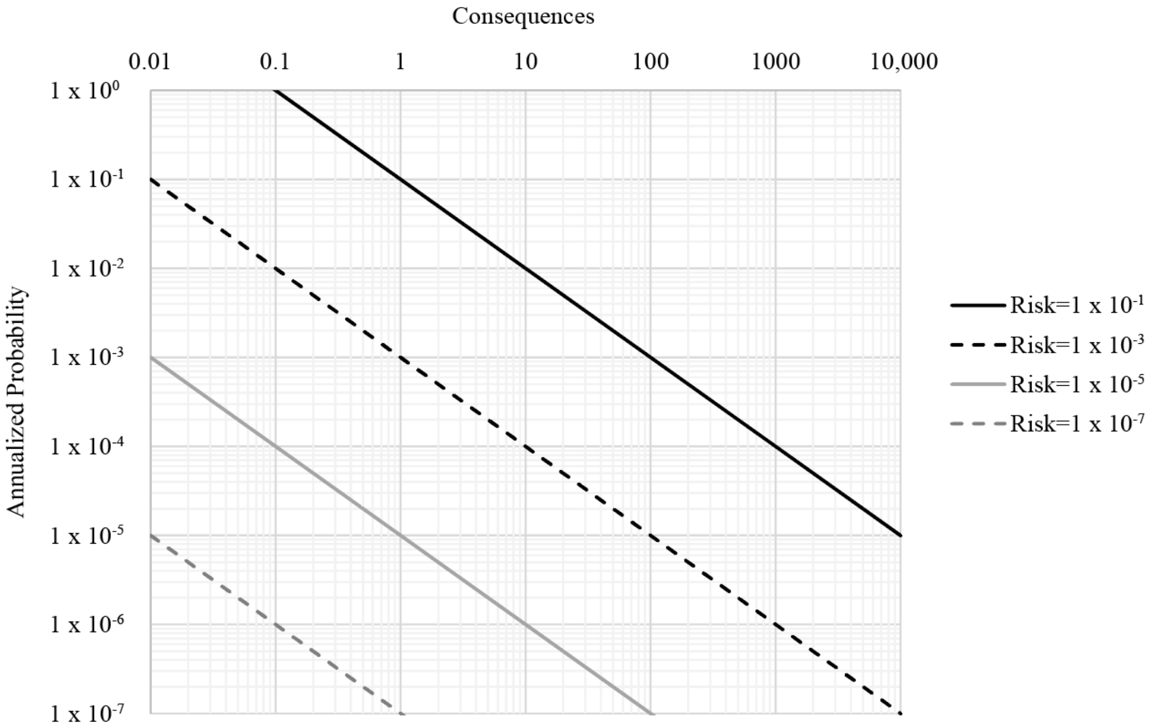
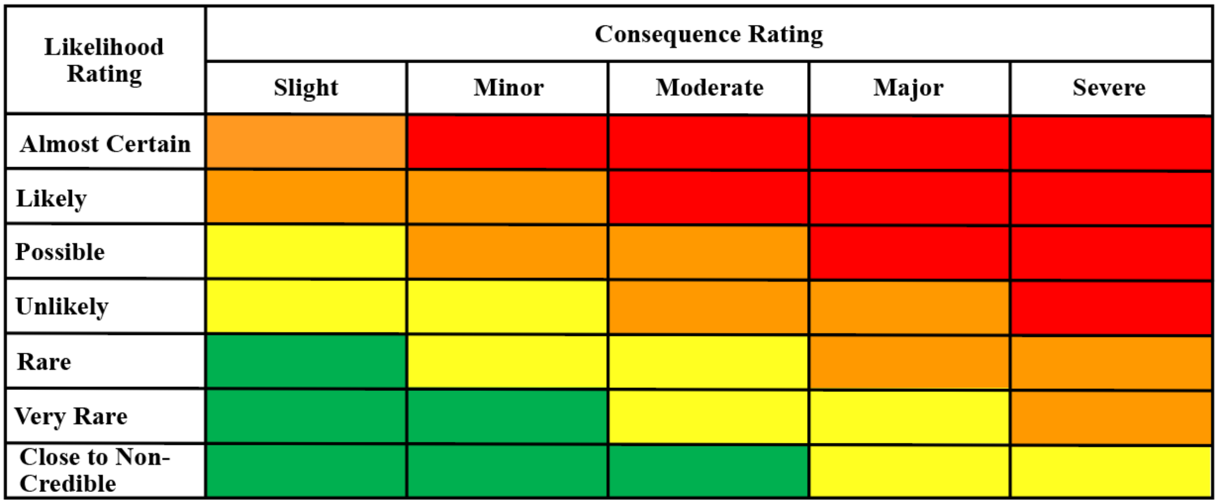


Figure 4-6: Iso-contours of equal risk

Table 4-13: Assigned risk categories to iso-contour risk levels

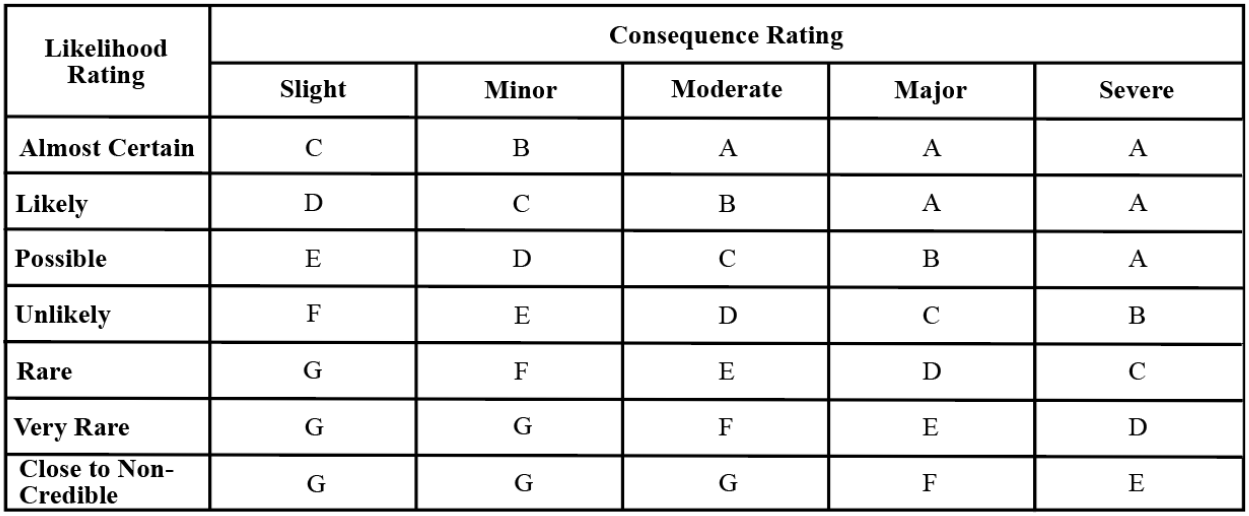
Risk Category	**Risk Level**
Red	$>1\times 10^{-1}$
Orange	$>1\times 10^{-3}$
Yellow	$>1\times 10^{-5}$
Green	$>1\times 10^{-7}$



Likelihood Rating	**Consequence Rating**				
	Slight	**Minor**	**Moderate**	**Major**	**Severe**
Almost Certain	🟧	🟥	🟥	🟥	🟥
Likely	🟧	🟧	🟥	🟥	🟥
Possible	🟨	🟧	🟧	🟥	🟥
Unlikely	🟨	🟨	🟧	🟧	🟥
Rare	🟩	🟨	🟨	🟧	🟧
Very Rare	🟩	🟩	🟨	🟨	🟧
Close to Non-Credible	🟩	🟩	🟩	🟨	🟨

Figure 4-7: Initial colour-coded risk matrix with consideration of iso-contours

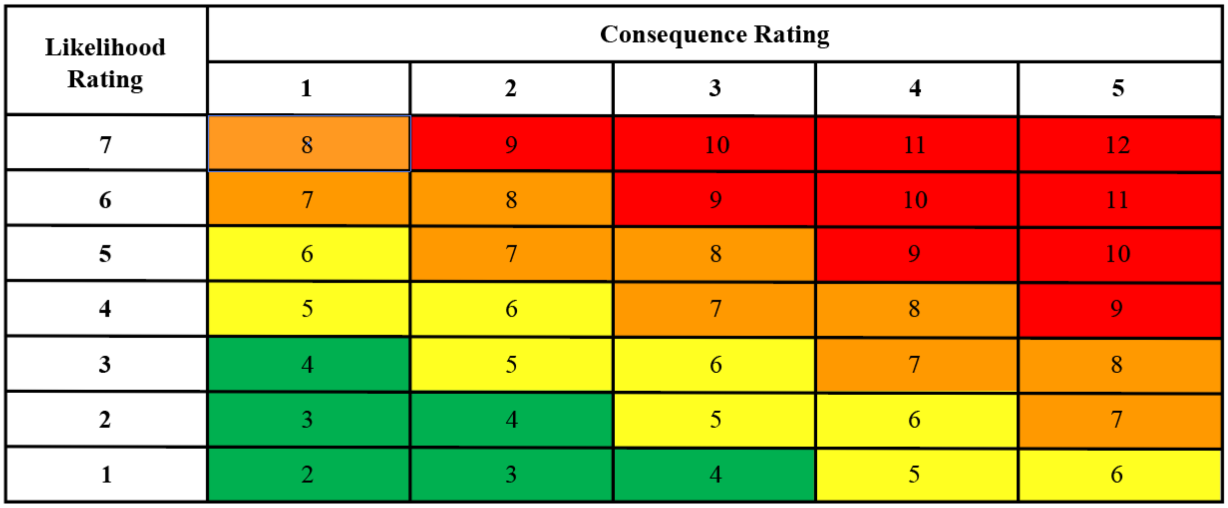
3. The initial colour-coded risk matrix was assessed to determine if it satisfied the Cox axioms (weak consistency, betweenness, and consistent colouring).
4. The risk matrix was assessed using the Levine (2012) lettering scheme. For this, logarithmic axes were used for the consequence and likelihood axes and straight-line iso-contours of equal risk were drawn (similar to Figure 4-6). Following this, each area was labelled with a letter as opposed to a colour, as shown in Figure 4-8 (each line represents a new letter). Levine's method results in a matrix that is somewhat unintuitive, but this prevents risk matrix users from making assumptions about risks based on the colouring scheme. When a risk matrix is constructed in this manner, the following conclusions can be drawn:
    a. Risks in one letter category can only be distinguished from risks in another category if they are more than one letter apart (i.e., C > A, D > B).
    b. Risks in categories that are zero or one letter distant are not able to be distinguished from another (i.e., it is not known if C > B or B > C).



Likelihood Rating	**Consequence Rating**				
	Slight	**Minor**	**Moderate**	**Major**	**Severe**
Almost Certain	C	B	A	A	A
Likely	D	C	B	A	A
Possible	E	D	C	B	A
Unlikely	F	E	D	C	B
Rare	G	F	E	D	C
Very Rare	G	G	F	E	D
Close to Non-Credible	G	G	G	F	E

Figure 4-8: Risk matrix based on Levine (2012)

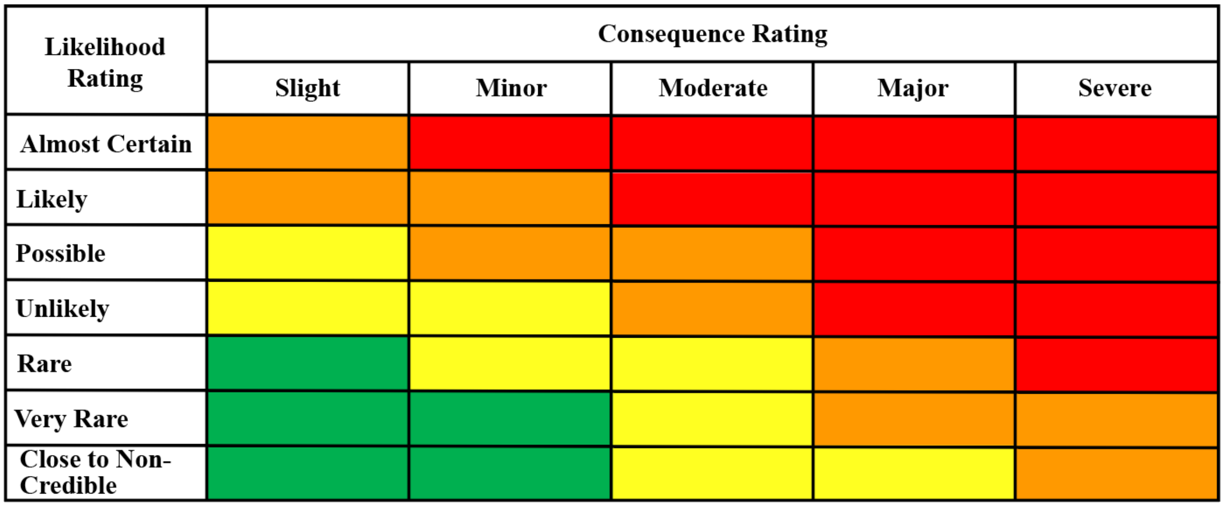
5. As noted by Duijm (2015), another way to develop risk scores and colouring is by using basic arithmetic (multiplication and addition) based on ordinal numbers assigned to each consequence and probability category. As the categories were logarithmically spaced, the addition of the ordinal numbers was used, as shown in Figure 4-9. For this example, this results in a risk matrix that is colour coded in the same way as Figure 4-7.



Likelihood Rating	Consequence Rating				
	1	2	3	4	5
7	🟧 8	🟥 9	🟥 10	🟥 11	🟥 12
6	🟧 7	🟧 8	🟥 9	🟥 10	🟥 11
5	🟨 6	🟧 7	🟧 8	🟥 9	🟥 10
4	🟨 5	🟨 6	🟧 7	🟧 8	🟥 9
3	🟩 4	🟨 5	🟨 6	🟧 7	🟧 8
2	🟩 3	🟩 4	🟨 5	🟨 6	🟧 7
1	🟩 2	🟩 3	🟩 4	🟨 5	🟨 6

Figure 4-9: Colour-coded risk matrix based on addition of ordinal pairs

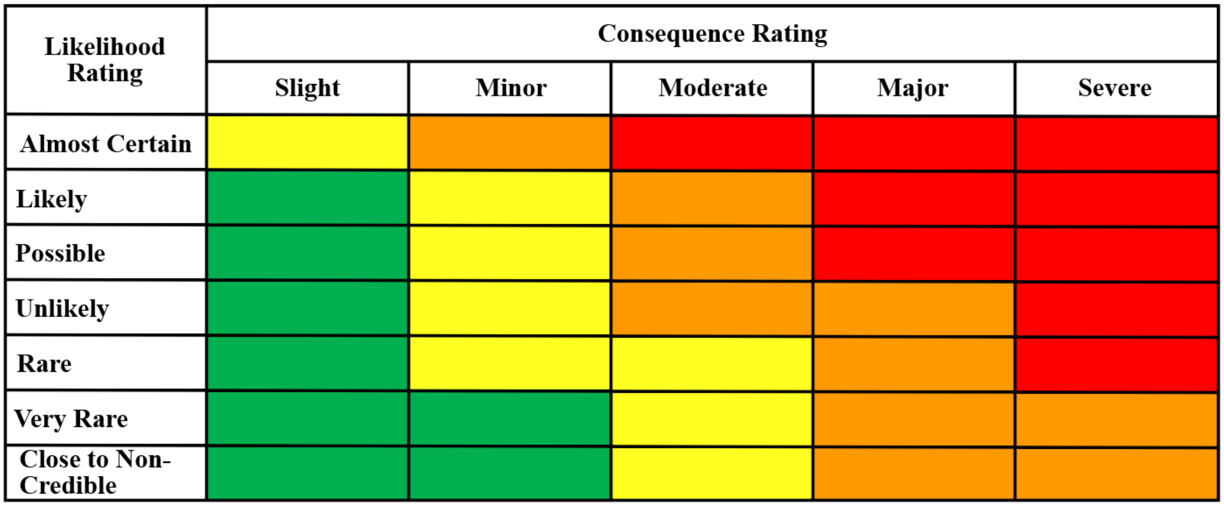
6. Major hazard aversion was applied to the risk matrix in Figure 4-7 to assign a higher risk rating to high-probability–low-consequence events, as these events were considered to be of greater concern, as shown in Figure 4-10.



Likelihood Rating	Consequence Rating				
	Slight	Minor	Moderate	Major	Severe
Almost Certain	🟧	🟥	🟥	🟥	🟥
Likely	🟧	🟧	🟥	🟥	🟥
Possible	🟨	🟧	🟧	🟥	🟥
Unlikely	🟨	🟨	🟧	🟥	🟥
Rare	🟩	🟨	🟨	🟧	🟥
Very Rare	🟩	🟩	🟨	🟧	🟧
Close to Non-Credible	🟩	🟩	🟨	🟨	🟧

Figure 4-10: Colour-coded risk matrix following application of major hazard aversion

7. Following the application of major hazard aversion, the risk matrix was stress tested by evaluating its performance in different scenarios and evaluating what the risk matrix told the user. The evaluation showed that the yielded risk ratings from Figure 4-10 for the 'Slight' and 'Minor' consequence rating columns were too high. Some amendments were made to the risk matrix, and it was stress tested again. This resulted in the final example risk matrix in Figure 4-11.



Likelihood Rating	Consequence Rating				
	Slight	Minor	Moderate	Major	Severe
Almost Certain	🟨	🟧	🟥	🟥	🟥
Likely	🟩	🟨	🟧	🟥	🟥
Possible	🟩	🟨	🟧	🟥	🟥
Unlikely	🟩	🟨	🟧	🟧	🟥
Rare	🟩	🟨	🟨	🟧	🟥
Very Rare	🟩	🟩	🟨	🟧	🟧
Close to Non-Credible	🟩	🟩	🟨	🟧	🟧

Figure 4-11: Example colour-coded risk matrix

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5 SITE SPECIFIC APPLICATION OF G-FMEA

To demonstrate the applicability of the G-FMEA framework, an oil sands case study was assessed, and the framework was applied. The work was published in the Minerals Journal, and this section presents the journal paper in full. Slight modifications were made to align the paper with the thesis structure and format.

5.1 Applying a Generalized FMEA Framework to an Oil Sands Tailings Dam Closure Plan in Alberta, Canada

Abstract

Historically, tailings facilities have been designed primarily with consideration of the mine's active life. This is problematic, as the lifespan of a tailings dam may far exceed the life of the mine. Over time, it is expected that these structures will transform into a mine waste structure and then eventually a landform. In Alberta, Canada, dam owners can submit a decommissioning, closure, and abandonment (DCA) plan and completion reports to apply for the facility to be de-registered as a dam. If successful, the structure would be considered a solid waste structure and may be reclassified and regulated as a mine waste dump. The Alberta Energy Regulator expects DCAs to be accompanied and supported by risk assessments that consider long-term physical failure modes, including failure modes that may not be applicable during operations, in accordance with Manual 019. To help support the process of de-registering a tailings dam, a risk management tool, referred to as a Generalized Failure Modes Effects Analysis (G-FMEA) framework, was developed and presented in the Journal of Minerals in the Special Issue Tailings Dams: Design, Characterization, Monitoring, and Risk Assessment. The G-FMEA was designed to be used for assessing risks of an external tailings facility in closure, with the goal of assessing the long-term risk of geotechnical failure to support the process of de-registration. In Alberta, a number of tailings dams are undergoing closure and reclamation activities. This paper applies the developed G-FMEA framework to an oil sands tailings dam in Alberta to demonstrate the application of the framework. The paper assesses two specific failure modes of two different elements, including clogging of the drains and surface erosion of the berm. The failure modes are assessed over different timescales to demonstrate how the consequence, likelihood, and risk rating may change over time. The results

of this process are discussed in the context of the potential for the facility to be de-registered as a dam.

5.1.1 Introduction

Many tailings storage facilities (TSFs) in Alberta are in the process of being reclaimed and closed. The goal following closure is for the dam owner to submit a decommissioning, closure, and abandonment (DCA) plan and completion reports to apply for the facility to undergo de-registration as a dam (AER 2020). Following this process, the structure would be reclassified and regulated as a mine waste dump under the Oil Sands Conservation Act of the Coal Conservation Act (AER 2020). The Alberta Energy Regulator (AER), who is responsible for the regulation of energy dams, developed Manual 019: Decommissioning, Closure, and Abandonment of Dams at Energy Projects (Manual 019) to accompany the Alberta Dam and Canal Safety Directive (the Directive). Manual 019 specifies that this risk assessment must consider long-term physical failure modes, including failure modes that may not be applicable during operations (AER 2020). It is important to note that Manual 019 indicates that "risk cannot be reduced to zero for oil sands tailings facilities, or any manmade structure for that matter" and that the ideal lowest consequence category would be comparable to natural analogues with an extremely low likelihood (AER 2020). It is expected that active management should continue until the regulator accepts the completion report, at which point the operator is no longer required to actively manage and report on the structure as a dam (AER 2020). In some cases, a tailings dam may require long-term active management if the residual risk is deemed to be too high (AER 2020).

To help support the process of de-registering a tailings dam as a dam in Alberta, a risk management tool (the Generalized Failure Modes Effects (G-FMEA) framework) was developed. The tool is summarized in Section 4. De-registration, defined here, is when the regulating governmental body assesses a dam structure to evaluate if it can be de-classified as a dam, so that it is no longer regulated as a dam. The term de-register is not a regulatory or legal term and has been commonly used in industry to describe this process. Throughout the literature, the terms de-license (i.e., Oil Sands Tailings Dam Committee (OSTDC) (2014)) and de-regulate (i.e., Oberle et al. (2020)) have also been used to describe this process.

There are three different configurations of TSFs that may exist at an oil sands mine as defined by AER (2020):

> *"(1) External tailings facilities where perimeter containment is formed by perimeter dams and rising topography in some cases. The tailings are deposited entirely on natural topography above ground.*
>
> *(2) Tailings stored in pit but a full height dam separates the tailings from the receiving environment.*
>
> *(3) Tailings stored in pit but capacity of the pit container is increased by constructing a perimeter dam along a portion or the entire pit crest."*

The goal of the G-FMEA is to assess the long-term geotechnical risks of an external tailings facility (ETF) during the closure phase to support the process of de-registration (Schafer et al. 2021). However, the risk management tool should be able to be adapted for other configurations to account for additional risks that exist for those scenarios if needed. The G-FMEA should be used at the conceptual design stage, if possible, to assess the closure plan and evaluate the potential for de-registration (Schafer et al. 2021). It should be updated throughout the project life and can also be used for dams that have already been constructed or are orphaned (Schafer et al. 2021). This paper demonstrates how the G-FMEA can be used and applied in practice for a case study oil sands external tailings facility in Alberta, Canada. The G-FMEA charts presented in Section 4.1.6 are used to evaluate the potential failure modes of an oil sands ETF closure plan using an element approach. This process demonstrates how the framework can be used to go from a generalized list of failure modes and applied directly to a case study. This process requires an evaluation of serviceability failure of each element. The paper then shows how to apply the risk matrix framework to two select failure modes (clogging of drains and surface erosion of the berm) and how the risk of these failure modes changes over time. The site-specific G-FMEA is used to show how the framework can be used to support the closure process at different points of time (conceptual design or de-registration). Overall, the paper serves to demonstrate how risk management can be integrated into the process of closure design to support de-registration. Ultimately, this supports long-term closure goals with a risk management focus.

5.1.2 Background

The G-FMEA serves as a screening tool for the closure phase of an ETF, where hazards that are assessed as acceptable will not require additional analyses, but hazards that are assessed to have a higher risk rating (or where there are a number of low-risk hazards) could require more detailed and/or quantitative risk assessments. This may include reliability analyses for critical risks. However, challenges with quantifying uncertainties in climatic conditions in the long term would likely render uncertainty (particularly epistemic uncertainty) difficult to manage within reliability analyses.

The objective of the G-FMEA is: "How should geotechnical risks associated with an external tailings facility in Alberta be managed in the long term to achieve an acceptable closure plan, such that the facility is able to be de-registered as a dam?" (Schafer et al. 2021). The G-FMEA includes charts (provided in Section 4.1.6) for the drainage system, foundation, dam body, and landform that provide failure modes for different elements present in each system. These charts form the backbone of the G-FMEA framework. Applying the G-FMEA framework to a site involves first defining the system, developing a block diagram, and breaking the system down into key elements. Each element should have the function defined, as well as what constitutes serviceability failure. Once this step has been completed, each element can be screened for applicable failure modes using the G-FMEA charts. A risk assessment is then conducted for every applicable failure mode, which involves determining the likelihood and consequence ratings for each temporal scale and determining the risk rating. Appropriate risk mitigation options should be assessed and applied as appropriate.

The G-FMEA should be conducted for different assessment periods, including the immediate term, short term, medium term, and long term (Schafer et al. 2021). The goal with this is to account for time dependence, depreciation of system elements, and changing risk profiles, which are common critiques of failure modes effects analysis (Schafer et al. 2021).

The likelihood rating table (Table 4-5), consequence rating table (Table 4-6), and risk categories (Table 4-7) to be used in conjunction with the G-FMEA are provided in Section 4.1.4. Section 4.1 provides guidance on how a risk matrix can be colour coded and demonstrates the application through an example risk matrix. The example risk matrix, presented in Figure 4-5, will be used for the oil sands case study presented in this paper. The example risk matrix has a threshold line where hazards that have a risk rating higher than the threshold line may require additional analysis to adequately assess the risk. It should be noted that risk matrices used in practice should be developed with input from all relevant stakeholders.

5.1.3 Application of G-FMEA to a Case Study

The G-FMEA was used to evaluate an oil sands case study in Alberta, Canada. The purpose of this was to demonstrate the utility of the G-FMEA process.

5.1.3.1 Site Description (System Definition)

The first step of conducting the G-FMEA involves defining the system as described in Section 4.1.4. A base-level description of the site is provided here for information purposes. The ETF is a sand dam with a starter dyke constructed of overburden. The facility was constructed with a mixture of upstream and centreline construction. In upstream construction, tailings are discharged upstream from the crest of the dam (beginning first with the starter dyke) to form a beach, which becomes the foundation for subsequent raises (Vick 1990). In centreline construction, fill is placed on the downstream slope of the dam and tailings are discharged in the upstream direction to form a beach (Vick 1990). Consequently, the centreline of the dam remains at the same position relative to the starter dyke. Analysis of the facility for this paper was conducted at a section of the ETF that had been constructed using upstream construction with hydraulic fill deposition and cell construction. Cell construction involves discharging tailings to a cell where the solids settle, and water and fines are decanted (Lighthall et al. 1989). Dozers are used to maintain containment dykes and spread and compact the sand in the cell by using vibration (Lighthall et al. 1989, Martens and Lappin 2008). The water and fines that do not settle flow to the end of the cell and through a weir structure to the beach (Yano and Fair 1988).

The dam is composed of coarse sand tailings (CST) and beach deposits, including beach above water (BAW) and beach below water (BBW). CST is made up of the coarse fraction of whole tailings and is formed by cycloning the tailings (CTMC 2012). The BAW and BBW deposits are formed when tailings are discharged into the pond. The coarser tailings will settle first on the beach, leading to the formation of these two different deposits. The BAW and BBW can have variable gradation, solids content, hydraulic conductivity, and density (Lighthall et al. 1989). At the location of the analysed section, the dam contains fluid fine tailings (FFT). The dam has a toe berm constructed of lean oil sands (fines and a modest amount of bitumen) (Pollock et al. 2014), with benched slopes to provide stability to the facility. The foundation of the ETF at the analysed section is typical for the Fort McMurray area and consists of the McMurray formation, Pleistocene sands, and McMurray formation tidal flat mud and mud flat. It should be noted that there is a weak tailings layer at the base of the tailings deposit and the upstream constructed lifts of the dam. The weak tailings layer was formed due to initial deposition of tailings into standing water, has a high bitumen and fines content, and is considered liquefiable. This layer creates stability issues, which led to the design and construction of the toe berm that is currently in place. The section used for analysis is extensively instrumented and monitored.

Drainage at the facility consists of two levels of 200 mm diameter perforated collector pipes surrounded by a woven geotextile sock drain that run parallel to the dam centreline. Smaller outtake pipes connect to the collector pipes at approximately 150 m intervals and discharge water to a perimeter ditch.

As the facility operations proceed towards closure, it is expected that the facility will be infilled with CST, partially displacing the FFT. It is expected that this process will result in a zone of mixed CST and FFT. This zone will be covered by approximately 4 m of CST that will be placed and compacted using methods similar to cell construction to create a trafficable surface. The compacted CST will then be capped with mine waste to enable construction of the landform. The vegetative cover for the reclamation surface is not yet defined. The reclamation surface is expected to have hummocks and a system of drainage channels that direct flow towards the outlet of the facility. The outlet is designed to have a base width of 100 m and side slopes of 15 horizontal:1 vertical.

The case study cross-section analysed is provided in Figure 5-1.

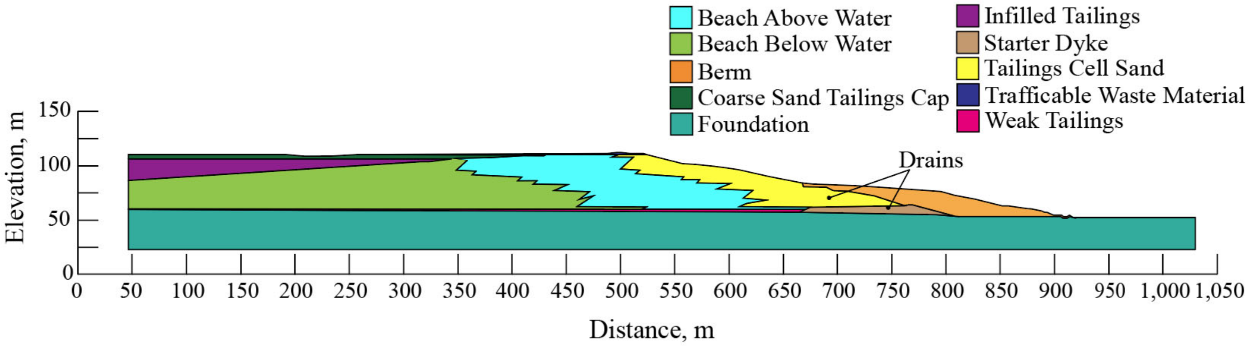

Figure 5-1: Case study cross-section

5.1.3.2 G-FMEA Steps 2 to 4

The next three steps of conducting the G-FMEA involve developing a block diagram, breaking the subsystem down into key elements and functions, and defining serviceability failure for each element. The block diagram is used to break the system down into functional subsystems that can be analysed and shows the relationships between those subsystems. The block diagram for the case study is shown in Figure 5-2. Table 5-1 provides descriptions of the elements, the function before and after closure, and serviceability failure for each element based on the defined function.

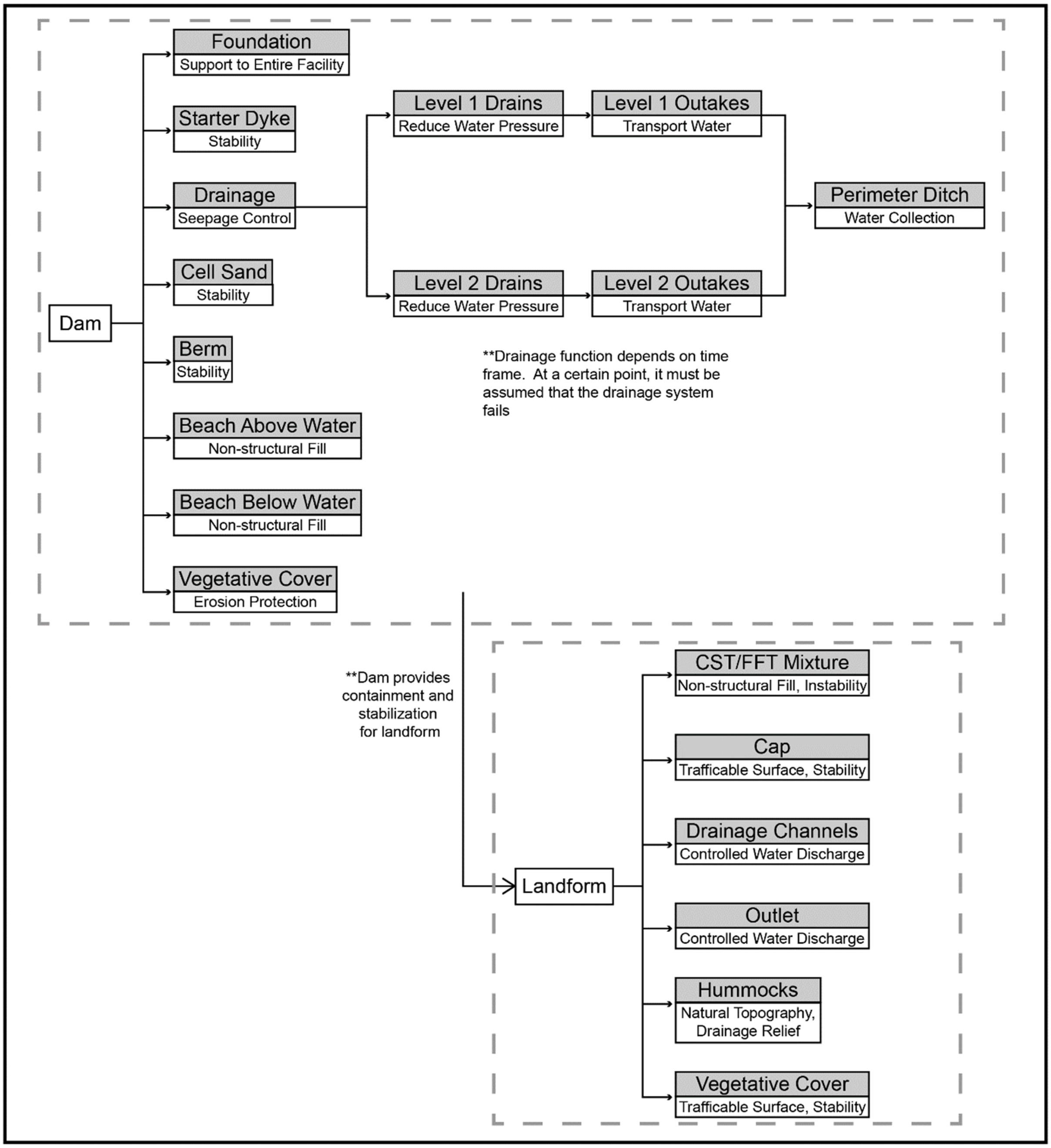

Figure 5-2: Case study block diagram

Table 5-1: Case study element functions and failure description

System	Elements	Function (Before Closure)	Function (After Closure)	Failure Description
Dam	Foundation	Supports capacity of the dam.	Supports capacity of the dam.	Instability associated with movements of the soil mass.
	Starter dyke	Allowed for initial containment of tailings. Provides stability.	Provides stability.	Instability.
	Drainage system	See drainage system.		
	Cell sand	Containment, dyke stability, provides stability.	Provides stability.	Instability.
	Berm	Provides stabilization against liquefaction with weak tailings layer present at base of facility.	Provides stabilization against liquefaction, with weak tailings layer present at base of facility.	Instability.
	Beach above water	Containment, dyke stability.	Non-structural fill.	Instability.
	Beach below water	Containment of tailings and dam raises.	Non-structural fill. Potential source of instability.	Instability.
	Vegetative cover	Erosion stabilization and protection of slope.	Erosion stabilization and protection of slope.	Fails to provide erosion protection.
Drainage System	Level 1 drains	Control the phreatic surface in the dam.	Controls phreatic surface in the dam up to a certain point of time (must be determined with modelling). After this point, the drains are assumed to fail and will no longer serve a function in closure.	Drains fail to control phreatic surface.
	Level 2 drains	Control the phreatic surface in the dam.	Controls phreatic surface in the dam up to a certain point of time (must be determined with modelling). After this point, the drains are assumed to fail and will no longer serve a function in closure.	Drains fail to control phreatic surface.
	Outtakes—level 1	Transmit water from drains to perimeter ditch.	Controls phreatic surface in the dam up to a certain point of time (must be determined with modelling). After this point, the drains are assumed to fail and will no longer serve a function in closure.	Drains fail to control phreatic surface.
	Outtakes—level 2	Transmit water from drains to perimeter ditch.	Controls phreatic surface in the dam up to a certain point of time (must be determined with modelling). After this point, the drains are assumed to fail and will no longer serve a function in closure.	Drains fail to control phreatic surface.
	Perimeter ditch	Collect water from drains and intercept seepage and sediment.	Water and sediment collection.	Fails to collect, intercept, and transport seepage.
Landform	Cap (overburden and coarse sand tailings)	N/A	Trafficable surface, stability to landform, limits infiltration.	Landform instability.
	Infilled coarse sand tailings mixed with FFT	N/A	Non-structural fill. Potential source of instability.	Landform instability.
	Hummocks	N/A	Provide topographic variation and diversity. Designed to keep the water table low in upland areas.	Fails to provide topographic variation and diversity. Fails to help control the water table.
	Drainage channels	N/A	Directs flow to the outlet to be carried away from the facility.	Fails to direct flow to the outlet.
	Outlet	N/A	To ensure controlled discharge under exceptional inflow conditions.	Fails to control discharge.
	Vegetative cover	N/A	Stabilization of landform. Erosion protection. Ecosystem creation. Wildlife habitat.	Fails to provide erosion protection.

5.1.3.3 Site Specific FMEA

Each element discussed in Table 5-1 was assessed using the appropriate chart from the G-FMEA to assign failure modes to the elements. Section 5.1.6 shows the 128 failure modes that were identified for the dam elements. The next steps in the FMEA are to assess the applicability of the failure modes, determine the failure effects and consequences, determine the risk rating for each temporal scale, and determine corresponding risk mitigation as required. This step has not been completed in full but has been completed for demonstration purposes for failure mode 34 and 87 in Table 5-6, which are summarized in Table 5-2. These failure modes were selected due to the way that they may change and develop over time. A detailed description of the clogging of the level 2 drains due to particulate clogging (failure mode 34) is provided in Section 5.1.3.3.1, and a description of the surface erosion failure of the berm is provided in Section 5.1.3.3.2. It should be noted that this work is not accompanied by a level-of-confidence assessment for each risk rating (as recommended in the G-FMEA steps), as this work is currently underway by a researcher at the University of Alberta.

Table 5-2: Demonstration failure modes

Element	Failure Mode Identification	Failure Mode Description	Potential Trigger/Cause	Failure Effects
Level 2 Drains	34	Clogging	Particulate clogging (sediment from perimeter ditch or other)	Lack of control of phreatic surface (potential rise in phreatic surface), increase in seepage, pond on reclamation surface, internal erosion, global instability, release of water into downstream shell, erosion on downstream slope
Berm	87	Surface erosion from wind and overland flow resulting in rills, gullies, or sheet erosion	Destruction of vegetation (FM 112), rainfall, melting of snow, wind, increased seepage on downstream slope from failure of drainage system, increased seepage from internal erosion in embankment	Slope failures (shallow surficial movement, slumps), change in downstream slope angle, blockage in perimeter channel with sediment, development of negative drainage, development of large erosion scarps

5.1.3.3.1 Clogging of the Level 2 Drains

The level 2 drains consist of a 200 mm perforated collector pipe surrounded by a woven geotextile sock placed on a bed of sand and gravel, and they are located in the cell sand. The function of the level 2 drains before closure is to control the phreatic surface of the dam. Following closure, the function of the drains changes over time, and they are required to contribute to the control of the phreatic surface for a period of time. At this mine site, it is assumed that the drains will fail in the long term, and the facility has been designed to support this assumption. However, the question of how long the drains will need to be operational to support the lowering of the phreatic surface is critical.

As part of this research, industry professionals were interviewed on tailings dam closure as discussed in Section 3. Notably, interview participants had conflicting comments regarding the progression of the phreatic surface over time (Schafer et al. 2019). Some participants indicated that it is expected that the phreatic surface will go down in the long term, while others indicated that there are a number of conditions under which this may not be true, such as the drains clogging (Schafer et al. 2019). This shows the importance of assessing drain performance over time, as it may have a critical role in how the phreatic surface changes over time, which ultimately may impact the stability of the structure.

Drains may fail in a number of ways, as shown in Table 5-6, which may include a breakage of the pipe due to buckling or physical degradation, clogging (chemical, biological, particulate, failure from the outtakes), clogging of the surround (biological, chemical, particulate), or a breakage of the connection between the drain and outlet pipe. This section focuses on the clogging of the level 2 drains due to particulate clogging.

As per the G-FMEA framework, the analysis should take place over four temporal scales: immediate term, short term, medium term, and long term. For this tailings facility, it is expected that the immediate-term and short-term period will fall within the adaptive management period, as the mine site will still be mining following closure of the facility. The medium-term period will fall within the reactive management period, and the long-term period occurs at about 1000 years. For the purposes of this analysis, it was assumed that the drains were required to control the phreatic surface for the immediate-term, short-term, and medium-term periods. As such, failure occurs when the drain is no longer able to control the phreatic surface. For the long-term period, the drains were assumed to fail and are no longer considered to be a controlling feature of stability. Consequently, long-term risk assessment was not conducted for this failure mode.

The completed risk assessments for the immediate-term, short-term, and medium-term temporal scales for particulate clogging of the level 2 drains are provided in Table 5-3. As the temporal scale increases, there is an increase in likelihood of the drains failing due to particulate clogging, from very rare in the immediate term to possible in the medium term.

The consequences also change as the temporal scale increases. The phreatic surface has continued to drop in the facility. For the purposes of this work, it is assumed that the phreatic surface may be below the drain location at some spots throughout the facility at the time of closure. This hypothesis should be supported by modelling and on-site monitoring, which are beyond the scope of this work. Using these assumptions, it is expected that the failure of the level 2 drains may result in a minor rise in the phreatic surface, but this is not expected to result in global failure. In the immediate term and short term, it is expected that failure of the element may have cascading consequences. However, these cascading consequences are not expected to result in global failure due to other controls in place during the adaptive management phase, resulting in a minor consequence rating. This is coupled with the potential for minor or localized intervention, which is possible due to the presence of staff on-site. Due to the expected consequences, a rating of slight was assigned in the environment and community categories.

In the medium term, if the facility requires the level 2 drains to function for stability, it is expected that failure could result in a rise in the phreatic surface, an increase in seepage, and formation of ponds on the reclamation surface, but these consequences are not expected to result in global failure, resulting in a moderate consequence rating. However, this failure may require human intervention or maintenance to limit the extent of the cascading consequences (i.e., if extensive ponds formed on the reclamation surface), resulting in a moderate consequence rating. A slight consequence rating was assigned to the environment category as no tailings are expected to move beyond the footprint from this failure. It is expected that there may be a short-term impact on the local community if ponds form on the reclamation surface, depending on the end land use, resulting in a minor consequence rating. Modelling must be conducted to determine the influence of drain failure on the phreatic surface and if drain function is required to maintain stability in the medium term (i.e., to keep the phreatic surface low such that the potentially liquefiable units de-saturate). Modelling is an effort to reduce the uncertainty associated with the risk assessment, not necessarily reducing the likelihood or consequences. However, understanding the failure mode may result in the likelihood or consequence rating being reduced. Following the completion of the modelling, more targeted controls to reduce the likelihood and consequence can be developed, if needed.

As shown in Table 5-3, this results in risk ratings that increase as the temporal scale increases for the failure consequences, human intervention, community, and end land use consequence categories. The risk rating for the environment consequence category remains low for the different temporal scales as tailings are not expected to go beyond the facility footprint due to a failure of the level 2 drains.

Table 5-3: Immediate-term, short-term, and medium-term risk assessments for particulate clogging of level 2 drains

Temporal Scale	**Likelihood**	**Consequences**				**Risk Rating**				**Controls**
		Element failure consequence	**Human Intervention**	**Environment**	**Community**	**Element failure consequence**	**Human Intervention**	**Environment**	**Community**	
Immediate term	Very rare	Minor	Minor	Slight	Slight	L	L	L	L	No control needed
Short term	Rare	Minor	Minor	Slight	Slight	M	M	L	L	No control needed
Medium term	Possible	Moderate	Moderate	Slight	Minor	H	H	L	M	Modelling to predict drain performance and location of phreatic surface over time, monitoring of porewater pressures

5.1.3.3.2 Surface Erosion of the Berm

The berm consists of lean oil sands with benched slopes to provide stability. The function of the berm before and after closure is to provide stabilization against liquefaction due to a weak tailings layer present at the base of the facility. Failure of the berm (instability) may occur due to a number of different failure modes, as shown in Table 5-6, including vertical deformation, seismic liquefaction, static liquefaction, shear failure, internal erosion, surface erosion, and toe erosion. This section focuses on surface erosion from wind and overland flow.

Unlike the particulate clogging of the level 2 drains, the risk assessment for the surface erosion of the berm was completed over all four temporal scales. The completed risk assessments for all four temporal scales for surface erosion of the berm are provided in Table 5-4. It is common practice during operations for erosion gullies to be repaired on an ongoing basis as they develop in the downstream, bare sand slopes. Similarly, erosion events may be less critical in the immediate term and short term due to the opportunity for maintenance.

Slingerland et al. (2018a, 2018b) conducted a study to investigate erosion of a sand dam in the Alberta oil sands using a Landscape Evolution Model (LEM) to aid in assessing the long-term geomorphic stability. The results of the study for a 200-year simulation period indicated that the morphology of the structure was well established within 60 years, with gullies most frequently forming in areas of concentrated flow (i.e., horizontally concave dam sections) and retrogressively travelling inward towards the pond (Slingerland et al. 2018a, 2018b). The development of erosional features on a dam may be impacted by the dam height (including the length of the slope), the grain size distribution of the material, and the climate (Slingerland et al. 2018b). The results showed that some potential areas of concern in the long term may be substantial sediment discharge off-site, the formation of deep gullies (greater than 15 m deep), and the filling of drainage channels (Slingerland et al. 2018b). The results also suggested that it would be advantageous to grade dams such that surface water is collected and directed toward armored swales and transported to the perimeter channel, as opposed to having a uniform slope that allows sheet flow (Slingerland et al. 2018b).

Slingerland et al. (2018a, 2018b) also showed that vegetation played a huge role in reducing erosion. Overall, major gullies started to form before the vegetation matured, with no major gullies forming following vegetation maturity (Slingerland et al. 2018a). Erosion gullies began to form near the bottom of the slope as the soil typically has a higher water content, resulting in the flow transitioning from dispersive flow to centralized, efficient flow paths (Slingerland et al. 2018a). This centralized flow allows the water to gain speed and increases its erosive power (Slingerland et al. 2018a). Erosion gullies also formed from surface water being directed and concentrated in one location and then finding the easiest route to travel (Slingerland et al. 2018a). Overall, the results of the study indicated that erosion in the long term may result in the structure not functioning as designed, resulting in failure of the structure to retain tailings. This indicates a potential need for ongoing maintenance of the structure.

The section being analysed (and taken to be representative of the facility) has mature vegetation on the downstream slope. Consequently, it is expected that erosion events will occur with a 'possible' likelihood in the immediate term and the short term. As time progresses, it is expected that the likelihood will change from 'possible' to 'likely' as climate change occurs, leading to more extreme events and a transition of vegetation. Assessing the likelihood of surface erosion in the long term is further complicated by the potential for anthropogenic activities, which may alter the projected landscape and amplify the likelihood of surface erosion (i.e., clearcutting all trees on the downstream slope).

Table 5-4 shows how the risk rating increases as the temporal scale increases in the different consequence categories. In all cases, it is not expected that erosion of the berm would result in a global failure of the facility. For the element failure consequence, there is an increase from a moderate risk rating to a high-risk rating due to a change in the consequence category rating. Reviewing Table 4-5 a consequence rating of minor and moderate have the same definition for the element failure consequence category. The moderate consequence category was assigned for the medium term and long term due to the unknowns associated with these time frames. For the human intervention category, there is a change from a moderate risk rating in the immediate term, short term, and medium term to a high-risk rating in the long term. This is due to a moderate consequence rating assigned in the human intervention category for the long-term temporal scale, due to the potential need to employ intervention or maintenance to limit cascading consequences and prevent global failure. In the environment category, the risk rating changes from moderate in the immediate. term, short term, and medium term to a high-risk rating in the long term. This is due to a change in the consequence rating from minor to moderate. It should be noted that this assumed that the tailings are not toxic. For the community, the risk rating increases from low in the immediate term and short term to moderate in the medium term to high in the long term. It is assumed that no fatalities will occur due to a failure of the element, but that there may be short-term impacts to the community as a failure may impact the post mining land use, require intervention and maintenance, and result in tailings being carried away from the footprint, which has the potential to impact fishing and so on.

For controls, this failure mode should be analysed with an LEM to evaluate geomorphic evolution, monitoring to evaluate erosion progression in the vegetated slope and confirm if it aligns with the LEM, and defined maintenance thresholds, if necessary.

Table 5-4: Immediate-term, short-term, medium-term, and long-term risk assessments for surface erosion of the berm

Temporal Scale	**Likelihood**	**Consequences**				**Risk Rating**				**Controls**
		Element failure consequence	**Human Intervention**	**Environment**	**Community**	**Element failure consequence**	**Human Intervention**	**Environment**	**Community**	
Immediate term	Possible	Minor	Minor	Minor	Slight	M	M	M	L	N/A
Short term	Possible	Minor	Minor	Minor	Slight	M	M	M	L	N/A
Medium term	Likely	Moderate	Minor	Minor	Minor	H	M	M	M	LEM to evaluate geomorphic evolution, monitoring, maintenance thresholds
Long term	Likely	Moderate	Moderate	Moderate	Moderate	H	H	H	H	LEM to evaluate geomorphic evolution, monitoring, maintenance thresholds

5.1.4 Discussion

Risk management consists of two main components, including risk assessment and risk control, and is a systematic process where risks are recognized and assessed, and appropriate control measures are implemented (ISO 2009). The G-FMEA framework outlines the steps for conducting both risk assessment and risk control. Step 8 of the process involves assessing appropriate risk mitigation options based on the risk rating for each temporal scale and then repeating the risk assessment process as needed. Controls are briefly discussed for the two different failure modes that had risk assessments completed using the risk matrix. These controls focus on two key elements, including detailed modelling and monitoring and maintenance. The monitoring and maintenance requirements must be clearly outlined and must be in line with the long-term closure plan. This means that if the long-term closure goals include walk-away closure with no maintenance, then the use of monitoring and maintenance as a control is not appropriate, in contrast to a closure plan that includes targeted monitoring and maintenance. Once the risk mitigation/controls are outlined and completed (in the case of modelling), the risk assessment can be repeated to re-assess the risk. This process may result in a need to alter the closure plan to adequately reduce the risk. The success of risk mitigation methods may depend on where the ETF is at in its life cycle. The earlier risk management practices are employed in the closure planning process, the easier it is to make meaningful changes that will positively impact the long-term risk. For example, Slingerland (2019) investigated the impact of different dam slope shapes on surface erosion using LEM and found that the shape of the downstream slope had a substantial impact on the erodibility of the slope, where uniform slopes contribute to the development of focused drainage patterns and thus an increase in erosion. Slingerland (2019) noted that implementing these dam shapes into the initial dyke design is an important element to success. Once the dam is farther into its life cycle, these types of design changes to aid in mitigating the risks associated with erosion would be more difficult to employ, and maintenance controls may need to be relied on more heavily.

While the G-FMEA was not completed in full for the case study dam, the application of the framework was demonstrated. Completion of the G-FMEA may indicate that some failure modes require additional risk assessment to adequately quantify the risk. The framework and example risk matrix outlined in Section 4.1.4 states that a threshold can be used with the risk matrix where hazards that fall above the threshold may require further risk assessment methods. This is due to the known pitfalls of risk matrices. If a threshold value is adopted, careful consideration should be given to hazards that fall above the threshold, particularly those with a high-risk rating, where as low as reasonably practical (ALARP) principles may be employed. Assessment of risk using risk matrices should always be conducted with awareness of the shortfalls of risk matrices.

Once the G-FMEA has been completed for all the failure modes, this can be used to assess the success of the closure plan to support de-registration. If this is in the earlier stages of design, this process can be highly effective at making meaningful changes to the design of the facility and the closure plan to reduce long-term risks. This process would be highly effective if integrated into the process of landform design, which is defined as "the integrated, multidisciplinary design and construction of mining landforms and landscapes, directed by a dedicated team working with different mine operations groups and others over the life of the mine and beyond" (LDI 2021). Landform design has a focus on integration – including integration across time scales and disciplines (LDI 2021). The process of integrating risk management of the closure plan into the overall design of the facility and designing with the end in mind is the best tool for successful de-registration. The G-FMEA can then be re-visited and updated, as necessary, over the life of the facility. In all cases, an essential element is that the risk mitigation options are assessed and implemented with consideration of the long-term custodial transfer plans.

Once a facility has reached the stage of reclamation and closure, as with the oil sands dam presented in this case study, the completed G-FMEA can be used to help support the de-registration process. Manual 019 released by the AER in 2020 requires dam owners to complete risk assessment to support DCA plans and completion reports (AER 2020). A requirement of the DCA plan is to assess risk using FMEA or a similar method, and this should include identification of hazards and potential failure modes, analyzing the hazards, assessment of the consequences and likelihoods, characterizing the overall acceptability of the residual risk, and redesigning to reduce the residual risk if needed (AER 2020). The G-FMEA can be used for this purpose to aid in assessing and managing the risks associated with closure.

5.1.5 Summary and Conclusions

Globally, mining companies and regulators are working towards how to close tailings facilities in a responsible and sustainable way to achieve the goal of physical, chemical, ecological, and social stability, with no further risks to life or the environment, as outlined by ICOLD Tailings Dam Committee (2013). Getting to this point requires collaboration between industry, regulators, and academia. The Alberta Energy Regulator (AER) has developed new guidance for closure of tailings dams, referred to as Manual 019, which requires risk assessments that consider long-term physical failure modes (AER 2020). To help support the effort of de-registering a tailings dam in Alberta, the G-FMEA Framework outlined in Section 4 was developed to evaluate the geotechnical risks associated with closure of external tailings facilities and assess if the closure plan is sufficient to support de-registration. The framework was developed through collaboration between industry, the regulator, and academia.

This paper shows how the G-FMEA framework presented in Section 4 can be applied to a case study site. The case study site used for this work is an external tailings facility located at an oil sands site in northern Alberta. For the oil sands facility, the system definition and block diagram were developed and used to develop failure modes for the individual dam elements using the generalized charts from the G-FMEA. From there, select failure modes (clogging of drains and surface erosion of the berm) were used to demonstrate how the risk matrix can be used to assign risk ratings. The failure modes were assessed over different temporal scales to demonstrate how the risk may change over time. In both cases, the risk rating increases as the temporal scale increases (from immediate term to long term). In part, uncertainty contributes to the increasing likelihood, and modelling may be a useful exercise to aid in informing risk decisions. Full completion of the G-FMEA can be used to assess a closure plan based on the residual risk and if this closure plan will support the de-registration, which is a vital step to fulfilling long-term closure goals and satisfying the social license to operate. A level-of-confidence rating was not applied to the individual risk ratings as this work is currently being developed at the University of Alberta. The G-FMEA is intended to be used and applied throughout the life of a structure (from the planning phase to assessing risks associated with closure).

Limitations of the G-FMEA process lie in the tremendous amount of information required to do a comprehensive evaluation of a tailings facility for de-registration, especially at the conceptual planning stage when data is more limited. The G-FMEA also uses a risk matrix for evaluation of risk. Risk matrices have a number of pitfalls that risk matrix developers and users must be aware of that are outlined comprehensively in Section 4.1.3.

The G-FMEA framework takes an element approach to evaluating the risk of a tailings facility and encourages risk assessors to evaluate the interactions between individual components. This is different from many FMEAs being conducted in industry that look at the tailings facility as an entire structure and evaluate global stability (ultimate failure), rather than breaking the structure down into individual elements and evaluating function failure of each element. While the overall process may be time intensive, it is necessary to evaluate the long-term risk of a tailings facility. Specifically, incorporating the G-FMEA into the early processes of design may allow for closure-based decision making to be used in the overall design process (i.e., if erosion is identified as being critical to long-term stability, the downstream slopes could be modified at the onset to minimize long-term erosion).

The overall G-FMEA framework may be adapted for other structures and jurisdictions, as needed. This would require an adaptation of the G-FMEA generalized charts, the likelihood table, consequence table, and risk rating presented in Section 4. Regardless, the overall methodology is transferable across the mining industry.

5.1.6 Appendix A: Application of G-FMEA to a Case Study Side

Table 5-5: Recommended G-FMEA worksheet (Reprinted from Schafer et al. (2021))

Element	Failure mode identification	Failure mode description	Potential trigger/cause	Screening assessment of failure mode	Is this failure mode applicable?	If yes, is there sufficient data to evaluate the risk? List any resource gaps.	Failure effects	Immediate-term/Short-term/Medium-term/Long-term Assessment *														
								Likelihood	Consequences				Risk Rating				Level of Confidence				Controls	Remarks
									Element failure consequence	Human intervention	Environment	Community	Element failure consequence	Human intervention	Environment	Community	Element failure consequence	Human intervention	Environment	Community		

Table 5-6: Application of G-FMEA to a case study site

Element	Failure mode identification	Failure mode description	Potential trigger/cause	Screening assessment of failure mode	Failure effects
Perimeter ditch	1	Blockage	Sedimentation	Is there erosion protection in place? What is the slope of the ditch? Is it sufficient to keep particles suspended? What is the strength of material? Have there been failures in this material before?	Flooding, discharge of process effected water to the environment, blockage of level 1/level 2 drain outlet, rise in phreatic surface, increase in seepage, pond on reclamation surface, internal erosion, global instability, toe erosion
	2	Blockage	Sloughing/slope failure of walls	What is the slope of the side slopes? What is the strength of material? Have there been failures in this material before?	Flooding, discharge of process effected water to the environment, blockage of level 1/level 2 drain outlet, rise in phreatic surface, increase in seepage, pond on reclamation surface, internal erosion, global instability, toe erosion
	3	Blockage	Beaver dams	Are there beavers in the area?	Flooding, discharge of process effected water to the environment, blockage of level 1/level 2 drain outlet, rise in phreatic surface, increase in seepage, pond on reclamation surface, internal erosion, global instability, toe erosion
	4	Blockage	Icing	Is the mine located in an area that could experience icing?	Flooding, discharge of process effected water to the environment, blockage of level 1/level 2 drain outlet, rise in phreatic surface, increase in seepage, pond on reclamation surface, internal erosion, global instability, toe erosion
	5	Reduction in cross-sectional area	Sloughing/slope failure of walls	What is the slope of the side slopes? What is the strength of material? Have there been failures in this material before?	Reduced capacity, erosion, potential flooding, discharge of process affected water to the environment, blockage of level 1/level 2 drain outlet, rise in phreatic surface, increase in seepage, pond on reclamation surface, internal erosion, global instability, toe erosion
	6	Reduction in cross-sectional area	Excessive Vegetation	Will the ditch regularly have water running through it or will it stay dry for a portion of the year? Are there deterrents in place to prevent the growth of vegetation?	Reduced capacity, erosion, potential flooding, discharge of process affected water to the environment, blockage of level 1/level 2 drain outlet, rise in phreatic surface, increase in seepage, pond on reclamation surface, internal erosion, global instability, toe erosion
	7	Change in slope	Erosion	Is there erosion protection in place?	Water discharge velocity change, local instability of dam
	8	Change in slope	Differential Settlement	Does the material have the potential to consolidate or settle over time? Is it a cut into natural ground or is the material placed?	Creation of secondary channels, localized areas of erosion, local instability of dam
	9	Sand channel buoyancy	Freezing conditions in channels composed of sand	Are the drainage channels constructed of sand? Could the channel experience freezing?	Flooding, discharge of process affected water to the environment, blockage of level 1/level 2 drain outlet, rise in phreatic surface, increase in seepage, pond on reclamation surface, internal erosion, global instability, toe erosion
Outtakes - Level 1	10	Breakage of pipe	Break in pipe	Is the pipe capable of breaking?	Release of water into downstream shell, lack of control of phreatic surface (potential rise in phreatic surface), increase in seepage, pond on reclamation surface, internal erosion, global instability, erosion on downstream slope

Element	Failure mode identification	Failure mode description	Potential trigger/cause	Screening assessment of failure mode	Failure effects
	11	Breakage of pipe	Buckling	Is the pipe capable of buckling?	Release of water into downstream shell, lack of control of phreatic surface (potential rise in phreatic surface), increase in seepage, pond on reclamation surface, internal erosion, global instability, erosion on downstream slope
	12	Breakage of pipe	Physical degradation	Is the pipe capable of physically degrading over time?	Release of water into downstream shell, lack of control of phreatic surface (potential rise in phreatic surface), increase in seepage, pond on reclamation surface, internal erosion, global instability, erosion on downstream slope
	13	Clogging	Chemical or biological	Is chemical or biological clogging possible?	Failure to transmit water to perimeter ditch, clogging of level 1 drains, lack of control of phreatic surface (potential rise in phreatic surface), increase in seepage, pond on reclamation surface, internal erosion, global instability, release of water into downstream shell, erosion on downstream slope
	14	Clogging	Particulate clogging (sediment from perimeter ditch or other)	Is sediment capable of clogging the pipe?	Failure to transmit water to perimeter ditch, clogging of level 1 drains, lack of control of phreatic surface (potential rise in phreatic surface), increase in seepage, pond on reclamation surface, internal erosion, global instability, release of water into downstream shell, erosion on downstream slope
	15	Blockage	Perimeter channel (FM 1-6) or other (snow, debris, etc.)	Is the pipe outlet close enough to the base of the perimeter channel that it could become blocked?	Failure to transmit water to perimeter ditch, clogging of level 1 drains, lack of control of phreatic surface (potential rise in phreatic surface), increase in seepage, pond on reclamation surface, internal erosion, global instability
Level 1 Drains	16	Breakage of pipe	Break in pipe	Is the pipe capable of breaking?	Lack of control of phreatic surface (potential rise in phreatic surface), increase in seepage, pond on reclamation surface, internal erosion, global instability, release of water into downstream shell, erosion on downstream slope
	17	Breakage of pipe	Buckling	Is the pipe capable of buckling?	Lack of control of phreatic surface (potential rise in phreatic surface), increase in seepage, pond on reclamation surface, internal erosion, global instability, release of water into downstream shell, erosion on downstream slope
	18	Breakage of pipe	Physical degradation	Is the pipe capable of physically degrading over time?	Lack of control of phreatic surface (potential rise in phreatic surface), increase in seepage, pond on reclamation surface, internal erosion, global instability, release of water into downstream shell, erosion on downstream slope
	19	Clogging	Chemical or biological	Is chemical or biological clogging possible?	Lack of control of phreatic surface (potential rise in phreatic surface), increase in seepage, pond on reclamation surface, internal erosion, global instability, release of water into downstream shell, erosion on downstream slope
	20	Clogging	Particulate clogging (sediment from perimeter ditch or other)	Is sediment capable of clogging the pipe?	Lack of control of phreatic surface (potential rise in phreatic surface), increase in seepage, pond on reclamation surface, internal erosion, global instability, release of water into downstream shell, erosion on downstream slope
	21	Clogging	Failure in Level 1 Outtakes (FM 13-15)	Is it possible for level 1 outtakes to fail?	Lack of control of phreatic surface (potential rise in phreatic surface), increase in seepage, pond on reclamation surface, internal erosion, global instability, release of water into downstream shell, erosion on downstream slope
	22	Clogging surround (woven sock or sand and gravel bed)	Biological, chemical, or particulate clogging	Is it possible for the material surrounding the pipe to become clogged?	Lack of control of phreatic surface (potential rise in phreatic surface), increase in seepage, pond on reclamation surface, internal erosion, global instability, release of water into downstream shell, erosion on downstream slope
	23	Breakage of connection between a drain and outlet pipe	Overloading, degradation of connection, poor installation	How are the drain and outtake connected?	Lack of control of phreatic surface (potential rise in phreatic surface), increase in seepage, pond on reclamation surface, internal erosion, global instability, release of water into downstream shell, erosion on downstream slope
Outtakes - Level 2	24	Breakage of pipe	Break in pipe	Is the pipe capable of breaking?	Release of water into downstream shell, lack of control of phreatic surface (potential rise in phreatic surface), increase in seepage, pond on reclamation surface, internal erosion, global instability, erosion on downstream slope
	25	Breakage of pipe	Buckling	Is the pipe capable of buckling?	Release of water into downstream shell, lack of control of phreatic surface (potential rise in phreatic surface), increase in seepage, pond on reclamation surface, internal erosion, global instability, erosion on downstream slope
	26	Breakage of pipe	Physical degradation	Is the pipe capable of physically degrading over time?	Release of water into downstream shell, lack of control of phreatic surface (potential rise in phreatic surface), increase in seepage, pond on reclamation surface, internal erosion, global instability, erosion on downstream slope
	27	Clogging	Chemical or biological	Is chemical or biological clogging possible?	Failure to transmit water to perimeter ditch, clogging of level 2 drains, lack of control of phreatic surface (potential rise in phreatic surface), increase in seepage, pond on reclamation surface, internal erosion, global instability, release of water into downstream shell, erosion on downstream slope
	28	Clogging	particulate clogging (sediment from perimeter ditch or other)	Is sediment capable of clogging the pipe?	Failure to transmit water to perimeter ditch, clogging of level 2 drains, lack of control of phreatic surface (potential rise in phreatic surface), increase in seepage, pond on reclamation surface, internal erosion, global instability, release of water into downstream shell, erosion on downstream slope
	29	Blockage	Perimeter channel (FM 1-6) or other (snow, debris, etc.)	Is the pipe outlet close enough to the base of the perimeter channel that it could become blocked?	Failure to transmit water to perimeter ditch, clogging of level 2 drains, lack of control of phreatic surface (potential rise in phreatic surface), increase in seepage, pond on reclamation surface, internal erosion, global instability
Level 2 Drains	30	Breakage of pipe	Break in pipe	Is the pipe capable of breaking?	Lack of control of phreatic surface (potential rise in phreatic surface), increase in seepage, pond on reclamation surface, internal erosion, global instability, release of water into downstream shell, erosion on downstream slope

Element	Failure mode identification	Failure mode description	Potential trigger/cause	Screening assessment of failure mode	Failure effects
	31	Breakage of pipe	Buckling	Is the pipe capable of buckling?	Lack of control of phreatic surface (potential rise in phreatic surface), increase in seepage, pond on reclamation surface, internal erosion, global instability, release of water into downstream shell, erosion on downstream slope
	32	Breakage of pipe	Physical degradation	Is the pipe capable of physically degrading over time?	Lack of control of phreatic surface (potential rise in phreatic surface), increase in seepage, pond on reclamation surface, internal erosion, global instability, release of water into downstream shell, erosion on downstream slope
	33	Clogging	Chemical or biological	Is chemical or biological clogging possible?	Lack of control of phreatic surface (potential rise in phreatic surface), increase in seepage, pond on reclamation surface, internal erosion, global instability, release of water into downstream shell, erosion on downstream slope
	34	Clogging	Particulate clogging (sediment from perimeter ditch or other)	Is sediment capable of clogging the pipe?	Lack of control of phreatic surface (potential rise in phreatic surface), increase in seepage, pond on reclamation surface, internal erosion, global instability, release of water into downstream shell, erosion on downstream slope
	35	Clogging	Failure in Level 2 Outtakes (FM 27-29)	Is it possible for the level 2 outtakes to fail?	Lack of control of phreatic surface (potential rise in phreatic surface), increase in seepage, pond on reclamation surface, internal erosion, global instability, release of water into downstream shell, erosion on downstream slope
	36	Clogging surround (woven sock or sand and gravel bed)	Biological, chemical, or particulate clogging	Is it possible for the material surrounding the pipe to become clogged?	Lack of control of phreatic surface (potential rise in phreatic surface), increase in seepage, pond on reclamation surface, internal erosion, global instability, release of water into downstream shell, erosion on downstream slope
	37	Breakage of connection between a drain and outlet pipe	Overloading, degradation of connection, poor installation	How are the drain and outtake connected?	Lack of control of phreatic surface (potential rise in phreatic surface), increase in seepage, pond on reclamation surface, internal erosion, global instability, release of water into downstream shell, erosion on downstream slope
Foundation	38	Heave (seepage forces create zero effective stress condition)	Embankment loading, excessive rainfall, embankment seepage	What are the current hydraulic gradients and maximum possible due to geometry? What are the materials present? Are there cohesionless soils confined by an overlying lower permeability layer?	Global instability
	39	Vertical deformation from collapse of karst formation	Collapse of karst formation	Is there karst present in the foundation?	Cracking (transverse cracks - perpendicular to dam crest are larger problems than longitudinal cracks) in dam, internal erosion in dam, crest subsidence
	40	Vertical deformation caused by settlement of material	Consolidation	Will the materials in the foundation consolidate over time? How much consolidation has already occurred? Does the material have the potential to collapse?	Cracking (transverse cracks - perpendicular to dam crest are larger problems than longitudinal cracks) in dam, internal erosion in dam, crest subsidence
	41	Excessive/uncontrolled seepage through foundation or foundation/dam contact	Excessive rainfall	Is there potential for seepage through the foundation? What is the permeability of the materials?	Erosion of downstream toe, increase in porewater pressure in dam, global instability
	42	Shear failure along pre-existing shear plane from changing shear stress	Loading/unloading of foundation, earthquake, subsurface stress changes (geothermal development, in situ oil or gas production, wastewater injection, etc.)	Are there pre-existing shear planes? Is there the potential for anthropogenic loading or unloading events? Is the material erodible?	Slumping of downstream slope, translational slide, rotational slide, static liquefaction
	43	Shear failure along new shear plane from changing shear stress	Loading/unloading of foundation, earthquake, subsurface stress changes (geothermal development, in situ oil or gas production, wastewater injection, etc.)	Is there the potential for anthropogenic loading or unloading events? Is the material erodible?	Slumping of downstream slope, translational slide, rotational slide, static liquefaction
	44	Shear failure along pre-existing shear plane from changing shear strength	Degradation/weathering, porewater pressure change, progressive failure of strain softening materials, brittle failure of contractive materials	Are there pre-existing shear planes? Is there the potential for degradation or weathering of the material? Is the material strain softening or brittle?	Slumping of downstream slope, translational slide, rotational slide, static liquefaction
	45	Shear failure along new shear plane from changing shear strength	Degradation/weathering, porewater pressure change, progressive failure of strain softening materials, brittle failure of contractive materials	Is there the potential for degradation or weathering of the material? Is the material strain softening or brittle?	Slumping of downstream slope, translational slide, rotational slide, static liquefaction
	46	Internal erosion in foundation or dam/foundation contact from global backward erosion	Failure of soil above or around a backward erosion pipe to hold a roof, heave, high hydraulic gradients, design/construction defect, presence of non-plastic soils in the foundation	Are there non-plastic soils in the foundation?	Static liquefaction, global instability, unravelling/sloughing of downstream face, sub vertical cavities
	47	Internal erosion in foundation or dam/foundation contact from backward erosion piping	Heave, high hydraulic gradients, design/construction defect, presence of non-plastic soils that are capable of holding a roof	Are there non-plastic soils in the foundation and soils capable of 'holding a roof'?	Enlargement of pipe, global instability, static liquefaction
	48	Internal erosion in foundation or dam/foundation contact from contact erosion	Parallel flow in coarser layer to the interface between the coarse-grained and fine-grained soil, high hydraulic gradients, design/construction defect	Is there a contact between a coarse-grained and a fine-grained soil? Is the geometrical and hydraulic condition for contact erosion met?	Global instability, static liquefaction, settlement of the crest, loss of stability or unravelling, eroded material can clog the permeable layer and increase the porewater pressure (could result in hydraulic fracture and uplift of the downstream toe or a rise in the phreatic surface), development of a pipe
	49	Internal erosion in foundation or dam/foundation contact from suffusion	High hydraulic gradients, design/construction defect, presence of widely gap-graded or non-plastic gap-graded soils	Is the material widely gap-graded or gap-graded non plastic?	Global instability, seepage on the downstream slope, settlement of the crest, permeability may increase as erosion progresses or decrease if clogging occurs
	50	Internal erosion in foundation or dam/foundation contact from concentrated leak	Fracture in foundation soil, hydraulic fracture, high hydraulic gradient, cracks at dam/foundation contact from vertical deformation in foundation or poor construction practices or differential settlement, design/construction defects	Is there a crack or gap that could allow for a concentrated leak to develop?	Global instability, development of a pipe
	51	Thawing of foundation permafrost	Climate change	Is there permafrost in the foundation?	Cracking (transverse cracks - perpendicular to dam crest are larger problems than longitudinal cracks) in dam, piping in dam, crest subsidence

Element	Failure mode identification	Failure mode description	Potential trigger/cause	Screening assessment of failure mode	Failure effects
Starter Dyke	52	Vertical deformation (differential or otherwise) from consolidation	Consolidation/settlement	Does the material have the potential to consolidate? How much consolidation has occurred already? How much is expected to occur?	Release of pore water and loss of height (potential for pond to develop on reclamation surface), development of cracks above starter dyke, internal erosion, overtopping
	53	Seismic liquefaction	Earthquakes, induced seismicity, construction traffic, blasting	Seismic events in area? Induced seismicity? Density of material (contractive or dilative)? Saturated or unsaturated? Hydraulically placed or compacted?	Global instability
	54	Static liquefaction from changing shear stress	Loading/unloading; overloading, including increasing the load, construction activities at the crest, fill placement at toe; over steepening of downstream slope or toe, including erosion or excavation (slumping of downstream slope from shear failure); foundation shear (FM 42-45), surface erosion of cell sand or berm on downstream slope (FM 74-75, 87-89); excessive and uncontrolled seepage through foundation resulting in erosion of toe (FM 41); slumping of downstream slope from shear failure (FM 42-45, 58, 59, 69, 70, 82, 83, 96, 97, 107, 108)	Density of material (contractive or dilative)? Hydraulically placed or compacted? Saturated or unsaturated? Is there a likelihood for anthropogenic contributions in the future (i.e., unexpected construction)? Is the site remote? What is the material of the downstream slope? Is there a nearby river?	Global instability
	55	Static liquefaction from changing mean effective stress	Change in pore pressures caused by a phreatic surface change (failure of level 1 and level 2 drains (FM 16-23 and 30-37))	Density of material (contractive or dilative)? Saturated or unsaturated? Hydraulically placed or compacted? Does control of the phreatic surface rely on drain function? Could drains become clogged or fail in the future?	Global instability
	56	Static liquefaction from long-term change in material properties resulting in changing shear strength	Changing shear strength caused by degradation/weathering, progressive failure, porewater pressure change, failure of level 1 and level 2 drains (FM 16-23 and 30-37)	Density of material (contractive or dilative)? Hydraulically placed or compacted? Saturated or unsaturated? To what extent could weathering or degradation of the material occur? Will it result in an increase or decrease in strength? Will a change in the phreatic surface impact the strength of the material?	Global instability
	57	Static liquefaction from changing shear stress and mean effective stress	Lateral extrusion	Density of material (contractive or dilative)? Hydraulically placed or compacted? Saturated or unsaturated? Weak layers interbedded in tailings? Could the tailings 'squish' out like toothpaste during loading?	Global instability
	58	Shear failure from changing shear stress	Loading/unloading crest, toe, upstream, downstream; surface erosion of cell sand or berm on downstream slope (FM 74-75, 87-89); excessive and uncontrolled seepage through foundation resulting in erosion of toe (FM 41)	Is there potential for anthropogenic contributions (i.e., excavations or construction)? Erodibility of material?	Slumping of downstream slope, translational slide, rotational slide
	59	Shear failure from changing shear strength	Degradation/weathering, porewater pressure change, change in permeability over time, failure of drains, progressive failure of strain softening materials, brittle failure of contractive materials, failure of level 1 and level 2 drains (FM 16-23 and 30-37)	Is there potential for weathering or degradation of materials? Does the porewater pressure rely on drain performance? Could drains fail over time? Are the materials strain softening or brittle?	Slumping of downstream slope, translational slide, rotational slide
	60	Internal erosion in dam from contact erosion	Parallel flow in coarser layer to the interface between the coarse-grained and fine-grained soil, high hydraulic gradients, design/construction defects	Is there a contact between a coarse and fine-grained soil? Is there a filter in place?	Global instability, static liquefaction, settlement of the crest, loss of stability or unravelling, eroded material can clog the permeable layer and increase the porewater pressure (could result in hydraulic fracture and uplift of the downstream toe or a rise in the phreatic surface), development of a pipe
	61	Internal erosion in dam from suffusion	High hydraulic gradients, design/construction defect, presence of widely gap-graded or non-plastic gap-graded soils	Is the material widely gap-graded or gap-graded non plastic?	Global instability, seepage on the downstream slope, settlement of the crest, permeability may increase as erosion progresses or decrease if clogging occurs
	62	Internal erosion in dam - concentrated leak	Cracks from foundation (FM 39-40, 51), tunnels created by burrowing animals, hydraulic fracture, high hydraulic gradient, design/construction defects	Is there a crack or gap that could allow for a concentrated leak to develop?	Global instability, development of a pipe
Cell Sand	63	Vertical deformation (differential or otherwise) from consolidation	Consolidation/settlement	Does the material have the potential to consolidate? How much consolidation has occurred already? How much is expected to occur?	Release of porewater and loss of height (potential for pond to develop on reclamation surface), development of cracks, internal erosion
	64	Seismic liquefaction	Earthquakes, induced seismicity, construction traffic, blasting	Seismic events in area? Induced seismicity? Density of material (contractive or dilative)? Saturated or unsaturated? Hydraulically placed or compacted?	Global instability

Element	Failure mode identification	Failure mode description	Potential trigger/cause	Screening assessment of failure mode	Failure effects
	65	Static liquefaction from changing shear stress	Loading/unloading; overloading, including increasing the load, construction activities at the crest, fill placement at toe; over steepening of downstream slope or toe, including erosion or excavation (slumping of downstream slope from shear failure); foundation shear (FM 42-45); shear in the starter dyke (FM 58-59); surface erosion of cell sand or berm on downstream slope (FM 74-75. 87-89); excessive and uncontrolled seepage through foundation resulting in erosion of toe (FM 41); slumping of downstream slope from shear failure (FM 42-45, 58, 59, 69, 70, 82, 83, 96, 97, 107, 108)	Density of material (contractive or dilative)? Hydraulically placed or compacted? Saturated or unsaturated? Is there a likelihood for anthropogenic contributions in the future (i.e., unexpected construction)? Is the site remote? What is the material of the downstream slope? Is there a nearby river?	Global instability
	66	Static liquefaction from changing mean effective stress	Change in pore pressures caused phreatic surface change (i.e., failure of level 1 and level 2 drains (FM 16-23 and 30-37))	Density of material (contractive or dilative)? Saturated or unsaturated? Hydraulically placed or compacted? Does control of the phreatic surface rely on drain function? Could drains become clogged or fail in the future?	Global instability
	67	Static liquefaction from long-term change in material properties resulting in changing shear strength	Change in shear strength caused by degradation/weathering, progressive failure, porewater pressure change, failure of level 1 and level 2 drains (FM 16-23 and 30-37)	Density of material (contractive or dilative)? Hydraulically placed or compacted? Saturated or unsaturated? To what extent could weathering or degradation of the material occur? Will it result in an increase or decrease in strength? Will a change in the phreatic surface impact the strength of the material?	Global instability
	68	Static liquefaction from changing shear stress and mean effective stress	Lateral extrusion	Density of material (contractive or dilative)? Hydraulically placed or compacted? Saturated or unsaturated? Weak layers interbedded in tailings? Could the tailings 'squish' out like toothpaste during loading?	Global instability
	69	Shear failure from changing shear stress	Loading/unloading crest, toe, upstream, downstream; surface erosion of berm on downstream slope (FM 87-89); excessive and uncontrolled seepage through foundation resulting in erosion of toe (FM 41)	Is there potential for anthropogenic contributions (i.e., excavations or construction)? Erodibility of material?	Slumping of downstream slope, translational slide, rotational slide
	70	Shear failure from changing shear strength	Degradation/weathering, porewater pressure change, change in permeability over time, failure of drains, progressive failure of strain softening materials, brittle failure of contractive materials, failure of level 1 and level 2 drains (FM 16-23 and 30-37)	Is there potential for weathering or degradation of materials? Does the porewater pressure rely on drain performance? Could drains fail over time? Are the materials strain softening or brittle?	Slumping of downstream slope, translational slide, rotational slide
	71	Internal erosion in dam from contact erosion	Parallel flow in coarser layer to the interface between the coarse-grained and fine-grained soil, high hydraulic gradients, design/construction defects	Is there a contact between a coarse and fine-grained soil? Is there a filter in place?	Global instability, static liquefaction, settlement of the crest, loss of stability or unravelling, eroded material can clog the permeable layer and increase the porewater pressure (could result in hydraulic fracture and uplift of the downstream toe or a rise in the phreatic surface), development of a pipe
	72	Internal erosion in dam from suffusion	High hydraulic gradients, design/construction defect, presence of widely gap-graded or non-plastic gap-graded soils	Is the material widely gap-graded or gap-graded non plastic?	Global instability, seepage on the downstream slope, settlement of the crest, permeability may increase as erosion progresses or decrease if clogging occurs
	73	Internal erosion in dam from concentrated leak	Cracks from vertical deformation in foundation (FM 39-40, 51), cracks from vertical deformation in starter dyke (FM 52), cracks from vertical deformation in BAW (FM 90), cracks from vertical deformation in BBW (FM 101), tunnels created by burrowing animals, hydraulic fracture, high hydraulic gradient, design/construction defects	Is there a crack or gap that could allow for a concentrated leak to develop?	Global instability, development of a pipe
	74	Surface erosion from wind and overland flow resulting in rills, gullies, or sheet erosion	Destruction of vegetation (FM 112), rainfall, melting of snow, wind, increased seepage on downstream slope from failure of drainage system, increased seepage from internal erosion in embankment	Is the material susceptible to erosion? Is there a vegetative cover or erosion protection?	Slope failures (shallow surficial movement, slumps), change in downstream slope angle, blockage in perimeter channel with sediment, development of negative drainage, development of large erosion scarps
	75	Surface erosion - spring sapping (headward erosion of gullies due to concentration of seepage forces at the locus of the gully, which accentuates erosion)	Destruction of vegetation (FM 112), increased seepage on downstream slope from failure of level 1 or 2 drains (FM 10-37), increased seepage from internal erosion of starter dyke, cell sand, BAW, BBW (FM 60-61, 71-72, 98-99, 109-110)	Is the material susceptible to erosion? Is there a vegetative cover or erosion protection? Will seepage daylight on the downstream slope?	Slope failures (shallow surficial movement, slumps), change in downstream slope angle, blockage in perimeter channel with sediment, development of negative drainage, development of large erosion scarps
Berm	76	Vertical deformation (differential or otherwise) from consolidation	Consolidation/settlement	Does the material have the potential to consolidate? How much consolidation has occurred already? How much is expected to occur?	Release of pore water and loss of height (potential for pond to develop on reclamation surface), development of cracks, internal erosion
	77	Seismic liquefaction	Earthquakes, induced seismicity, construction traffic, blasting	Seismic events in area? Induced seismicity? Density of material (contractive or dilative)? Saturated or unsaturated? Hydraulically placed or compacted?	Global instability
	78	Static liquefaction from changing shear stress	Loading/unloading; overloading, including increasing the load, construction activities at the crest, fill placement at toe; over steepening of downstream slope or toe, including erosion or excavation (slumping of downstream slope from shear	Density of material (contractive or dilative)? Hydraulically placed or compacted? Saturated or unsaturated? Is there a likelihood for anthropogenic	Global instability

Element	Failure mode identification	Failure mode description	Potential trigger/cause	Screening assessment of failure mode	Failure effects
			failure); foundation shear (FM 42-45); shear in the starter dyke (FM 58-59); shear in cell sand (FM 69-70); surface erosion of cell sand or berm on downstream slope (FM 74-75, 87-89); excessive and uncontrolled seepage through foundation resulting in erosion of toe (FM 41); slumping of downstream slope from shear failure (FM 42-45, 58, 59, 69, 70, 82, 83, 96, 97, 107, 108)	contributions in the future (i.e., unexpected construction)? Is the site remote? What is the material of the downstream slope? Is there a nearby river?	
	79	Static liquefaction from changing mean effective stress	Change in pore pressures caused by a phreatic surface change (failure of level 1 and level 2 drains (FM 16-23 and 30-37))	Density of material (contractive or dilative)? Saturated or unsaturated? Hydraulically placed or compacted? Does control of the phreatic surface rely on drain function? Could drains become clogged or fail in the future?	Global instability
	80	Static liquefaction from long-term change in material properties resulting in changing shear strength	Changing shear strength caused by degradation/weathering, progressive failure, porewater pressure change, failure of level 1 and level 2 drains (FM 16-23 and 30-37)	Density of material (contractive or dilative)? Hydraulically placed or compacted? Saturated or unsaturated? To what extent could weathering or degradation of the material occur? Will it result in an increase or decrease in strength? Will a change in the phreatic surface impact the strength of the material?	Global instability
	81	Static liquefaction from changing shear stress and mean effective stress	Lateral extrusion	Density of material (contractive or dilative)? Hydraulically placed or compacted? Saturated or unsaturated? Weak layers interbedded in tailings? Could the tailings 'squish' out like toothpaste during loading?	Global instability
	82	Shear failure from changing shear stress	Loading/unloading crest, toe, upstream, downstream; surface erosion of cell sand or berm on downstream slope (FM 74-75, 87-89); excessive and uncontrolled seepage through foundation resulting in erosion of toe (FM 41)	Is there potential for anthropogenic contributions (i.e., excavations or construction)? Erodibility of material?	Slumping of downstream slope, translational slide, rotational slide
	83	Shear failure from changing shear strength	Degradation/weathering; porewater pressure change, change in permeability over time, failure of drains, progressive failure of strain softening materials, brittle failure of contractive materials, failure of level 1 and level 2 drains (FM 16-23 and 30-37)	Is there potential for weathering or degradation of materials? Does the porewater pressure rely on drain performance? Could drains fail over time? Are the materials strain softening or brittle?	Slumping of downstream slope, translational slide, rotational slide
	84	Internal erosion in dam from contact erosion	Parallel flow in coarser layer to the interface between the coarse-grained and fine-grained soil, high hydraulic gradients, design/construction defects	Is there a contact between a coarse and fine-grained soil? Is there a filter in place?	Global instability, static liquefaction, settlement of the crest, loss of stability or unravelling, eroded material can clog the permeable layer and increase the porewater pressure (could result in hydraulic fracture and uplift of the downstream toe or a rise in the phreatic surface), development of a pipe
	85	Internal erosion in dam from suffusion	High hydraulic gradients, design/construction defect, presence of widely gap-graded or non-plastic gap-graded soils	Is the material widely gap-graded or gap-graded non plastic?	Global instability, seepage on the downstream slope, settlement of the crest, permeability may increase as erosion progresses or decrease if clogging occurs
	86	Internal erosion in dam from concentrated leak	Cracks from vertical deformation in foundation (FM 39-40, 51), cracks from vertical deformation in starter dyke (FM 52), cracks from vertical deformation in cell sand (FM 63)), tunnels created by burrowing animals, hydraulic fracture, high hydraulic gradient, design/construction defects	Is there a crack or gap that could allow for a concentrated leak to develop?	Global instability, development of a pipe
	87	Surface erosion from wind and overland flow resulting in rills, gullies, or sheet erosion	Destruction of vegetation (FM 112), rainfall, melting of snow, wind, increased seepage on downstream slope from failure of drainage system, increased seepage from internal erosion in embankment	Is the material susceptible to erosion? Is there a vegetative cover or erosion protection?	Slope failures (shallow surficial movement, slumps), change in downstream slope angle, blockage in perimeter channel with sediment, development of negative drainage, development of large erosion scarps
	88	Surface erosion from spring sapping (headward erosion of gullies due to concentration of seepage forces at the locus of the gully, which accentuates erosion)	Destruction of vegetation (FM 112); increased seepage on downstream slope from failure of level 1 or 2 drain system (FM 10-37); excessive erosion from internal erosion of berm, starter dyke, cell sand, BAW, BBW (FM 60-61, 71-72, 98-99, 109-110)	Is the material susceptible to erosion? Is there a vegetative cover or erosion protection? Will seepage daylight on the downstream slope?	Slope failures (shallow surficial movement, slumps), change in downstream slope angle, blockage in perimeter channel with sediment, development of negative drainage, development of large erosion scarps
	89	Toe erosion	Flow action from perimeter ditch or nearby river, release of a dam from a beaver, flood event, river changing course over time, destruction of vegetation (FM 110), excessive seepage and toe erosion (FM 41), excessive erosion from internal erosion (FM 84-85)	Is the material susceptible to erosion? Is there a vegetative cover or erosion protection? Is there a nearby perimeter ditch or river? Is there known animal activity in the area?	Slope failures (shallow surficial movement, slumps), change in downstream slope angle, blockage in perimeter channel with sediment, development of negative drainage, development of large erosion scarps, beaver bafflers
Beach above water	90	Vertical deformation (differential or otherwise) from consolidation	Consolidation/settlement	Does the material have the potential to consolidate? How much consolidation has occurred already? How much is expected to occur?	Release of pore water and loss of height (potential for pond to develop on reclamation surface), development of cracks, internal erosion
	91	Seismic liquefaction	Earthquakes, induced seismicity, construction traffic, blasting	Seismic events in area? Induced seismicity? Density of material (contractive or dilative)? Saturated or unsaturated? Hydraulically placed or compacted?	Global instability
	92	Static liquefaction from changing shear stress	Loading/unloading; overloading, including increasing the load, construction activities at the crest, fill placement at toe; over steepening of downstream slope or toe, including erosion or excavation (slumping of downstream slope from shear failure); foundation shear (FM 42-45); shear in the BBW (FM 107-108); surface erosion of cell sand or berm on downstream slope (FM 74-75, 87-89); excessive	Density of material (contractive or dilative)? Hydraulically placed or compacted? Saturated or unsaturated? Is there a likelihood for anthropogenic contributions in the future (i.e., unexpected construction)? Is the site remote? What is the	Global instability

Element	Failure mode identification	Failure mode description	Potential trigger/cause	Screening assessment of failure mode	Failure effects
			and uncontrolled seepage through foundation resulting in erosion of toe (FM 41); slumping of downstream slope from shear failure (FM 42-45, 58, 59, 69, 70, 82, 83, 96, 97, 107, 108)	material of the downstream slope? Is there a nearby river?	
	93	Static liquefaction from changing mean effective stress	Change in pore pressures caused by a phreatic surface change (failure of level 1 and level 2 drains (FM 16-23 and 30-37))	Density of material (contractive or dilative)? Saturated or unsaturated? Hydraulically placed or compacted? Does control of the phreatic surface rely on drain function? Could drains become clogged or fail in the future?	Global instability
	94	Static liquefaction from long-term change in material properties resulting in changing shear strength	Changing shear strength caused by degradation/weathering, progressive failure, porewater pressure change, failure of level 1 and level 2 drains (FM 16-23 and 30-37)	Density of material (contractive or dilative)? Hydraulically placed or compacted? Saturated or unsaturated? To what extent could weathering or degradation of the material occur? Will it result in an increase or decrease in strength? Will a change in the phreatic surface impact the strength of the material?	Global instability
	95	Static liquefaction from changing shear stress and mean effective stress	Lateral extrusion	Density of material (contractive or dilative)? Hydraulically placed or compacted? Saturated or unsaturated? Weak layers interbedded in tailings? Could the tailings 'squish' out like toothpaste during loading?	Global instability
	96	Shear failure from changing shear stress	Loading/unloading crest, toe, upstream, downstream; surface erosion of cell sand on downstream slope (FM 74-75), surface erosion of berm on downstream slope (FM 87-89); excessive and uncontrolled seepage through foundation resulting in erosion of toe (FM 41)	Is there potential for anthropogenic contributions (i.e., excavations or construction)? Erodibility of material?	Slumping of downstream slope, translational slide, rotational slide
	97	Shear failure from changing shear strength	Degradation/weathering, porewater pressure change, change in permeability over time, failure of drains, progressive failure of strain softening materials, brittle failure of contractive materials, failure of level 1 and level 2 drains (FM 16-23 and 30-37)	Is there potential for weathering or degradation of materials? Does the porewater pressure rely on drain performance? Could drains fail over time? Are the materials strain softening or brittle?	Slumping of downstream slope, translational slide, rotational slide
	98	Internal erosion in dam from contact erosion	Parallel flow in coarser layer to the interface between the coarse-grained and fine-grained soil, high hydraulic gradients, design/construction defects	Is there a contact between a coarse and fine-grained soil? Is there a filter in place?	Global instability, static liquefaction, settlement of the crest, loss of stability or unravelling, eroded material can clog the permeable layer and increase the porewater pressure (could result in hydraulic fracture and uplift of the downstream toe or a rise in the phreatic surface), development of a pipe
	99	Internal erosion in dam from suffusion	High hydraulic gradients, design/construction defect, presence of widely gap-graded or non-plastic gap-graded soils	Is the material widely gap-graded or gap-graded non plastic?	Global instability, seepage on the downstream slope, settlement of the crest, permeability may increase as erosion progresses or decrease if clogging occurs
	100	Internal erosion in dam - concentrated leak	Cracks from vertical deformation in BBW (FM 101), cracks from vertical cracks in foundation (FM 39-40, 50), tunnels created by burrowing animals, hydraulic fracture, high hydraulic gradient, design/construction defects	Is there a crack or gap that could allow for a concentrated leak to develop?	Global instability, development of a pipe
Beach below water	101	Vertical deformation (differential or otherwise) from consolidation	Consolidation/settlement	Does the material have the potential to consolidate? How much consolidation has occurred already? How much is expected to occur?	Release of pore water and loss of height (potential for pond to develop on reclamation surface), development of cracks, internal erosion
	102	Seismic liquefaction	Earthquakes, induced seismicity, construction traffic, blasting	Seismic events in area? Induced seismicity? Density of material (contractive or dilative)? Saturated or unsaturated? Hydraulically placed or compacted?	Global instability
	103	Static liquefaction from changing shear stress	Loading/unloading; overloading, including increasing the load, construction activities at the crest, fill placement at toe; over steepening of downstream slope or toe, including erosion or excavation (slumping of downstream slope from shear failure); foundation shear (FM 42-45); surface erosion of cell sand or berm on downstream slope (FM 74-75, 87-89); excessive and uncontrolled seepage through foundation resulting in erosion of toe (FM 41); slumping of downstream slope from shear failure (FM 42-45, 58, 59, 69, 70, 82, 83, 96, 97, 107, 108)	Density of material (contractive or dilative)? Hydraulically placed or compacted? Saturated or unsaturated? Is there a likelihood for anthropogenic contributions in the future (i.e., unexpected construction)? Is the site remote? What is the material of the downstream slope? Is there a nearby river?	Global instability
	104	Static liquefaction from changing mean effective stress	Change in pore pressures caused by a phreatic surface change (failure of level 1 and level 2 drains (FM 16-23 and 30-37))	Density of material (contractive or dilative)? Saturated or unsaturated? Hydraulically placed or compacted? Does control of the phreatic surface rely on drain function? Could drains become clogged or fail in the future?	Global instability
	105	Static liquefaction from long-term change in material properties resulting in changing shear strength	Changing shear strength caused by degradation/weathering, progressive failure, porewater pressure change, failure of level 1 and level 2 drains (FM 16-23 and 30-37)	Density of material (contractive or dilative)? Hydraulically placed or compacted? Saturated or unsaturated? To what extent could weathering or degradation of the material occur? Will it result in an increase or decrease in strength? Will a change	Global instability

Element	Failure mode identification	Failure mode description	Potential trigger/cause	Screening assessment of failure mode	Failure effects
				in the phreatic surface impact the strength of the material?	
	106	Static liquefaction from changing shear stress and mean effective stress	Lateral extrusion	Density of material (contractive or dilative)? Hydraulically placed or compacted? Saturated or unsaturated? Weak layers interbedded in tailings? Could the tailings 'squish' out like toothpaste during loading?	Global instability
	107	Shear failure from changing shear stress	Loading/unloading crest, toe, upstream, downstream; surface erosion of cell sand on downstream slope (FM 74-75); surface erosion of berm on downstream slope (FM 87-89); excessive and uncontrolled seepage through foundation resulting in erosion of toe (FM 41)	Is there potential for anthropogenic contributions (i.e., excavations or construction)? Erodibility of material?	Slumping of downstream slope, translational slide, rotational slide
	108	Shear failure from changing shear strength	Degradation/weathering, porewater pressure change, change in permeability over time, failure of drains, progressive failure of strain softening materials, brittle failure of contractive materials, failure of level 1 and level 2 drains (FM 16-23 and 30-37)	Is there potential for weathering or degradation of materials? Does the porewater pressure rely on drain performance? Could drains fail over time? Are the materials strain softening or brittle?	Slumping of downstream slope, translational slide, rotational slide
	109	Internal erosion in dam from contact erosion	Parallel flow in coarser layer to the interface between the coarse-grained and fine-grained soil, high hydraulic gradients, design/construction defects	Is there a contact between a coarse and fine-grained soil? Is there a filter in place?	Global instability, static liquefaction, settlement of the crest, loss of stability or unravelling, eroded material can clog the permeable layer and increase the porewater pressure (could result in hydraulic fracture and uplift of the downstream toe or a rise in the phreatic surface), development of a pipe
	110	Internal erosion in dam from suffusion	High hydraulic gradients, design/construction defect, presence of widely gap-graded or non-plastic gap-graded soils	Is the material widely gap-graded or gap-graded non plastic?	Global instability, seepage on the downstream slope, settlement of the crest, permeability may increase as erosion progresses or decrease if clogging occurs
	111	Internal erosion in dam - concentrated leak	Cracks from vertical deformation in foundation (FM 39-40, 51), tunnels created by burrowing animals, hydraulic fracture, high hydraulic gradient, design/construction defects	Is there a crack or gap that could allow for a concentrated leak to develop?	Global instability, development of a pipe
Vegetative cover	112	Destruction of vegetation	Suffocation by eroded material, forest fires, pests and disease, climate change, large storm event, anthropogenic contributions, surface erosion in cell sand or berm (FM 74-75, FM 87-89), evolution of vegetation over time due to climate change	Does the resistance to erosion rely on the vegetation? Is the area susceptible to forest fires? Are there pests/disease that could lead to vegetation destruction? What is the downstream slope? Is the area remote? Are there surrounding communities that could lead to destruction of vegetation (i.e., recreational vehicles)?	Increase in surface erosion, instability of downstream slope, global instability, change in overall evapotranspiration and water balance impacts (infiltration versus runoff)
Cap (overburden and coarse sand tailings)	113	Excessive settlement	Consolidation	Does the material have the potential to settle over time?	Formation of ponds on reclamation surface, overtopping, piping (increase in seepage forces and gradients)
	114	Differential settlement	Consolidation, poor construction practices	Does the material have the potential to settle over time? Are there areas that have the potential to settle more that others?	Formation of ponds on reclamation surface, failure to direct surface water runoff towards drainage channels, development of cracks, formation of preferential flow paths, localized depressions, increased infiltration, increased phreatic surface
Infilled coarse sand tailings mixed with FFT	115	Excessive settlement	Consolidation	Does the material have the potential to settle over time?	Formation of ponds on reclamation surface, overtopping, piping (increase in seepage forces and gradients)
	116	Differential settlement	Consolidation, poor construction practices	Are there areas that have the potential to settle more than others?	Formation of ponds on reclamation surface, overtopping, piping (increase in seepage forces and gradients), failure of drainage channels to behave as intended, localized depressions
Hummocks	117	Shear failure from changing shear stress	Loading/unloading crest, toe, surface erosion on slopes, failure of underlying material to support hummock	Is there potential for anthropogenic contributions (i.e., excavations or construction)? Erodibility of material?	Slumping, translational slide, rotational slide, blockage of drainage channels
	118	Shear failure from changing shear strength	Degradation/weathering, porewater pressure change, change in permeability over time, failure of drains, progressive failure of strain softening materials, brittle failure of contractive materials	Is there potential for weathering or degradation of materials? Are the materials strain softening or brittle?	Slumping of slopes, translational slide, rotational slide, blockage of drainage channels
	119	Surface erosion from wind and overland flow resulting in rills, gullies, or sheet erosion	Destruction of vegetation, rainfall, melting of snow, wind	Is the material susceptible to erosion? Is there a vegetative cover or erosion protection?	Slope failures (shallow surficial movement, slumps), change in downstream slope angle, blockage in drainage channel with sediment, development of negative drainage, development of large erosion scarps
Drainage channels	120	Washout of erosion protection (riprap)	Precipitation event larger than design events (including extreme or repeat events)	What precipitation event are the channels designed for? What is the chance of exceedance over 1000 years? How susceptible are the underlying materials to erosion?	Excessive erosion (erosion gullies etc.), change in slope of drainage channels, erosion and release of materials underlying drainage channels

Element	Failure mode identification	Failure mode description	Potential trigger/cause	Screening assessment of failure mode	Failure effects
	121	Blockage (complete or partial)	Debris, beaver dam, icing, sedimentation, slumping from slope failure, ingress of vegetation, slope failure/excessive erosion from nearby hummock	Are there beavers in the area? Is there a chance for a slope failure? Could debris be carried downstream and deposited in the channels resulting in a complete or partial blockage? Is the mine located in an area that could experience icing?	Formation of a pond upstream of the drainage channel, blockage breakthrough resulting in flooding, overtopping from pond formation, revert back to a pond, piping through dam (increase in seepage forces and gradient)
	122	Sand channel buoyancy	Freezing conditions in channels composed of sand	Are the drainage channels constructed of sand? Could the channel experience freezing?	Flooding
	123	Erosion control failure	Improper design/construction, differential settlement	Do the drainage channels rely on erosion control for stability? Is there the chance for differential settlement of the channel?	Excessive erosion (erosion gullies etc.), change in slope of drainage channel, erosion and release of materials underlying drainage channel, formation of secondary channel
Outlet	124	Washout of erosion protection (riprap)	Precipitation event larger than design event (including extreme or repeat events), flood following sand channel buoyancy event in drainage channel	What precipitation event is the outlet designed for? What is the chance of exceedance over 1000 years? How susceptible are the underlying materials to erosion?	Excessive erosion (erosion gullies etc.), change in slope of outlet, erosion and release of materials underlying outlet
	125	Blockage (complete or partial)	Debris, beaver dam, icing, sedimentation, slumping from slope failure, ingress of vegetation, increase in depositional material due to failure of erosion protection in drainage channels upstream	Are there beavers in the area? Is there a chance for a slope failure? Could debris be carried downstream and deposited in the outlet resulting in a complete or partial blockage? Is the mine located in an area that could experience icing?	Formation of a pond upstream of the outlet, blockage breakthrough resulting in flooding, overtopping from pond formation, revert back to a pond, piping through dam (increase in seepage forces and gradient)
	126	Sand channel buoyancy	Freezing conditions in channels composed of sand	Is the outlet constructed of sand? Could the channel experience freezing?	Flooding
	127	Erosion control failure	Improper design/construction, differential settlement	Does the outlet rely on erosion control for stability? Is there the chance for differential settlement of the channel?	Excessive erosion (erosion gullies etc.), change in slope of outlet, erosion and release of materials underlying outlet, formation of secondary channel
Vegetative cover	128	Destruction of vegetation	Suffocation by eroded material, forest fires, pests and disease, climate change, large storm event, anthropogenic contributions,	Does the resistance to erosion rely on the vegetation? Is the area susceptible to forest fires? Are there pests/disease that could lead to vegetation destruction? Is the area remote? Are there surrounding communities that could lead to destruction of vegetation (i.e., recreational vehicles)?	Increase in surface erosion, deposition of material in drainage channels that could lead to a blockage via sedimentation, development of negative drainage on reclamation surface, ponding of water near dam crest, internal erosion (increase in seepage forces and hydraulic gradient)

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6 EVOLUTION OF PHREATIC SURFACE

An assessment was conducted to evaluate how the phreatic surface may evolve in a tailings dam over time in response to different scenarios to assess the susceptibility to failure in the long term as a way of reducing uncertainty in the evaluation of closure strategies. The assessment aims to evaluate a commonly made assumption that the phreatic surface of a reclaimed tailings dam will decrease over time. This was a major area of uncertainty identified during the interviews discussed in Section 3. The assessment involved a detailed literature review (outlined in Section 6.1) and seepage modelling (outlined in Section 6.2) to evaluate how the phreatic surface changed in the long term. This was used to provide guidance on areas of uncertainty that may impact such an assumption and recommendations on what information should be collected and considered when evaluating the long-term evolution of the phreatic surface.

This assessment was used to develop a framework of the elements that must be considered in making assumptions regarding the evolution of the seepage system in a tailings dam in the long term as discussed in Section 6.3.2.

6.1 Literature Review

A literature review was conducted to evaluate published data on long-term phreatic surface changes. Overall, there is a major literature gap with regard to publications that document the behaviour of tailings dams following reclamation and compare them to the anticipated behaviour. This gap should be addressed by industry by actively sharing successes and failures following closure with accompanying learnings for improvement. Szymanski and Davies (2004) provides an overview of challenges and design criteria associated with tailings dam closure. In doing so, they note that some practitioners may take comfort knowing that certain factors may improve stability, such as the water level lowering (Szymanski and Davies 2004); however they also acknowledge that “chemical reactions in a tailings deposit may result in a long-term rise of the phreatic surface and/or perched water table as a result of ‘hardpan’ formation (the authors conducted a dam safety review in 2003 at a mine site where such a rise was already observed during the production phase)” (Szymanski and Davies 2004). Unfortunately, these references to long-term changes in tailings dams are not common in literature. To aid in mitigating this, publicly available dam safety information (including dam safety inspection (DSI) reports, geotechnical annual reports, external reviews of DSIs, and annual reclamation reports) for closed tailings storage facilities in British Columbia were reviewed. The intent of this exercise was to investigate if there were any tailings dams that showed a sustained decrease in the phreatic surface over time and if any dams reported changes in the phreatic surface level with external changes.

The mines listed in Table 6-1 represent mines with TSFs that are listed as ‘Closed Care and Maintenance’, ‘Closed Reclamation Long-term Maintenance and Water Treatment’, and ‘Closed Reclamation Long-term Maintenance’ by the British Columbia Ministry of Energy, Mines, and Low Carbon Innovation. This list is not exhaustive as the Ministry notes that more mines and related documents are added on an ongoing basis and is representative of information available at the time of the review (review completed March 2022). A number of mines (27 out of 40) were excluded from the review for various reasons, including (but not limited to): no instrumentation data, no discernable trends based on when the facility was closed, water covers, or ponds with plans for reopening. Unfortunately, there are several facilities that have been closed for many years with no instrumentation data or information on how the phreatic surface has changed over time. Some examples include the TSFs at Boss Mountain Mine, Golden Bear Mine, Red Mountain Mine, and Gallowai Bull River Mine. These facilities represent missed learning opportunities for the industry as a whole. Some of these facilities have still been included in the review if the relevant reports included sufficient observations.

Table 6-1: Closed mines in British Columbia with available dam safety information as per Ministry of Energy, Mines, and Low Carbon Innovation (review of database completed March 2022)

Mine	Status	Included in Review? (Y/N)	Reason for Exclusion (if applicable)
Basin Coal Mine	Closed care and maintenance	N	No instrumentation data.
Beaverdell Mine	Closed reclamation long-term maintenance	N	Historical piezometers non-functional. New piezometers not installed until 2019. Not enough data to make any conclusions.
Bell Mine	Closed reclamation long-term maintenance and water treatment	N	Pond present.
Blackdome Mine	Closed reclamation long-term maintenance	N	Pond present.
Boss Mountain Mine	Closed reclamation long-term maintenance	N	No instrumentation data.

Mine	Status	Included in Review? (Y/N)	Reason for Exclusion (if applicable)
Bralorne Gold Mine	Closed reclamation long-term maintenance and water treatment	N	Facility is in care and maintenance with construction occurring up to 2015 with emergency spillway and dam raises. Not enough data to evaluate any long-term trend.
Brenda Mine	Closed reclamation long-term maintenance and water treatment	N	Water cover.
Bullmoose Mine	Closed reclamation long-term maintenance	Y	N/A
Dankoe Mine	Closed reclamation long-term maintenance	Y	N/A
Endako Mine	Closed care and maintenance	N	Pond present at all TSFs.
Equity Silver Project	Closed reclamation long-term maintenance and water treatment	N	Water cover.
Eskay Creek Mine	Closed reclamation long-term maintenance and water treatment	N	Tailings stored in natural lakes. No tailings dams.
Gallowai Bull River Mine	Closed care and maintenance	Y	N/A
Giant Nickel Mine	Closed reclamation long-term maintenance	Y	N/A
Golden Bear Mine	Closed reclamation long-term maintenance	Y	N/A
Goldstream Mine	Closed care and maintenance	N	Pond present.
Granisle Mine	Closed reclamation long-term maintenance and water treatment	N	No instrumentation.
Greenwood (Zip)	Closed care and maintenance	Y	N/A
HB Tailings Landfill	Closed unknown	N	Detailed closure and reclamation plan completed for facility in 2019. Watch this site for future progression.
Huckleberry Mine	Closed care and maintenance	N	TMF-2 is considered to be in a transition and closure-active care phase, but it does still have a pond present.
Johnny Mountain Mine	Closed reclamation long-term maintenance	N	Pond present.
Kemess	[1]Not started	N	Activities are currently focused on implementation of the reclamation and closure plan.
Ladner Creek Mine	Closed reclamation long-term maintenance	N	Pond present.
Max Moly Mine	Closed care and maintenance	N	Pond present.
May Mac Mine	Closed reclamation long-term maintenance	Y	N/A
Mount Polley Mine	Closed care and maintenance	N	Pond present.

Mine	Status	Included in Review? (Y/N)	Reason for Exclusion (if applicable)
Nickel Plate Mine	Closed reclamation long-term maintenance and water treatment	Y	N/A
Pinchi Lake Mine	Closed reclamation long-term maintenance	Y	N/A
Premier	Closed reclamation long-term maintenance and water treatment	N	Pond present.
Quinsam Coal Mine	Closed care and maintenance	N	Pond present.
Quintette Mine - Shikano	Closed care and maintenance	N	Pond present.
Quintette Mine - Plantsite	Closed care and maintenance	Y	N/A
Red Mountain (Good Friday and Jumbo)	[2]Not listed	Y	N/A
Sable/Shasta Mine	Closed care and maintenance	N	Pond present. Instrumentation not installed until 2017.
Samatosum	Closed reclamation long-term maintenance and water treatment	N	Water cover.
Silvana	Closed care and maintenance	Y	N/A
Sullivan Mine	Closed reclamation long-term maintenance and water treatment	Y	N/A
Table Mountain Gold	Closed care and maintenance	N	No instrumentation.
Taurus Gold	Closed	N	No instrumentation.
Yellowjacket Gold Mine	Closed care and maintenance	N	No instrumentation.

Notes: [1]Listed on the Ministry of Energy, Mines, and Low Carbon Innovation as 'Not Started', but the 2020 DSI indicates that mining and milling was completed in 2011 after 13 years of operation (Wood 2021). [2]Red Mountain Mine no longer appears in the list of facilities with available information.

Bullmoose Mine has a TSF with a reclaimed tailings surface with a pond on one side of the impoundment (KCB 2021a). The facility was reclaimed in 2003 (KCB 2021a). One piezometer has been showing a gradual decreasing trend since 2014, which has been taken to be evidence of drain down (KCB 2021a). Other piezometers installed in the foundation and fill at the downstream toe showed an increase in 2020, which is thought to be due to heavy rainfall that may have temporarily raised the water level (KCB 2021a). This rise was not taken to be indicative of a rise in the phreatic surface as other instruments installed mid-slope were stable or decreasing over the same period (KCB 2021a).

The TSF at Dankoe Mine ceased operations in 1989, and the tailings surface is dry with no indication that a significant amount of water ponds on the surface (Lighthall 2021a). There were no formal dam safety inspections from 1990 to 2014 (Lighthall 2021a). The piezometers were dry at the most recent available reading (November 2015 and October 2016) (Lighthall 2021a) and had previously decreased during 1970-1990 to dry as indicated by variable measurements in 1970, 1973, and 1990 (Lighthall 2014). It should be noted that this facility is underlain by pervious alluvial fan material (Lighthall 2014). Lighthall (2021a) recommends that the TSF be re-classified as a landform as "it is well demonstrated by its performance over the past 28 years since operations ceased that the facility is completely stable and represents no hazard to the public or the environment. There is no reason or benefit to ongoing monitoring or reporting on this facility".

Gallowai Bull River Mine has a TSF that was constructed from 1970 to 1971 and reclaimed approximately 4 to 5 years later (SNC Lavalin 2021). The tailings were covered, re-vegetated, and are considered dry (SNC Lavalin 2021). There is no instrumentation at this facility; however, the toe of the dam is reported to be dry and shows no evidence of seepage or vegetation associated with moist areas (SNC Lavalin 2021). SNC Lavalin (2021) notes that the facility is functioning more as a drained mine waste dump and that "the stored materials are considered to be consolidated and not at risk of failing in a flow type of movement".

Giant Nickel Mine ceased operations in 1974 and does not currently have a site presence (Knight Piesold Ltd. 2021a). The facility has two TSFs: the Lower TSF and the Upper TSF, which are considered to be in the passive care phase (Knight Piesold Ltd. 2021a). Reclamation work was completed on the Lower TSF at the end of 2018 (Knight Piesold Ltd. 2021a). Piezometers weren't installed until 2016 (Knight Piesold Ltd. 2021a). Overall, there are not enough data or time to make conclusions on long-term trends. However, as a reclaimed, instrumented site, the facilities at Giant Nickel Mine will be important to watch and learn from.

The Golden Bear Mine was closed and reclaimed in 2004 (Knight Piesold Ltd. 2014a). The TSF is considered to be in the passive care phase, and has no operating personnel or regular surveillance (Knight Piesold Ltd. 2014a). The site does not have any instrumentation; however, the cover has remained dry and firm with vegetation established on the surface (Knight Piesold Ltd. 2014a). There have not been any signs of erosion from surface water runoff (Knight Piesold Ltd. 2014a).

The Greenwood TSF has been in care and maintenance since 2008 (Lighthall 2020). This facility is different from other closed TSFs reported here in that it still has a pond and is completely lined by a geomembrane (Lighthall 2020). The 2019 DSI indicates that the piezometers are dry or stable at depths within the foundation, which indicates that there is no phreatic surface in the embankment (Lighthall 2020).

May Mac Mine has been inactive since 1985 (Lighthall 2021b). According to the 2020 DSI, the TSF has not had any care for more than 30 years and appears to be in satisfactory condition (Lighthall 2021b). The facility has not been intentionally reclaimed, but there is established vegetation and no active pond (Lighthall 2021b). Again, this facility represents a lost learning opportunity in the absence of historical instrumentation.

The Nickle Plate Mine has not been in operation since 1996, and the TSF is inactive, reclaimed, and is considered to be in the active closure phase (Knight Piesold Ltd. 2021b). The TSF tailings surface was capped in 1998 and has one area (former decant pond) that was not capped and stores a small volume of surface water (Knight Piesold Ltd. 2021b). The 2020 DSI indicated that there were a few vibrating wire piezometers (VWPs) that showed elevated PWPs that are above the trigger levels, which is not considered new (Knight Piesold Ltd. 2021b). In response, a buttress is planned to be constructed (Knight Piesold Ltd. 2021b). The 2017 DSI indicated that the long-term VWPs in the tailings embankment showed a seasonal fluctuation, and VWPs in the tailings deposit have been relatively stable with some seasonal fluctuation (Knight Piesold Ltd. 2018). The 2017 DSI noted that there was a "slight upward trend in the last three years, although the current readings are within the historical range of the piezometers" (Knight Piesold Ltd. 2018). The 2014 DSI noted that higher than normal phreatic surfaces were noted during freshet in some of the tailings embankment piezometers, which was attributed to "higher than normal precipitation and higher snowfall conditions at the site over the last three years has resulted in a general rise of the phreatic surface within the tailings facility" (Knight Piesold Ltd. 2014b). The Nickel Plate Mine shows the importance of long-term monitoring to understand porewater pressures within the TSFs. While a slight upward trend may not be concerning at this facility, it could be a cause for concern at another facility if it was combined with other external or internal changes to the dam facility, such as drains failing.

Pinchi Lake Mine has been in care and maintenance since 1975 (KCB 2020a). Reclamation and closure works on the TSF were completed in 2011, which included a glacial till cover and vegetation on the tailings surface (KCB 2020a). Prior to the installation of the piezometers in 2016, no instruments had been read since 2008; however, the 2020 DSI indicates that "the piezometric levels in the dam have gone down compared to the condition before the pond was drained" (KCB 2020a).

The Plantsite Tailings Dam at the Quintette Mine is considered to be in the active care phase and has been largely inactive since 1997 except for the construction of a closure spillway built from 2001 to 2002 (KCB 2020b). The 2016 DSI indicates that recent piezometer readings from the embankment are lower than when the facility was in operation (KCB 2016b).

Red Mountain Mine operated from 1966 to 1972, and there has been no construction at the TSFs (Good Friday and Jumbo) since 2004 when reclamation was completed (KCB 2014b). The instrumentation has not been read at the site since 2004 (KCB 2014b). The 2014 DSI suggests that the previously measured instrumentation data shows a reduction in the water levels in 2004 compared to earlier data based on a historical review (KCB 2014b).

The Silvana Mine has been in care and maintenance since 2010, and the tailings management facility (TMF) has not been in use since 2010, except for a 6-month period in 2013 (Tetra Tech Canada Inc. 2021). The TSF is partly covered with vegetation and has 5 standpipe piezometers (Tetra Tech Canada Inc. 2021). The 2016 DSI indicates that "… historical water level readings, along with a graph comparing water level readings from the past 20 years (APPENDIX A) indicates that water levels have been up to 2 m higher during active operations at the Silvana Mine TMF than when operations were inactive" (Golder Associates Ltd. 2016).

The Sullivan Mine was closed at the end of 2001, and the reclamation work on the tailings areas was formally initiated in 1990 and was mostly complete by 2008 (KCB 2021b). There are five TSFs (Iron TSF, Old Iron TSF, Silicious TSF, Gypsum TSF, and Calcine TSF), all of which are reclaimed except for the Iron TSF (KCB 2021b). The reclaimed TSFs have instrumentation installed, which generally shows a stable or decreasing piezometric level (some exceptions show a slight increase) (KCB 2021b). The three standpipe piezometers at the Calcine TSF were last read in 2004 and were noted to have been dry since 1986 (KCB 2021b).

The DSI review for TSFs in BC showed that there are facilities that seem to be demonstrating decreases in the phreatic surface over time following the removal of a pond from the tailings surface. However, for some of these facilities, this evidence is anecdotal due to a lack of long-term instrumentation. In some cases, the TSFs have not had monitoring or a site presence for a period of time and have not shown signs of instability. This information is encouraging; however, it would be beneficial to know how the phreatic surfaces (and TSFs in general) have changed over time in comparison to the design predictions. There are also some facilities that have shown an increase in piezometer readings in recent years with one being suspected to be due to increased precipitation and snowfall (Nickel Plate Mine). It is not possible to make conclusions about long-term phreatic surface conditions; however, the review does show that further research is needed to understand long-term phreatic surface changes.

As noted, there is not much literature related to how TSFs behave in the long term, but there has been an increasing push in industry for comprehensive monitoring plans in closure, such as Crossley et al. (2011) and Adamo et al. (2020). Such a change in industry should hopefully lead to an increase in the body of published literature on how TSFs behave following closure. There has also been an increase in literature published showing closure plans and construction of closure landforms (e.g., Adams et al. (2017), Adams et al. (2019), and Sotil et al. (2020)). These types of case studies could benefit industry greatly by being followed up with further publications showing how the constructed landforms are performing over time in comparison to the expected performance.

6.2 Numerical Modelling

An oil sands tailings dam was used as a case study to conduct two-dimensional numerical seepage modelling using SEEP/W in the GeoStudio 2019 R2 software package (GEO-SLOPE International Ltd. 2015). Modelling has the ability to enhance engineering judgement with regard to assessing the long-term phreatic surface of a tailings dam. The primary reasons to model include: making quantitative predictions, comparing alternatives, identifying governing parameters, and understanding processes to train our thinking (GEO-SLOPE International Ltd. 2015). Identifying why a modelling exercise is being conducted and the associated objective is essential to successful modelling and should be decided prior to the start of modelling. This starting point enables the modeller to design the modelling exercise appropriately and evaluate the results in the context of the objective. For example, the degree of calibration (and corresponding effort) and the associated calibration targets is dependent on the overall reason for modelling. This particular modelling exercise was conducted to understand processes and train our thinking. The overall objective was to evaluate how long-term changes may impact the phreatic surface of a closed tailings dam, which guided the process of calibration, interrogation of results, sensitivity analysis, and scenario analysis.

SEEP/W assumes that water flow through saturated and unsaturated soil follows Darcy's Law as shown in Equation 6-1 (GEO-SLOPE International Ltd. 2015).

$$q = ki \tag{6-1}$$

Where: q is the specific discharge, k is the hydraulic conductivity, and i is the gradient of total hydraulic head.

The general governing differential equation for two-dimensional seepage is described as shown in Equation 6-2 (GEO-SLOPE International Ltd. 2015).

$$\frac{\partial}{\partial x}\left(k_x \frac{\partial H}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_y \frac{\partial H}{\partial y}\right) + Q = \frac{\partial \theta}{\partial t} \tag{6-2}$$

Where: H is the total head, k_x is the hydraulic conductivity in the x-direction, k_y is the hydraulic conductivity in the y-direction, Q is the applied boundary flux, θ is the volumetric water content, and t is the time.

The modelling occurred in two main phases, including steady state modelling and transient modelling. Calibration of the model was conducted using steady state modelling to determine the material properties and boundary conditions. The model was calibrated to data provided by the oil sands operator, including measured pore pressures from piezometers and measured drain outflows. For the steady state modelling, the dam geometry reflected the conditions prior to closure works (i.e., there will still be a pond). During this modelling stage, sensitivity analysis was conducted to evaluate the variation in the porewater pressure conditions and drain outflows to changes in boundary conditions and material properties. All models were assessed for convergence using the convergence checks integrated into the SEEP/W software. For steady state models, models were assessed to determine if there were any unconverged pressure nodes, which would signify non-convergence. Steady state models were also assessed based on a comparison between the input hydraulic conductivity functions and the actual functions used to obtain the solution. If the actual and input functions do not match, the solution has not converged. For the transient models, the water balance error was also assessed to evaluate convergence, in addition to the checks completed for the steady state models. The water balance error is a mathematical by-product of non-convergence and can be evaluated by comparing it to the cumulative change in domain water mass to get a relative water balance error. Convergence should be evaluated with consideration of the relative water balance error, pressure head convergence, material property functions, and engineering judgement to assess if a result is reasonable. It should be noted that the material property functions of the tailings sand in this research are quite steep. This means that small changes in the pore water pressures may result in larger water balance errors.

An important element to recognize with this modelling exercise is the non-uniqueness of the solution – meaning that a number of different combinations of material properties are capable of producing the same head and flow distribution.

2D numerical modelling was conducted that considers a section of the dam rather than a 3D model that captures the larger hydrogeological regime. This research focuses on the response of the structure itself under current far field conditions. Potential changes in the regional groundwater flow regime may have an impact on the dam phreatic surface, but this modelling is beyond the scope of this research.

The case study oil sands dam used for the seepage analysis corresponds to a real cross-section and material properties. The operator has requested anonymity. The transient scenarios analysed in Section 6.2.2 were designed to understand the uncertainty associated with the evolution of the phreatic surface.

6.2.1 Steady State Seepage Analysis

A steady state seepage analysis was conducted to facilitate calibration of the material properties. It should be noted that steady state seepage analysis only allows for the calibration of the transmissivity (hydraulic conductivity) in a given cross-section. The specific storage of a cross-section must be calibrated using transient modelling. There are some issues with completing a full calibration of the case study facility as the tailings dam has not been closed yet, and thus, there is not data to calibrate to. These issues, and determination of the soil water characteristic curves, will be discussed in detail in Section 6.2.2.

6.2.1.1 Model Geometry

The initial model geometry was established based on the dam geometry as of 2019 as opposed to the final closure geometry since the final closure landform has not been constructed. Consequently, there is not any data that could be used for calibration for the final closure landform geometry. The geometry was simplified to allow for model convergence. Some steps of the geometry simplification included smoothing the downstream slope and merging the beach above water and the majority of the beach below water deposit as these deposits were anticipated to have the same material properties for the purpose of the model. The initial geometry is provided in Figure 6-1. The elevation of the tips of the piezometers are provided in Table 6-2.

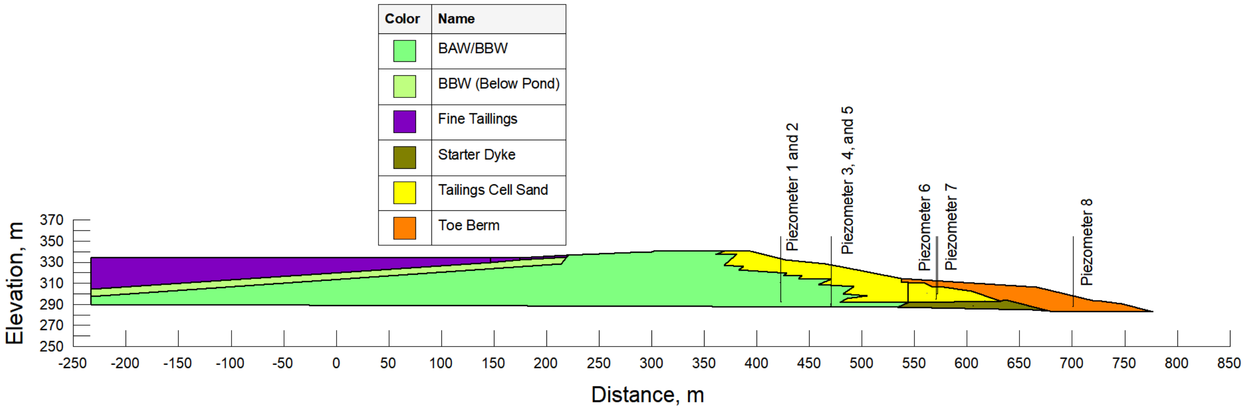


Figure 6-1: Steady state model geometry

Table 6-2: Piezometer tip elevations

Piezometer	**Tip Elevation (m)**
1	292.6
2	310.6
3	290.7
4	290.1
5	288.7
6	295.0
7	299.9
8	287.8

6.2.1.2 Material Parameters

The initial material properties for the dam materials were provided by the operator of the case study facility and were subsequently calibrated as discussed in Section 6.2.1.4. The calibrated hydraulic conductivity material properties are provided in Table 6-3 and the hydraulic conductivity functions for the materials are provided Figure 6-2. The calibration of the hydraulic conductivity curves is discussed in Section 6.2.1.4.

Table 6-3: Material parameters used in SEEP/W model following calibration in steady state modelling

Material	**Saturated K_x (m/s)**	**K_y/K_x**
Fine tailings	$1x10^{-7}$	0.1
BBW	$2x10^{-6}$	0.005
BBW/BAW	$2x10^{-5}$	0.0333
Cell Sand	$9x10^{-6}$	0.1
Starter Dyke	$1x10^{-8}$	0.2
Berm	$1x10^{-8}$	0.2

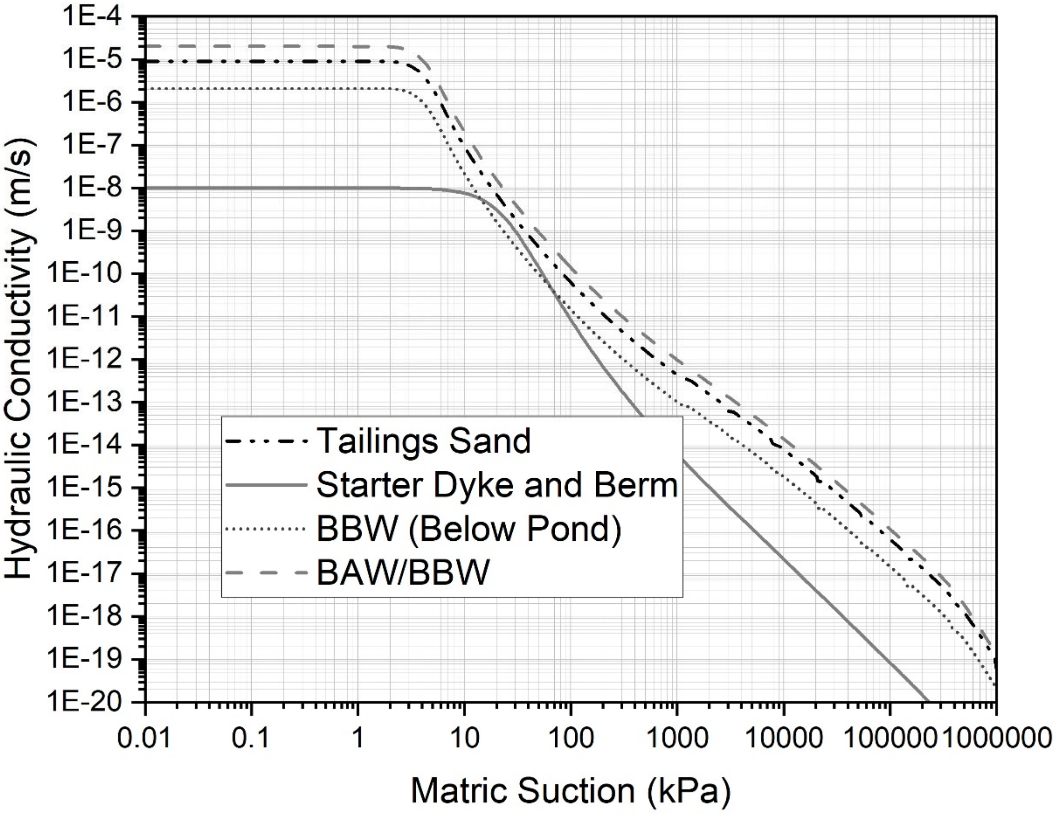


Figure 6-2: Calibrated hydraulic conductivity functions

6.2.1.3 Mesh and Boundary Conditions

SEEP/W, like all finite element numerical models, requires the domain to be subdivided into smaller pieces using the process of discretization or meshing (GEO-SLOPE International Ltd. 2015). The meshing in SEEP/W is fully automatic and users are unable to draw individual elements; however, modellers may change the element size or pattern (GEO-SLOPE International Ltd. 2015). A mesh pattern of quadrilateral and triangular elements was used for the steady state model. A global element size of 4 m was used, but localized areas had a smaller element size applied (user defined). Smaller element sizes were applied to the areas surrounding the drains and for thinner layers. Element size is known to have some impact on modelling results (GEO-SLOPE International Ltd. 2015). Evaluation of the impact of element size was out of the scope of this research.

The boundary conditions used in the steady state seepage analysis are provided in Table 6-4. Boundary conditions can only take the form of a specified head or flow, but they can be applied in different ways (GEO-SLOPE International Ltd. 2015). In some cases, the head or flow may be unknown, such as a seepage face where it is known that the porewater pressure (PWP) at the location of the seepage face is zero but the exact location of that seepage face is unknown (GEO-SLOPE International Ltd. 2015). This type of boundary condition is solved through an iterative process until a correct solution is obtained and takes the form of a 'potential seepage face' in the software.

Table 6-4: Steady state seepage analysis boundary conditions

Location	Boundary Condition	Comments
Far left	Water flux=0 $m^3/s/m^2$	No flow boundary
Far right	Water total head=283 m	Total head at downstream toe
Bottom	Water flux=0 $m^3/s/m^2$	No flow boundary
Drains	Water rate=0 m^3/s	Potential seepage face
Pond	Water total head=337 m	Pond elevation
Crest	Water flux=1.2684×10^{-8} $m^3/s/m^2$	Infiltration=400 mm/yr
Cell sand: downstream slope	Water flux=4.7565×10^{-9} $m^3/s/m^2$	Potential seepage face Infiltration=150 mm/yr
Berm: downstream slope	Water flux=3.17098×10^{-11} $m^3/s/m^2$	Potential seepage face Infiltration=1 mm/yr

The pond was extended upstream substantially so that a no flow boundary condition could be employed under the assumption that the pond extends past the hydraulic divide. Muskeg was not stripped prior to construction of the facility. The scenarios assessed for this research were constrained to the assumption that the hydraulic properties of the muskeg were sufficient to create a hydraulic barrier resulting in a no flow boundary condition, which would have to be evaluated when the facility is analysed for closure. The downstream seepage face, including the cell sand and the berm, were assumed to be potential seepage faces where the location of the seepage face is unknown. The infiltration for the crest and cell sand were provided by the operator and were assessed during calibration and sensitivity to evaluate their impact on the output. The berm was originally modelled as a zero-flux boundary to simulate an oil sands berm that restricted infiltration (low hydraulic conductivity and highly vegetated), similar to the work completed by Ferguson et al. (2009); however the calibration (Section 6.2.1.4) showed that an infiltration of 1 mm/year provided a better fit to the field piezometric conditions. This applied infiltration shows the non-uniqueness of the solution.

The drains were modelled as circular floating regions using a potential seepage face and a water rate of 0 m^3/s. It should be noted that there are different ways to model drains. An additional method includes modelling the drains as a point in the domain and assigning the pressure head equal to zero. This particular method assumes that the drain can handle the inflow and is only applicable in such scenarios. In the calibration and sensitivity stages of this work, the drains were modelled both ways to assess if this had an impact on the results. Ultimately, the drains were modelled as circular floating regions as this eliminates any issues with potential drain capacity during the transient modelling stages.

6.2.1.4 Calibration

In accordance with ASTM D5981/D5981M–18 the calibration was conducted by (ASTM International 2001):

- Establishing calibration targets;
- Identifying calibration parameters; and
- History matching

Material properties were provided by the operator. These material properties and boundary conditions established during the conceptual modelling stage were used to develop an initial model for the calibration process. Following the development of the initial model, the calibration targets were established, which involves determining the best estimate of a value of the head and/or flow rate. The steady state seepage analysis was calibrated using 2019 piezometer data for eight (8) piezometers and 2019 outflow data for the level 1 and level 2 drains provided by the operator. The process of establishing calibration targets also involves the determination of acceptable residuals (Equation 6-3), which must involve consideration of the research objectives. Residual statistics are also used to compare model outputs to site specific data using the residual mean error (Equation 6-4), residual mean absolute error (Equation 6-5), and root mean squared error (Equation 6-6) (Anderson et al. 2015).

$$r = h_s - H_m \tag{6-3}$$

$$ME = \frac{1}{n}\sum_{i=1}^{n} r_i \tag{6-4}$$

$$MAE = \frac{1}{n}\sum_{i=1}^{n} |r_i| \tag{6-5}$$

$$RMSE = \left(\frac{1}{n}\sum_{i=1}^{n} {r_i}^2\right)^{0.5} \tag{6-6}$$

Where r is the residual, h_s is the simulated head, H_m is the measured head, *ME* is the residual mean error, n is the number of residuals, *MAE* is the residual mean absolute error, *RMSE* is the root mean squared error.

As discussed by ASTM International (2001), a low-fidelity model would require fewer calibration targets and allow larger acceptable residuals compared to a high-fidelity model, where fidelity describes how closely a model application resembles the physical hydrogeologic system. The objective of this model is to evaluate how long-term changes may impact the phreatic surface of a closed facility with the goal of understanding processes to train our thinking. With this in mind, the model within this research can be described as a low to medium-fidelity model as it seeks to provide answers to questions as opposed to making specific predictions.

For the drains, the modelled drain outflows were required to fall within the range of outflows over the non-winter months. While this range is large for the drain outflows (4.4 L/s to 88.4 L/s for the level 1 drains and 6.8 L/s to 40.7 L/s for the level 2 drains in 2019), it does represent actual data and thus, the calibrated model must fall within this range. To aid in narrowing the range, effort was made to calibrate to the average drain outflow and ensure that the calibrated model did not fall at the extremes of the ranges. For the piezometers, the total head residual was initially set at 1 m (seasonal variation in 2019) of the established calibration target. During the calibration, reducing the total head residuals below the target threshold on all piezometers was not able to be achieved. A maximum total head residual of 1.25 m was accepted due to the fact that the model is a low to medium-fidelity model and aims to gain insight to general trends, not provide specific predictions.

The next step of the calibration process involved establishing the calibration parameters, which is the process of determining the properties or boundary conditions that are adjusted during the calibration process. The calibration parameters to be adjusted included: saturated hydraulic conductivities, anisotropy, infiltration rates, and the way the drains were modelled. As previously noted, the steady state seepage model calibration process is not suitable for calibration of volumetric water content functions, which must be addressed using transient methods.

The final stage of the calibration process involves history matching where the inputs (established calibration parameters) are varied until the model output reproduces the measured site-specific information (calibration targets) to the established accepted degree of accuracy. After an initial calibration process of trial and error to address non-convergence (unconverged pressure heads) issues in the model, a calibration sensitivity analysis was conducted by systematically varying the inputs to determine which of these values had the greatest impact on the modeled piezometric level and drain flow rates (ASTM International 2001). During the calibration sensitivity, 57 scenarios were completed (including the base model). A summary of the calibration sensitivity scenarios, measured drain outflows, piezometric residuals, residual mean error (ME), residual mean absolute error (MAE), and root mean squared error (RMSE) are provided in Table C-1 in Appendix C: Seepage Modelling. The calibration sensitivity analysis allowed the impact of an input to be evaluated as a way of guiding more refined calibration. This allowed for the inputs that had the greatest impact on the computed heads and flow rates to be identified for further calibration efforts.

The calibration sensitivity analysis showed that the modelled piezometric heads and drain outflows were the most sensitive to the hydraulic conductivity and anisotropy of the fine tailings, BBW below the pond, BAW, and cell sand as the drain outflows and residual statistics varies with changes in these inputs. It also showed that the modelled outputs were less sensitive to the hydraulic conductivity and anisotropy of the starter dyke and berm and the way the drains were modelled as shown by the drain outflows and residual statistics. For example, the drain outflows and residual statistics showed minimal change between the initial model and when the drains were modelled as a single point with a zero pressure head boundary condition (Scenario ID# 2) as shown by Table C-1 in Appendix C: Seepage Modelling. In contrast, the residual statistics change dramatically with changes in the saturated hydraulic conductivity of the fine tailings compared to the initial model (Scenarios ID# 13-17) as shown by Table C-1 in Appendix C: Seepage Modelling.

With regard to infiltration, infiltration in the crest and cell sand did not have a substantial impact on the output with the exception of when the infiltration became high at the crest (800 mm/yr). The calibration sensitivity analysis showed that the total head at Piezometer 8 (downstream toe) was largely impacted if infiltration was applied to the berm. To better match the observed field conditions, a 1 mm/yr infiltration was applied to the berm. Such an infiltration shows the non-uniqueness of the model.

The calibration sensitivity analysis guided the process of manual calibration moving forward by clearly showing variations in inputs that could be implemented to better match the observed field conditions. This process led to the establishment of the model parameters and boundary conditions presented in Table 6-3 and Table 6-4 and the final calibrated steady state model. As discussed, this did not allow for the volumetric water content functions to be calibrated. This will be discussed further in Section 6.2.2.

6.2.1.5 Sensitivity Analysis

Following the model calibration, a sensitivity analysis was conducted to identify the inputs that have the largest impact on the degree of calibration (ASTM International 2016). The model inputs that were varied were the same as those used during calibration. Following the completion of the sensitivity analysis, each input can be assessed to determine the type of sensitivity to that input. ASTM D5611-94 (Reapproved 2016) recommends Types I through IV that vary depending on if changes to the calibration residuals and model's conclusions are significant or insignificant as shown in Table 6-5 (ASTM International 2016).

Table 6-5: Sensitivity types based on residuals and model conclusions

Sensitivity Type	Residuals	Model Conclusions
Type I	Insignificant	Insignificant
Type II	Significant	Insignificant
Type III	Significant	Significant
Type IV	Insignificant	Significant

A complete summary of the 58 scenarios, measured drain outflows, piezometric residuals, residual mean error (ME), residual mean absolute error (MAE), and root mean squared error (RMSE) are provided in Table C-2 in Appendix C: Seepage Modelling. To assess the sensitivity type, the different scenarios can be grouped according to the type of input and plotted to evaluate the effect of variation on the RMSE and drain outflows as shown in Figure 6-3 to Figure 6-5. Based on the sensitivity analysis, each group of inputs can be assigned a sensitivity type based on the impact to the residuals and model conclusions (provided in Table 6-6). The impact on the residuals was determined to be significant if the RMSE was greater than 1, and the impact on the model conclusions (level 1 and level 2 drain outflows) was determined to be significant if the difference from the calibrated value was greater than 30%.

Of the 16 groups of inputs assessed, seven were assigned a Type I sensitivity and nine were assigned a Type III sensitivity. As noted by ASTM D5611-94 (Reapproved 2016), Type I sensitivity is of no concern as the conclusions will remain the same (ASTM International 2016). While Type III results in changes to the model conclusions with changes to the inputs, it is not concerning because variation in the parameters also results in the model becoming uncalibrated (ASTM International 2016). As a result, the calibration process will eliminate those values from being considered to be realistic (ASTM International 2016). This analysis shows that the model is the most sensitive to the fine tailings hydraulic conductivity, fine tailings anisotropy, cell sand hydraulic conductivity, and BAW/BBW hydraulic conductivity.

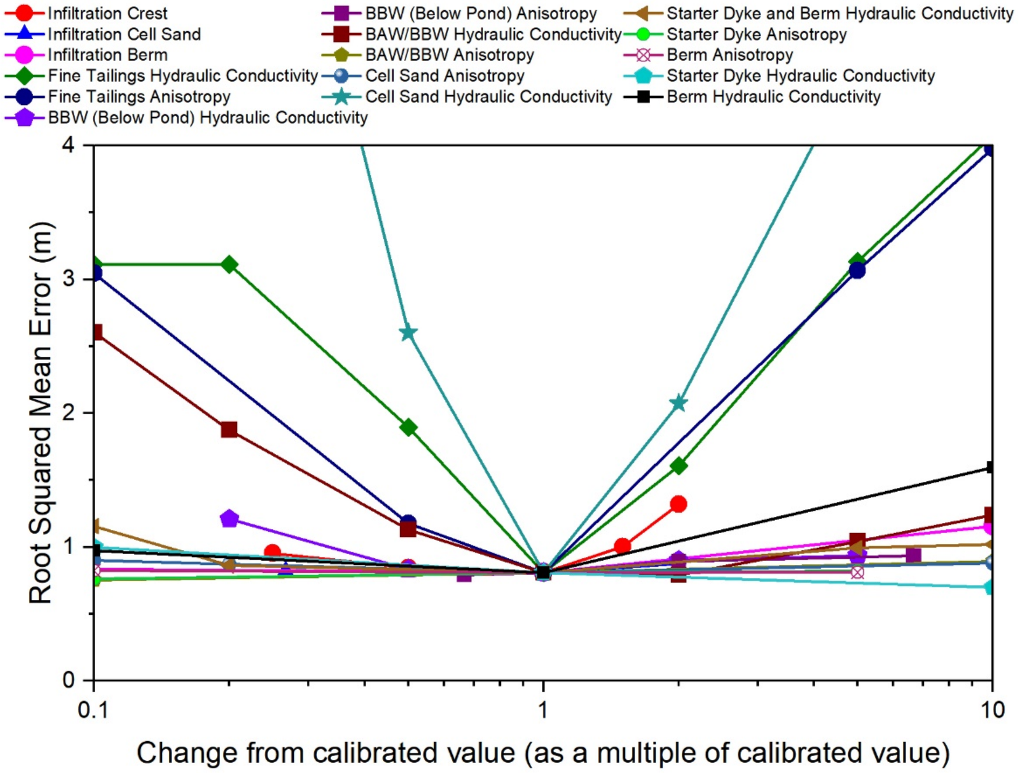


Figure 6-3: Root mean square error of modelled heads for sensitivity analysis

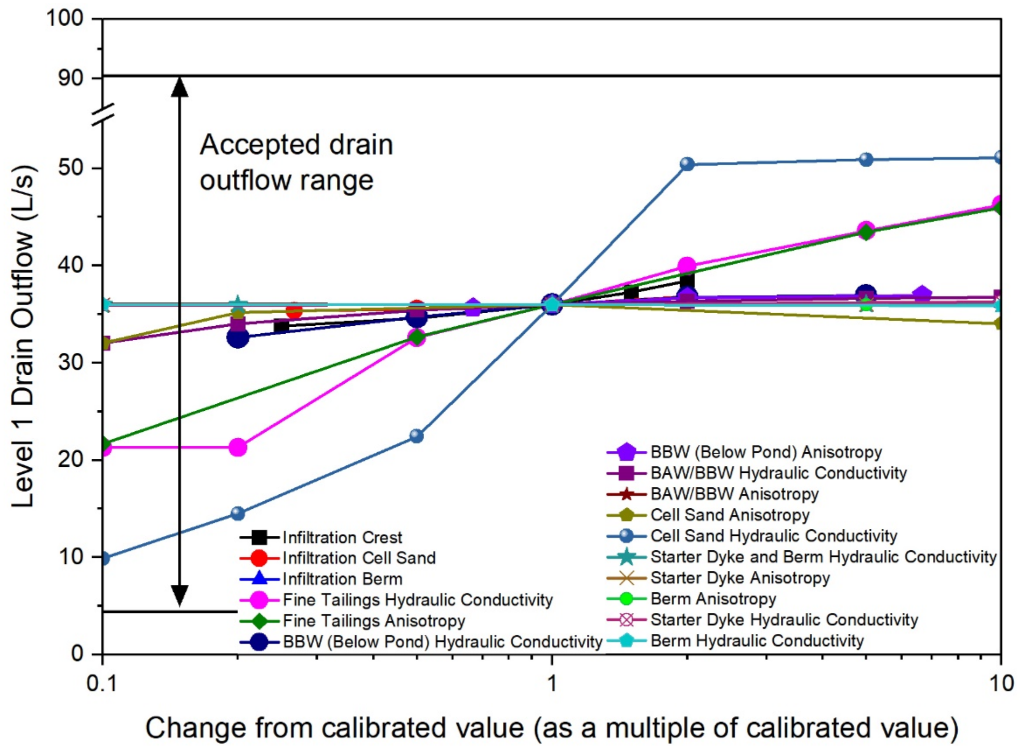


Figure 6-4: Level 1 drain outflow for sensitivity analysis

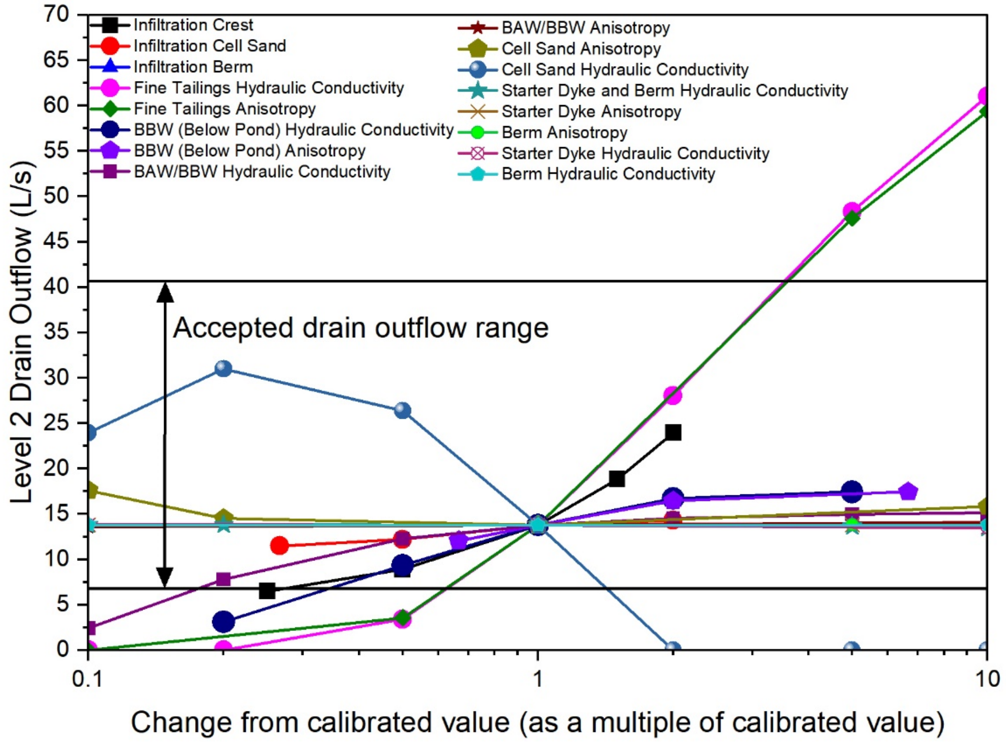


Figure 6-5: Level 2 drain outflow for steady state analysis

Table 6-6: Sensitivity scenarios and sensitivity type

Sensitivity Scenario	Residuals	Model Conclusions Level 1 Drains	Model Conclusions Level 2 Drains	Sensitivity Type
Crest Infiltration	Significant	Insignificant	Significant	Type III
Cell Sand Infiltration	Insignificant	Insignificant	Insignificant	Type I
Berm Infiltration[1]	Significant	Insignificant	Insignificant	[1]Type III
Fine Tailings Hydraulic Conductivity	Significant	Significant	Significant	Type III
Fine Tailings Anisotropy	Significant	Significant	Significant	Type III
BBW Below Pond Hydraulic Conductivity	Significant	Insignificant	Significant	Type III
BBW Below Pond Anisotropy	Insignificant	Insignificant	Insignificant	Type I
BAW/BBW Hydraulic Conductivity	Significant	Insignificant	Significant	Type III
BAW/BBW Anisotropy	Insignificant	Insignificant	Insignificant	Type I
Cell Sand Anisotropy	Insignificant	Insignificant	Insignificant	Type I
Cell Sand Hydraulic Conductivity	Significant	Significant	Significant	Type III
Starter Dyke and Berm Hydraulic Conductivity[1]	Significant	Insignificant	Insignificant	[1]Type III
Starter Dyke Anisotropy	Insignificant	Insignificant	Insignificant	Type I
Berm Anisotropy	Insignificant	Insignificant	Insignificant	Type I
Starter Dyke Hydraulic Conductivity	Insignificant	Insignificant	Insignificant	Type I
Berm Hydraulic Conductivity[1]	Significant	Insignificant	Insignificant	[1]Type III

Note: [1]The berm infiltration, starter dyke and berm hydraulic conductivity, and the berm hydraulic conductivity groups of inputs were assigned a Type III (instead of Type II) sensitivity despite having insignificant model conclusions based on the level 1 and level 2 drain outputs. This was based on the downstream phreatic surface daylighting at a much higher elevation than the calibrated model for certain scenarios. This effect is not captured in the level 1 and level 2 drain outputs but should be accounted for when assessing the sensitivity type.

6.2.2 Transient Modelling

Following the calibration and sensitivity analysis, the next stage of modelling commenced, which involved scenario analysis to evaluate the change in the seepage system over different time frames and different conditions using transient modelling.

6.2.2.1 Model Geometry

For the transient modelling, the geometry of the dam was altered to reflect the dam following reclamation works. The altered geometry assumes that the pond will be infilled with CST, partially displacing the fluid fine tailings, and will result in a zone of mixed CST and FFT deposited as BBW. The infilled zone will be covered by approximately 4 m of CST that will be placed and compacted using methods similar to cell construction to create a trafficable surface. The CST cover is then capped with mine waste material to create a trafficable surface. It is expected that a reclamation cover will be designed specifically for this facility by the operator and has not been included in the analysis. The reclamation surface is expected to have hummocks and a system of drainage channels that direct flow towards the outlet of the facility.

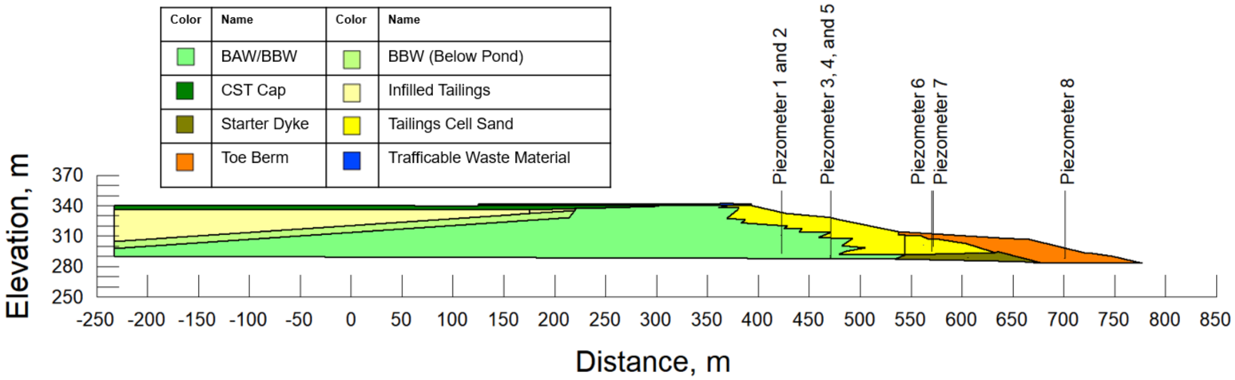


Figure 6-6: Transient model geometry

6.2.2.2 *Mesh*

The mesh techniques used in the steady state model were also employed in the transient modelling, including a mesh pattern of quadrilateral and triangular elements. The global element size of the elements was 4 m; however, localized areas used a smaller element size (i.e., areas surrounding the drains and thinner layers).

6.2.2.3 *Boundary Conditions*

The base boundary conditions used in the transient seepage analysis are provided in Table 6-7.

Table 6-7: Transient state seepage analysis boundary conditions

Location	Boundary Condition	Comments
Far left	Water flux=0 $m^3/s/m^2$	No flow boundary
Far right	Water total head=283 m	Total head at downstream toe
Bottom	Water flux=0 $m^3/s/m^2$	No flow boundary
Drains	Water rate=0 m^3/s	Potential seepage face
Upstream, Crest, Cell sand: downstream slope	Land climate interaction	Uses climate data
Berm: downstream slope	Land climate interaction	Uses climate data

The pond was extended upstream substantially so that a no flow boundary condition could be employed under the assumption that the pond extends past the hydraulic divide. Muskeg was not stripped prior to construction of the facility. The scenarios assessed for this research were constrained to the assumption that the hydraulic properties of the muskeg were sufficient to create a hydraulic barrier resulting in a no flow boundary condition, which would have to be evaluated when the facility is analysed for closure. The drains were modelled as circular floating regions using a potential seepage face and a water rate of 0 m^3/s.

A significant challenge with conducting the transient analysis on the dam is determining the net infiltration over long periods of time. GeoStudio uses a land-climate interaction (LCI) boundary condition to do this where climate data is input and given that climate data, the solver determines the net infiltration over time (GEO-SLOPE International Ltd. 2020). A challenge here is that for the solver to do this accurately, small time steps (in the order of 2 to 6 hours) should be used. For a 100-year long two-dimensional (2D) analysis, this will be computationally time intensive. An alternative is to run a 1-dimensional (1D) analysis with the LCI boundary condition (and associated imposed climate conditions). The water flux versus time at the surface in the 1D model can be determined, exported, and applied as the top boundary condition in the 2D domain. This method would then allow the time steps to be larger in the 2D model. As a check that this method is producing accurate results, the LCI boundary condition can be applied to the top of the 2D domain for a shorter period and compared to the results with the net infiltration applied. This alternative method was investigated, and the results are presented in Appendix C: Seepage Modelling. The output from the two different scenarios showed that they both follow the same trend over time. Based on the comparison, it is considered reasonable to use the water flux over time from the 1D LCI model as the upper boundary condition for the 2D model. While this technique would be deemed reasonable for the purposes of this modelling, non-convergence issues were experienced with the 1D LCI water flux approach when the model was extended to longer timescales. This is due to the large variations in water flux over time combined with the steep volumetric water content and hydraulic conductivity functions of the tailings sand. In contrast, the LCI boundary condition for the 2D model did not experience non-convergence issues when extended to longer timescales. As a result, the full 2D LCI boundary condition was used for the remainder of this research, despite the longer run times.

For the LCI boundary condition, GeoStudio offers three different evapotranspiration methods that may be employed, including: Penman-Wilson, Penman-Monteith, and User-Defined. A summary of the required data for the different methods is provided in Table 6-8. GeoStudio is also able to determine the root water uptake if vegetation characteristics (leaf area index versus time, plant moisture limiting function, root depth versus time, normalized root density, soil cover fraction versus time) are defined as part of the LCI boundary condition (GEO-SLOPE International Ltd. 2020). For this work, the Penman-Wilson method was employed due to a lack of information on vegetation height required for the Penman-Monteith method. Further, the root water uptake was not included in the LCI boundary condition due to a lack of vegetation information.

Table 6-8: Evapotranspiration methods for LCI boundary condition (GEO-SLOPE International Ltd. 2020)

Required Inputs	**Evapotranspiration Methods**		
	Penman-Wilson	**Penman-Monteith**	**User-Defined**
Air temperature versus time	X	X	X
Precipitation flux versus time	X	X	X
Relative humidity	X	X	X
Snow depth versus time (optional)	X	X	X
Snow density (optional)	X	X	X
Wind speed versus time	X	X	
Net radiation versus time	X	X	
Vegetation height versus time		X	
Potential evapotranspiration versus time			X

Climate data were collected from the Alberta Climate Information Service (ACIS) using their historical weather station data viewer for the Mildred Lake weather station to attain data from February 2009 to February 2019 (10 years). The weather station was used to attain hourly data for the air temperature, relative humidity, and wind speed from 2009 to 2019. Daily data were obtained for the precipitation flux. The data were quality controlled and compared to other nearby sites to highlight any inconsistencies and evaluate general agreement. Periods with irregular data or gaps were supplemented with data from the Government of Canada Historical Weather Data for the Mildred Lake Weather Station, assuming that the data before and after the gap agreed with the ACIS data. ACIS only had daily snow depth data available from 2014 to 2021. As a result, daily snow depth data were attained from 2009 to 2019 for the Aurora station from the Regional Aquatics Monitoring Program (RAMP). Gaps in the snow depth data were supplemented using the Mildred Lake weather station from ACIS, the Interpolated Weather Data for Alberta Townships provided by ACIS, and the Government of Canada Historical Weather Data for the Mildred Lake Weather Station. The 10 year record was looped to create a 100 year record for the seepage modelling.

The weather station data were not able to be used to generate a consistent record for the net radiation. GeoStudio provides an option to input the incoming solar radiation flux. This can be accomplished by using the measured solar radiation flux data or estimating the solar radiation flux given a user-defined latitude. As with the net radiation, a complete record for the incoming solar radiation flux was not able to be attained. As a result, the solar radiation flux was estimated using the user-defined latitude. This method requires an albedo versus time function to be provided where albedo is the percent of incident solar radiation reflected by the surface (Barry and Gan 2011). A step function was used for the albedo function. An albedo value of 0.7 was used for the duration of winter when there was snow present to simulate the lower bound value for fresh snow and upper bound value of old snow (Barry and Gan 2011). An albedo value of 0.25 was used for the remainder of the time to represent a lightly vegetated ground surface. The combination of the estimated solar radiation flux and albedo function (as opposed to a measured net radiation) introduces uncertainty. Ideally, the LCI boundary condition would be accompanied by a measured net radiation.

6.2.2.4 Establishing SWCC Functions

The hydraulic conductivity curves were calibrated using the steady state modelling calibration discussed in Section 6.2.1.4. The soil water characteristic curves (SWCCs) were not able to be calibrated using these methods. Generally, the SWCC would be calibrated using transient modelling. For the case study, the tailings dam has not been closed yet and there are not data to calibrate to at the current time. To mitigate these issues, a scenario analysis was conducted to determine the material properties that should be used for the remainder of the analysis by assessing the impact of different SWCCs on the overall conclusions of the model. The transient analysis involves a number of different materials, including: BAW/BBW, tailings cell sand, starter dyke/berm, mine waste material, CST cap, and infilled materials. These materials were categorized into two groups: tailings sand and lean oil sands. For these materials, published SWCCs (Ferguson et al. 2009, Price et al. 2010, Dobchuk et al. 2013, Torghabeh 2013, Kouakou 2014, Zheng 2019, Alam et al. 2020), were compared to SWCCs provided by the operator. The SWCCs for the tailings sand are provided in Figure 6-7, and the SWCCs for the lean oil sands are provided in Figure 6-8.

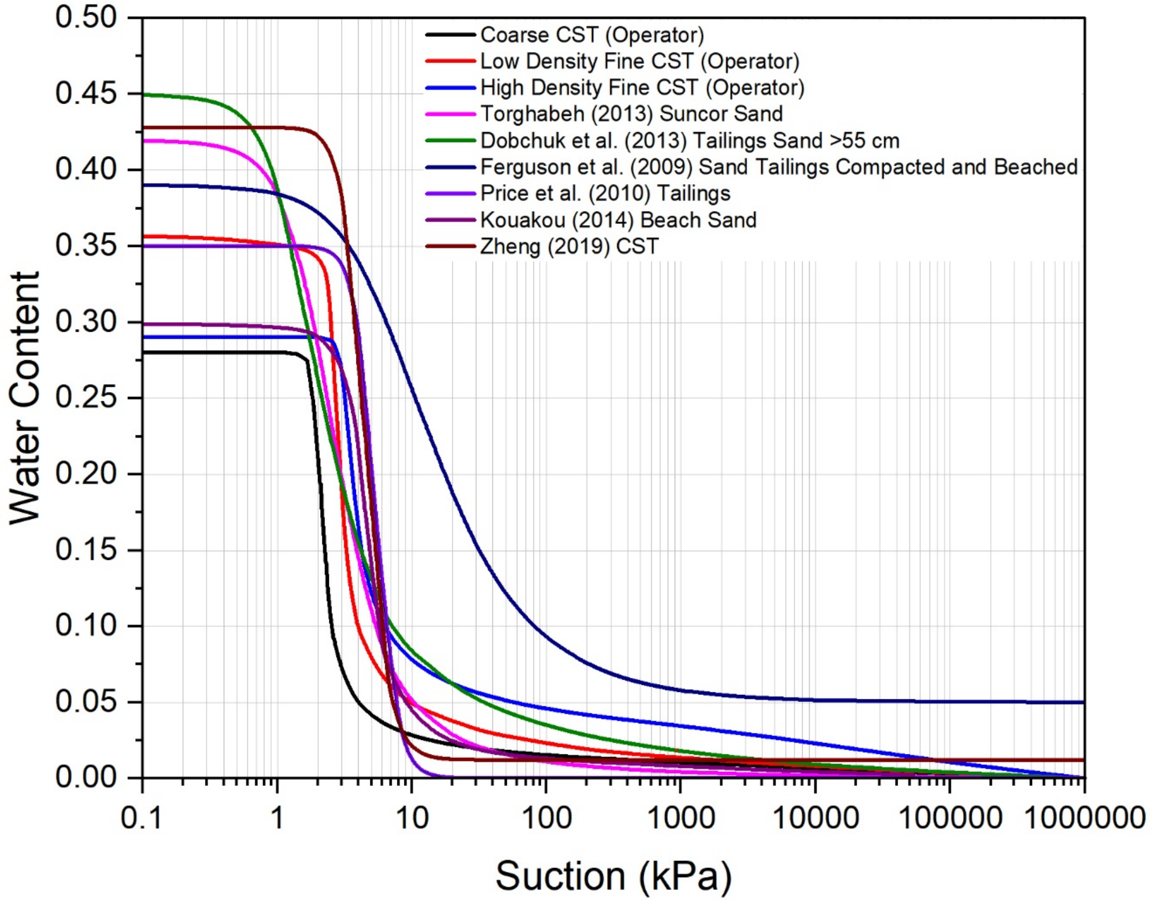


Figure 6-7: SWCCs for tailings sand

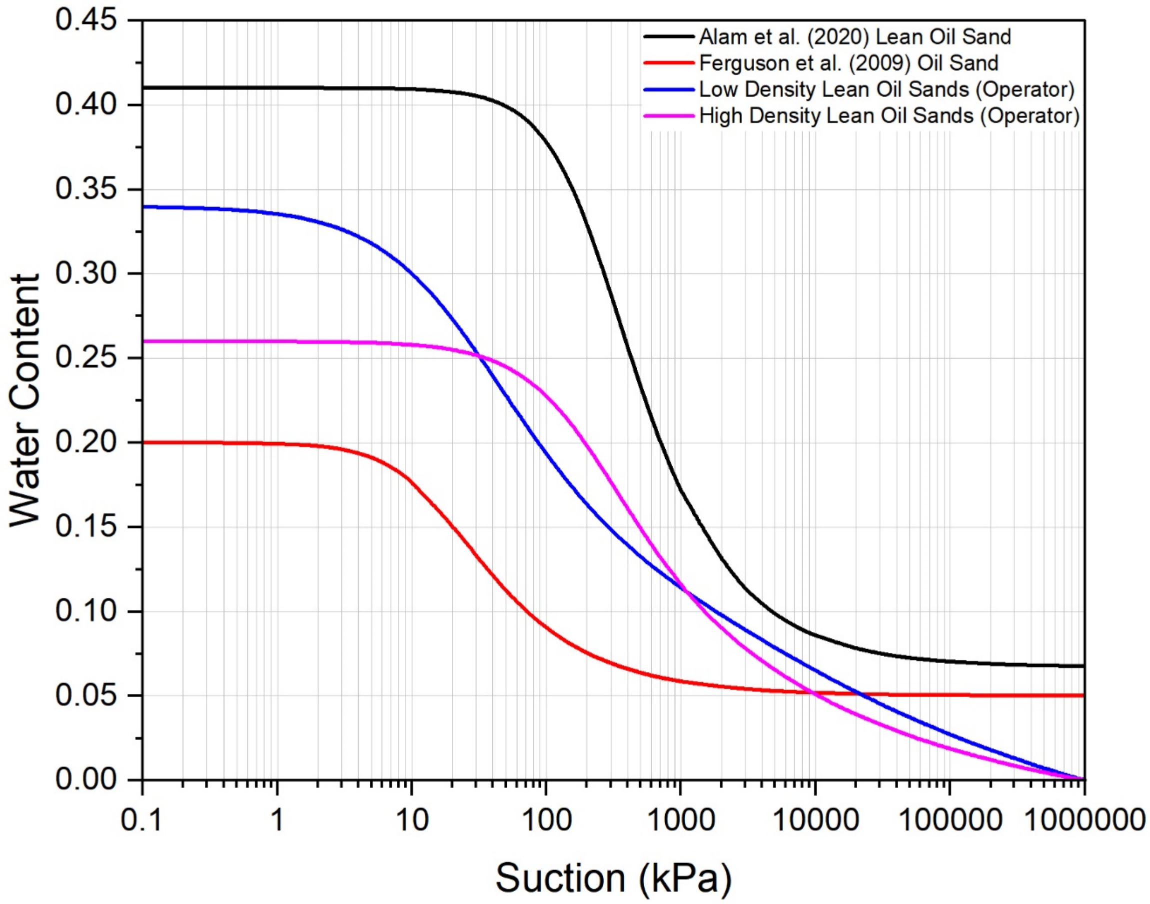


Figure 6-8: SWCCs for lean oil sands

To evaluate the impact of the SWCCs on the model conclusions, three potential SWCCs were chosen for each material type to be assessed. The selected SWCCs are provided in Table 6-9. Using these material properties, nine (9) different scenarios were modelled and evaluated to assess the impact of different SWCCs on the model conclusions (Table 6-10). The scenarios were modelled over a 100-year time frame using the LCI methodology discussed in Section 6.2.2.3.

Table 6-9: SWCCs for scenario analysis

Material	**SWCC**	**Material Property ID**
Tailings Sand	Low Density Fine CST (Operator)	TSA
	High Density Fine CST (Operator)	TSB
	Torghabeh (2013) Suncor Sand	TSC
Lean Oil Sands	High Density Lean Oil Sand (Operator)	LOS1
	Low Density Lean Oil Sand (Operator)	LOS2
	Alam et al. (2020) Lean Oil Sand	LOS3

Table 6-10: SWCC modelling scenarios

Scenario ID	Tailings Sand SWCC	Lean Oil Sand SWCC
1	TSA	LOS1
2	TSA	LOS2
3	TSA	LOS3
4	TSB	LOS1
5	TSB	LOS2
6	TSB	LOS3
7	TSC	LOS1
8	TSC	LOS2
9	TSC	LOS3

The different modelling scenarios were assessed based on the piezometer total heads over time, drain outflows over time, and the final phreatic surface after 100 years. The total heads over time for the 9 scenarios are provided in Figure 6-9. The drain outflows over time for the 9 scenarios are provided in Figure 6-10. The final phreatic surface after 100 years for the 9 scenarios are provided in Figure C-10 to Figure C-18 in Appendix C: Seepage Modelling.

In general, the total heads exhibit similar trends in groupings of three based on the location of the piezometer. For piezometers installed in the tailings sand (Piezometers 1-7), Scenarios 1-3 (TSA), Scenarios 4-6 (TSB), and Scenarios 7-9 (TSC) group together, which shows that the SWCC of the sand materials contributes greatly to the total head at these locations compared to varying the SWCC of the lean oil sand for these scenarios. Piezometer 8 is installed in the berm. For this piezometer, Scenarios 1, 4, and 7 group together (LOS1); Scenarios 2, 5, and 8 group together (LOS2); and Scenarios 3, 6, and 9 group together (LOS3). This indicates that at this location, the total head is most impacted by the SWCC of the lean oil sand. For Piezometer 8, scenarios with LOS2 (Scenario 2, 5, and 8) exhibit a more consistent change in head over time versus the remaining scenarios that use LOS1 and LOS3. For the drains, Figure 6-10 shows that Scenarios 7 to 9 take a longer period for the drain outflows to decrease when compared to Scenarios 1 to 6.

For the purposes of this work, the various scenarios result in similar model conclusions and long-term trends for the base case model (i.e., no imposed scenario changes over the modelled time). In light of this, TSB and LOS2 will be used for the remaining modelling work as they represent actual measured SWCCs provided by the operator. It should be noted that it would be ideal to have transient data to calibrate to in addition to the measured SWCC curves. Further, if the intent of this modelling was to determine quantitative behaviour (i.e., how long the drains would need to operate), then this type of scenario analysis would not be considered adequate. However, as the intent is to aid in advancing the understanding of long-term phreatic processes, this methodology is considered adequate.

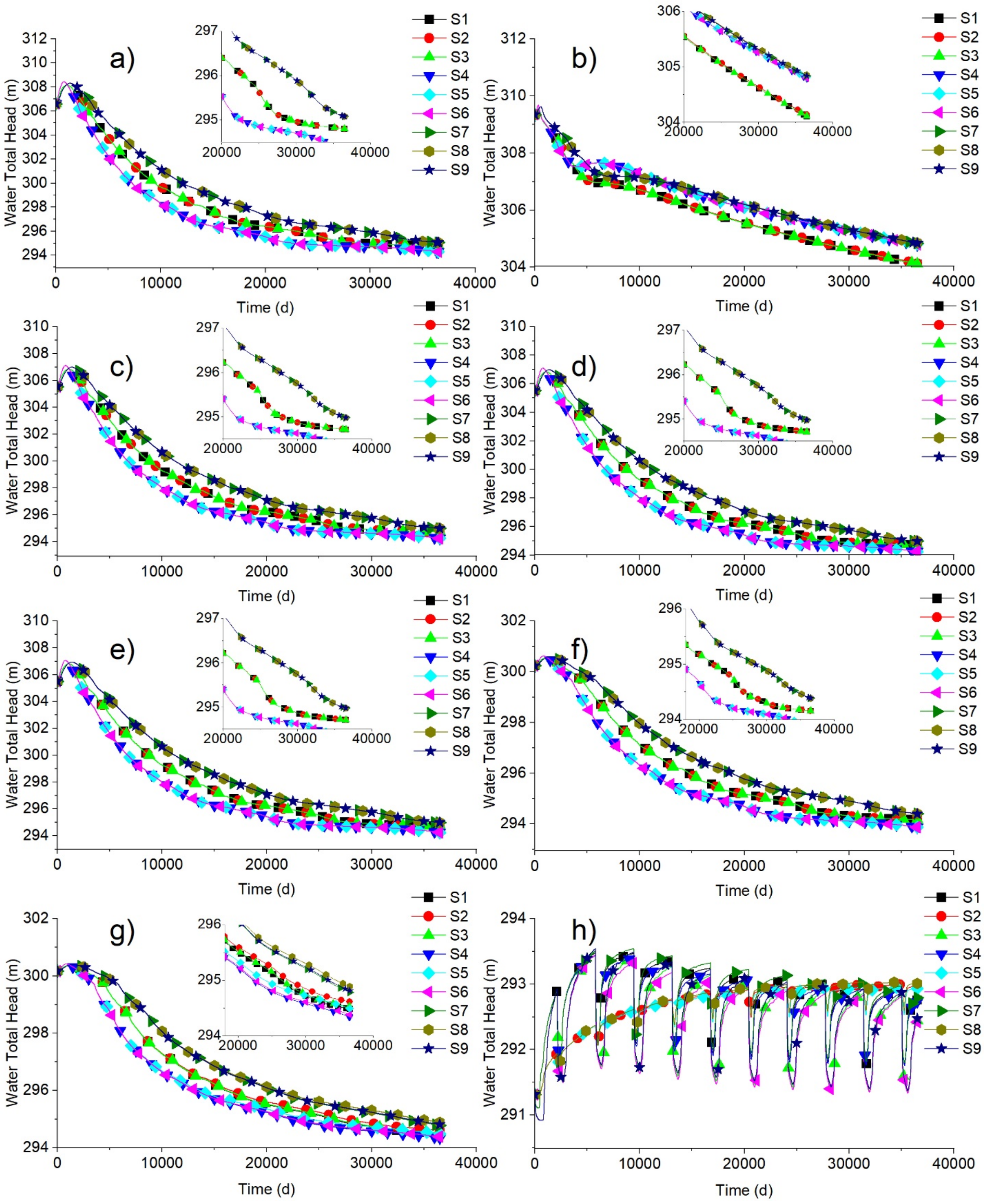


Figure 6-9: Total head over time for SWCC scenarios for a) Piezometer 1 b) Piezometer 2 c) Piezometer 3 d) Piezometer 4 e) Piezometer 5 f) Piezometer 6 g) Piezometer 7 h) Piezometer 8

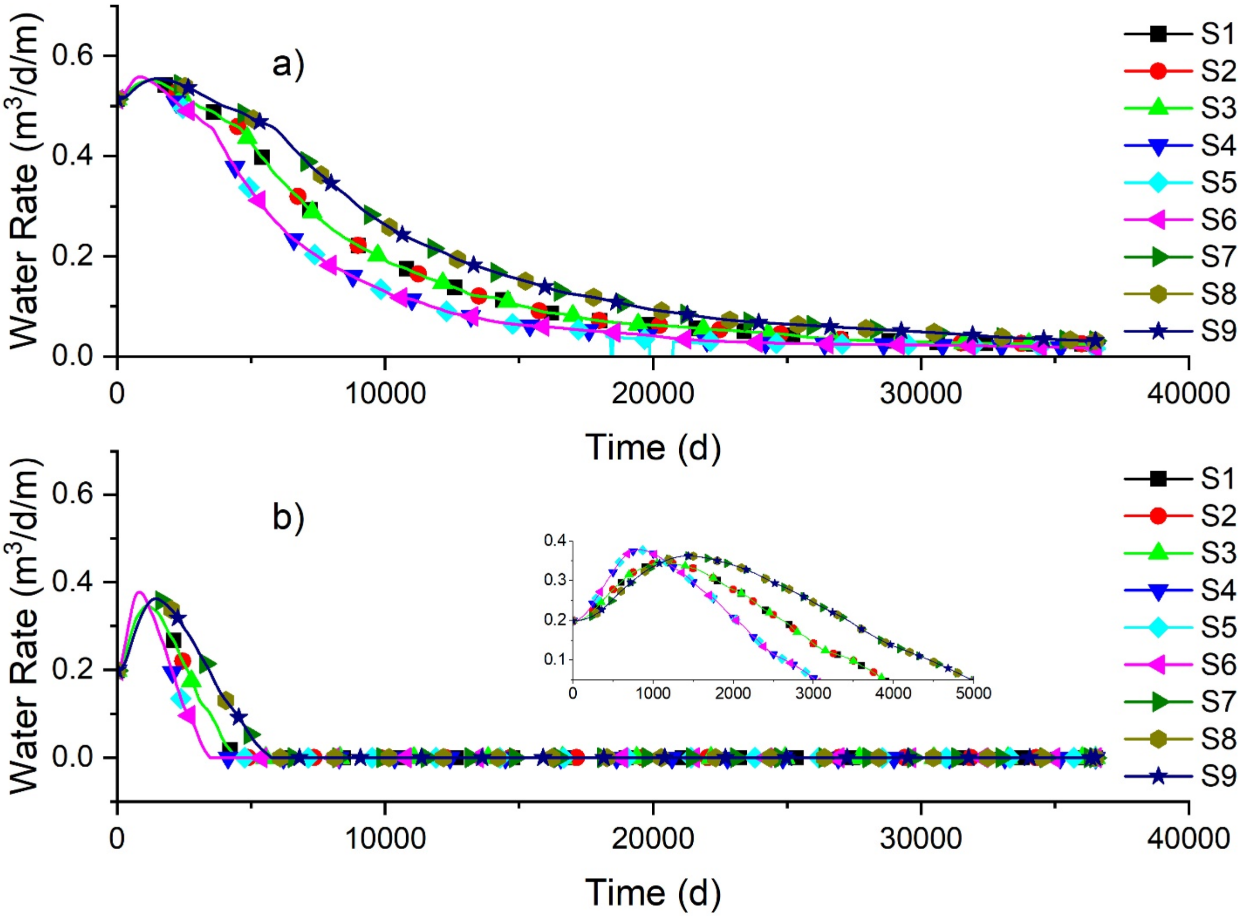


Figure 6-10: Drain outflows over time for SWCC scenarios for a) level 1 drains b) level 2 drains

6.2.2.5 Model Scenarios

The dam was evaluated to consider different potential changes in the dam over time that were identified during the interviews, including the following:

- Drain failure: drain failure may occur by a number of different mechanisms depending on the type of drain, including breakage of a pipe, clogging (biological, chemical, particulate clogging), blockage at an outlet, crushing of a granular drain, etc. Drain failure was modelled by changing the drain boundary condition;
- Formation of ponds on the reclamation surface: there is the potential for ponds to form on the reclamation surface as settling of the reclamation material (and underlying tailings) occurs. The potential formation of ponds was accounted for in the model by altering the upstream boundary conditions;

- Erosion impacting the downstream slope: it is expected that erosion will occur on the downstream slope, which may impact the seepage regime, including infiltration. Erosion was accounted for in the model by altering the downstream slope geometry; and
- Climate change: climate change was accounted for by changing the LCI boundary condition to account for different climate change scenarios.

6.2.2.5.1 Drain Failure

Drains can fail through a number of different mechanisms as shown in Table 4-8 in Section 4.1.6 depending on the type of drain. The failure modes specific to the case study facility are outlined in Table 5-6, which include breakage of the pipe (break in the pipe, buckling, physical degradation), clogging (chemical, biological, particulate clogging), blockage, clogging of the surround (biological, chemical, particulate clogging), or a breakage of the connection between the drain and the outlet pipe. Drains can have a critical impact on performance of a tailings dam in closure; however, it is becoming common practice to assume that drains fail in closure. The question becomes, does the facility require the drains to function for a certain amount of time prior to them failing, and if so, how critical is this to the stability of the facility? Different scenarios of drain failure were modelled for the case study facility, as outlined in Table 6-11. The drain scenarios were modelled by altering the boundary condition at the drain. The drains were modelled to be functioning or non-functioning (failed). The modelling did not consider partial failure or capacity. The level 2 drain failure was focused on the first 10 years as the phreatic surface drops below the level 2 drains before 10 years. Failure of the level 1 drains was spread out over the 100-year time scale (5 years, 25 years, 50 years, 75 years). Complete failure of the drain was modelled by removing the potential seepage face from the water rate boundary condition.

Table 6-11: Drain failure scenarios

Scenario ID	Level 1 Drains	Level 2 Drains
1	Functioning	Failed at 5 years
2	Functioning	Failed at 10 years
3	Failed at 5 years	Functioning
4	Failed at 25 years	Functioning
5	Failed at 50 years	Functioning
6	Failed at 75 years	Functioning
7	Failed at 5 years	Failed at 5 years

The different modelling scenarios were assessed based on the piezometer total heads over time (Figure 6-12), drain outflows over time (Figure 6-13), and the final phreatic surface after 100 years (Figure C-19 to Figure C-25 in Appendix C: Seepage Modelling). The base case where the drains have not failed were provided on Figure 6-12 and Figure 6-13 for comparison purposes. The difference between the scenario total heads at each of the piezometer locations and the base case where the drains have not failed were also evaluated and are summarized in the following:

- Table 6-12: The maximum total head difference measured over the 100-year modelling time;
- Table 6-13: Total head difference 1 year after the scenario change;
- Table 6-14: Total head difference 5 years after the scenario change; and
- Table 6-15: Total head difference 10 years after the scenario change.

Scenarios 1 and 2 evaluate the impact of the level 2 drains failing at 5 years and 10 years, respectively. For Scenario 1, the level 1 drain outflow temporarily increases in response to the level 2 drains failing. For the total heads, the maximum difference measured between the scenario and no failure base case does not exceed 1 m for all piezometers as shown in Table 6-12. Piezometer 6 and 7, which are in the proximity of the level 2 drains, show the largest increase in total head compared to the no failure base case with a maximum difference of 0.9 m and 1.0 m, respectively. Of interest, Table 6-13 shows that total heads rise rapidly to near their max in the first year following the drain failure and then begin to decrease as indicated by Table 6-14 and Table 6-15. For example, the maximum difference for Piezometer 7 is 1.0 m. The difference is 1.0 m at 1 year following failure, 0.2 m at 5 years following failure, and 0.1 m at 10 years following failure. For Scenario 2, the failure of the level 2 drains has no impact on the drain outflows (Figure 6-13) or the total heads (Figure 6-12, Table 6-12, Table 6-13, Table 6-14, and Table 6-15).

Scenarios 3 to 6 investigated the impact of the failure of the level 1 drains at different points in time. Scenario 3 (level 1 drains fail at 5 years) and Scenario 4 (level 1 drains fail at 25 years) show similar long-term trends on the total heads as represented in Figure 6-12, which have higher total heads for all piezometer locations (except for Piezometer 2) compared to the base case where failure has not occurred. Table 6-12 shows that the maximum total head difference between the no failure base case exceeds 5 m for all piezometer locations (except Piezometer 2) for Scenario 3 and 4. Scenario 3 also has a corresponding increase in the level 2 drain outflow.

Scenario 5 (level 1 drains fail at 50 years) also shows higher long-term total heads (although less than Scenarios 3 and 4) for all piezometer locations (except Piezometer 2) compared to the base case where failure does not occur. The maximum total head difference between the no failure base case is between 1 m to 3 m (except for Piezometer 2) as shown in Table 6-12. Scenario 6 (level 1 drains fail at 75 years) shows a minor increase in the long-term total heads compared to the base case where failure does not occur. For Scenarios 4, 5, and 6, the level 2 drains remain dry, indicating that the phreatic surface does not rise above the level 2 drains following failure of the level 1 drains at 25 years, 50 years, and 75 years.

The most substantial impact on the total heads is seen in Scenario 7 where the level 1 and level 2 drains fail at 5 years. As shown by the total heads, the phreatic surface in the facility rises quickly in response to the drain failure and then establishes a stable high phreatic surface with fluctuation at the location of Piezometer 8 in response to climatic data. The maximum total head difference established between the no failure base case and the scenario is greater than 7 m for all piezometer locations with Piezometer 8 reaching a 19.7 m difference (Table 6-12). Further, the total head difference does increase rapidly as shown in Table 6-13 to Table 6-15. For example, the total head difference for Piezometer 7 is 7.5 m at 1 year after failure, 12.1 m at 5 years after failure, and 13.8 m at 10 years after failure.

Evaluating the change in the total head difference between the scenarios and the no failure base case at different points in times is a useful tool when it comes to establishing monitoring and maintenance schedules and should be evaluated with consideration of historical piezometer trends and performance. With Scenario 7, there is a rapid increase in the total heads above the no failure base case. Such a scenario may warrant more regular monitoring schedules or drain maintenance until such a failure is deemed non-credible.

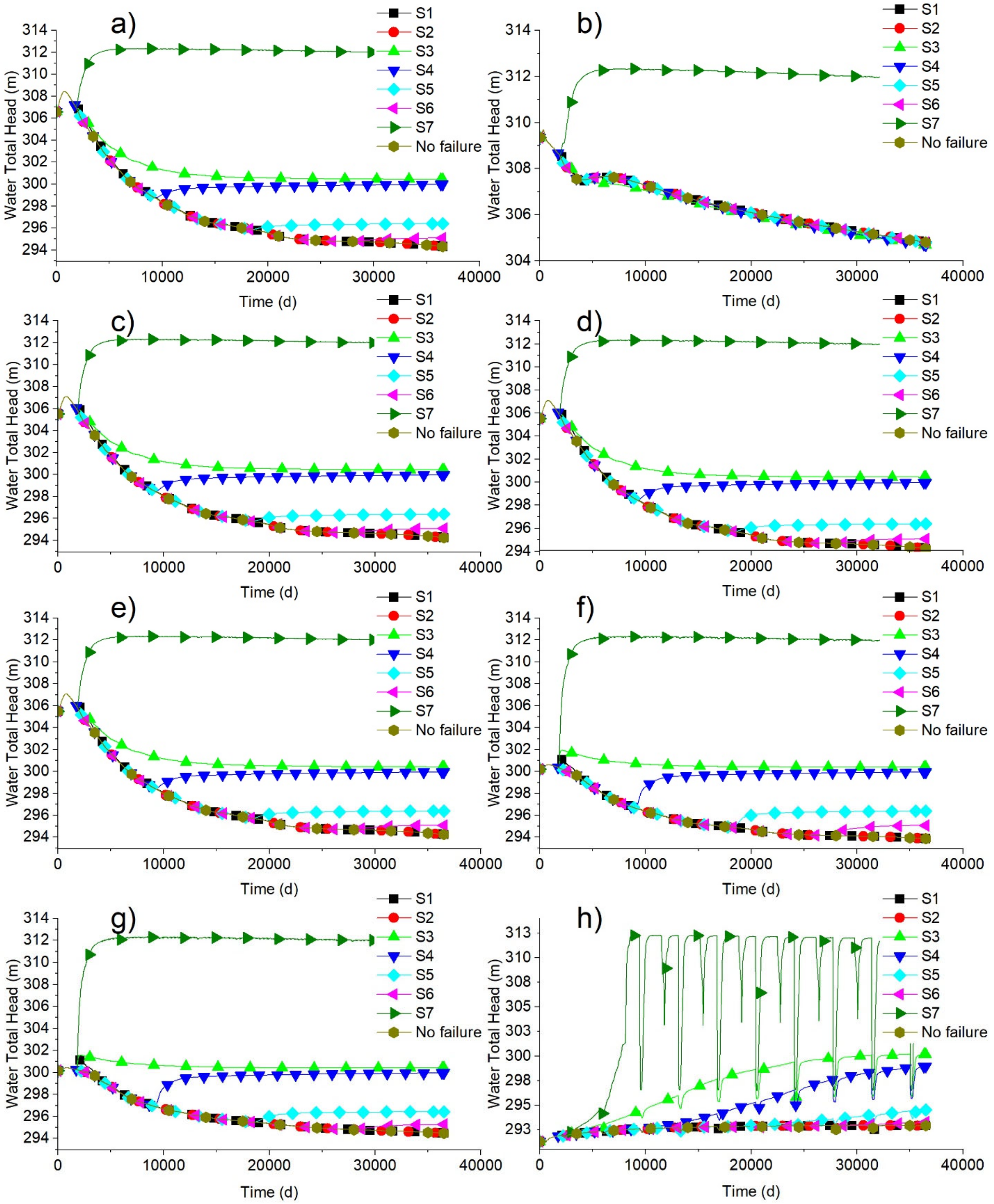


Figure 6-12: Total head over time for drain scenarios for a) Piezometer 1 b) Piezometer 2 c) Piezometer 3 d) Piezometer 4 e) Piezometer 5 f) Piezometer 6 g) Piezometer 7 h) Piezometer 8

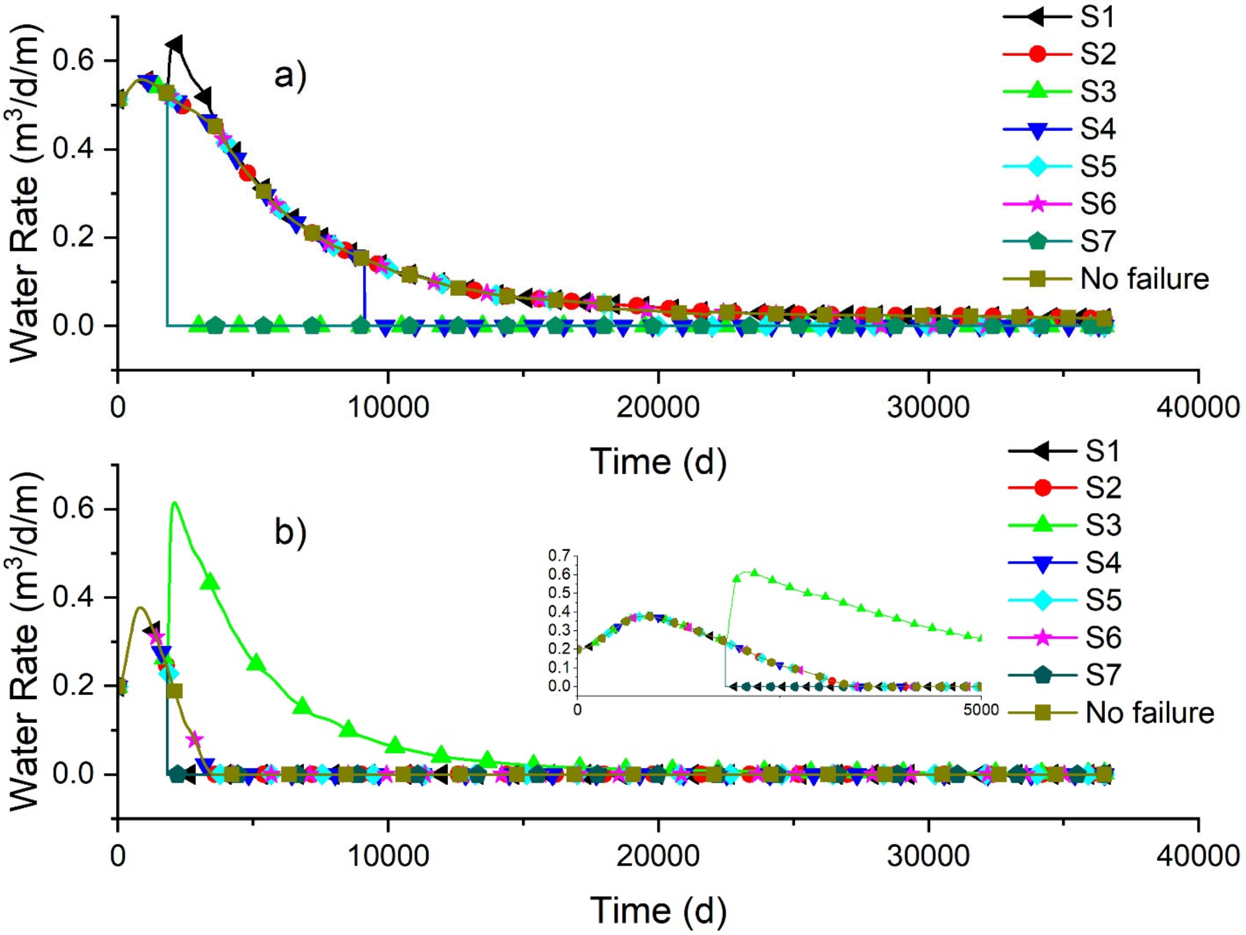


Figure 6-13: Drain outflows over time for drain scenarios for a) level 1 drains b) level 2 drains

Table 6-12: Maximum difference between scenario total head and no failure condition over model run time for all piezometers for drain scenarios

Legend	$\Delta H_{T(max)}$, t = 0 – 100 years		≤ 1 m		1-5 m		≥ 5 m	
Scenario ID	**Piezometer**							
	1	2	3	4	5	6	7	8
1	0.5	0.2	0.5	0.5	0.5	0.9	1.0	0.0
2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
3	6.1	0.2	6.2	6.2	6.2	6.5	5.9	7.2
4	5.7	0.0	5.7	5.7	5.7	6.1	5.5	6.0
5	2.1	0.0	2.1	2.1	2.1	2.5	1.9	1.6
6	0.8	0.0	0.8	0.8	0.8	1.2	0.8	0.4
7	17.6	7.1	17.7	17.7	17.7	18.1	17.4	19.7

Table 6-13: Difference between scenario total head and no failure condition 1 year after scenario change all piezometers for drain scenarios

Legend	ΔH_T, t = 1 year after change		≤ 1 m		1-5 m		≥ 5 m	
Scenario ID	**Piezometer**							
	1	2	3	4	5	6	7	8
1	0.4	0.2	0.5	0.5	0.5	0.9	1.0	0.0
2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
3	0.4	0.2	0.5	0.5	0.5	1.8	1.4	0.0
4	0.1	0.0	0.2	0.2	0.3	1.3	0.7	0.0
5	0.0	0.0	0.1	0.1	0.1	0.3	0.0	0.0
6	0.0	0.0	0.0	0.0	0.0	0.2	0.0	0.0
7	2.3	0.8	3.0	3.1	3.1	7.5	7.5	0.1

Table 6-14: Difference between scenario total head and no failure condition 5 years after scenario change all piezometers for drain scenarios

Legend	ΔH_T, t = 5 years after change		≤ 1 m		1-5 m		≥ 5 m	
Scenario ID	**Piezometer**							
	1	2	3	4	5	6	7	8
1	0.2	0.0	0.2	0.2	0.2	0.1	0.2	0.0
2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
3	0.7	0.1	0.7	0.8	0.8	2.0	1.7	0.3
4	1.4	0.0	1.7	1.7	1.7	3.1	2.7	0.2
5	0.6	0.0	0.7	0.7	0.7	1.3	0.7	0.0
6	0.1	0.0	0.2	0.2	0.2	0.6	0.2	0.0
7	7.7	4.2	8.4	8.4	8.4	12.1	12.1	0.7

Table 6-15: Difference between scenario total head and no failure condition 10 years after scenario change all piezometers for drain scenarios

Legend	ΔH_T, t = 10 years after change		≤ 1 m		1-5 m		≥ 5 m	
Scenario ID	**Piezometer**							
	1	2	3	4	5	6	7	8
1	0.1	0.0	0.1	0.1	0.1	0.1	0.1	0.0
2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
3	1.4	-0.3	1.6	1.6	1.6	2.8	2.5	0.6
4	2.6	0.0	2.8	2.8	2.8	3.9	3.4	0.4
5	1.1	0.0	1.2	1.2	1.2	1.8	1.1	0.2
6	0.3	0.0	0.4	0.4	0.4	0.8	0.4	0.1
7	10.5	4.6	11.0	11.0	11.1	13.9	13.8	1.9

6.2.2.5.2 Ponds on Reclamation Surface

Ponds may form on the reclamation surface via different mechanisms with the most predominate being consolidation and settlement of the landform cap or the infilled material. The formation of ponds on the reclamation surface represents both a dam evolution process and a hazard. It is expected that ponds may have a significant impact on the phreatic surface in a reclaimed tailings facility and should be investigated. The different pond formation scenarios that were modelled are outlined in Table 6-16. The pond formation scenarios were modelled using a total head boundary condition in a 1 m depression in the upstream area of the facility. In practice, this pond formation may be accompanied by substantial settlement; however, associated modelling of this is beyond the scope of this research. The pond formation scenarios evaluated the impacts of a pond forming at different points in time and assessed if the duration that a pond was present was important as a way to determine the importance of monitoring and maintenance. The response of the phreatic surface to the formation of a pond on the landform in the model should not be taken as a definitive indication of performance; rather, it should be used to understand how the phreatic surface might respond to pond formation.

Table 6-16: Pond formation scenarios

Scenario ID	Scenario Description
1	1 m deep pond forms at 10 years
2	1 m deep pond forms at 50 years
3	1 m deep pond forms at 75 years
4	1 m deep pond forms at 10 years and remains for 1 year
5	1 m deep pond forms at 10 years and remains for 10 years
6	0.5 m deep pond forms at 10 years

The different modelling scenarios were assessed based on the piezometer total heads over time (Figure 6-14), drain outflows over time (Figure 6-15), and the final phreatic surface after 100 years (Figure C-26 to Figure C-31 in Appendix C: Seepage Modelling). The base case where a pond does not form is provided on Figure 6-14 and Figure 6-15 for comparison purposes. Figure 6-14 and Figure 6-15 show that the formation of a pond on the reclamation surface has the potential to have a substantial impact on the phreatic surface as total heads at the piezometer locations and drain outflows rise above initial levels for some of the scenarios.

The difference between the scenario total heads at each of the piezometer locations and the base case where the drains have not failed were also evaluated and are summarized in the following:

- Table 6-17: The maximum total head difference measured over the 100-year modelling time;
- Table 6-18: Total head difference 1 year after the scenario change;
- Table 6-19: Total head difference 5 years after the scenario change; and
- Table 6-20: Total head difference 10 years after the scenario change.

Scenarios 1 to 3 evaluate the impact of a 1 m deep pond forming at different points in time and remaining for the duration of the model run. For these three scenarios, the total head for Piezometers 1 to 7 rises at the respective times (10, 50 and 75 years) to about the same total head (above the initial total head) and remains constant for the remainder of the model run. As shown in Table 6-17, the maximum difference between the scenario total heads and the base case where no pond forms is greater than 6.5 m for all piezometers (except for Piezometer 8). Table 6-18, shows that the total head is slow to increase 1 year after the ponds form. For example, for Scenario 1, the total head difference for Piezometer 1 at 1 year is 0 m. This changes rapidly with a total head difference of 8.4 m at 5 years (Table 6-19) and 12.4 m at 10 years (Table 6-20). Piezometer 8 shows less of a change in response to the pond formation compared to the other piezometers with a maximum difference from the base case of 0.6 m for Scenario 1, 0.4 m for Scenario 2, and 0.1 m for Scenario 3. Similar to the total heads, the drain outflows for Scenarios 1 to 3 rise to the same water rate at the respective times (10, 50, and 75 years). These scenarios show that a pond forming on the reclamation surface has the potential to impact the phreatic surface regardless of what point in time it forms.

Scenarios 4 and 5 investigated the impact of how long the pond remained on the reclamation surface. Scenario 4 considered the pond forming at year 10 and remaining for 1 year. For this scenario, the total heads for Piezometers 1 to 7 begin to rise initially and then decrease back down to the no pond condition following removal. The maximum total head difference between the scenario and the base case did not exceed 5 m for all piezometers (Table 6-17), and the total heads do not rise above the initial condition. The total head difference peaks between 1 year and 5 years following the pond formation and decreases after that. The level 2 drain outflow is not impacted at all, indicating that the formation of the pond did not result in a rise in the phreatic surface above the level 2 drains. The level 1 drains show an increase in the drain outflow initially that decreases following pond removal and does not rise above the initial drain outflow.

Scenario 5 considered the pond forming at year 10 and remaining for 10 years. For this scenario, the total head for Piezometers 1 to 7 rose to the same level as Scenarios 1 to 3 above the initial condition and then decreased back down to the no pond condition following pond removal. The level 1 and level 2 drain outflows show an increase in the drain outflow that decreases following pond removal. Scenarios 4 and 5 showed that the duration that a pond remains on the reclamation surface may be critical to the impact on the phreatic surface. This type of scenario analysis may be useful in guiding long-term maintenance and monitoring schedules.

Scenario 6 investigated the impact of the pond depth by evaluating the impact of a 0.5 m pond forming at year 10. For this scenario, the total heads and drain outflows increase similar to Scenario 1 (1 m pond); however, the total heads and drain outflows tend to be slightly below those of Scenario 1. For example, the maximum total head difference for Piezometer 1 for Scenario 6 is

17.9 m compared to 18.2 m for Scenario 1. This indicates that the depth of the pond can impact the phreatic surface, although the impacts experienced in this model were minor.

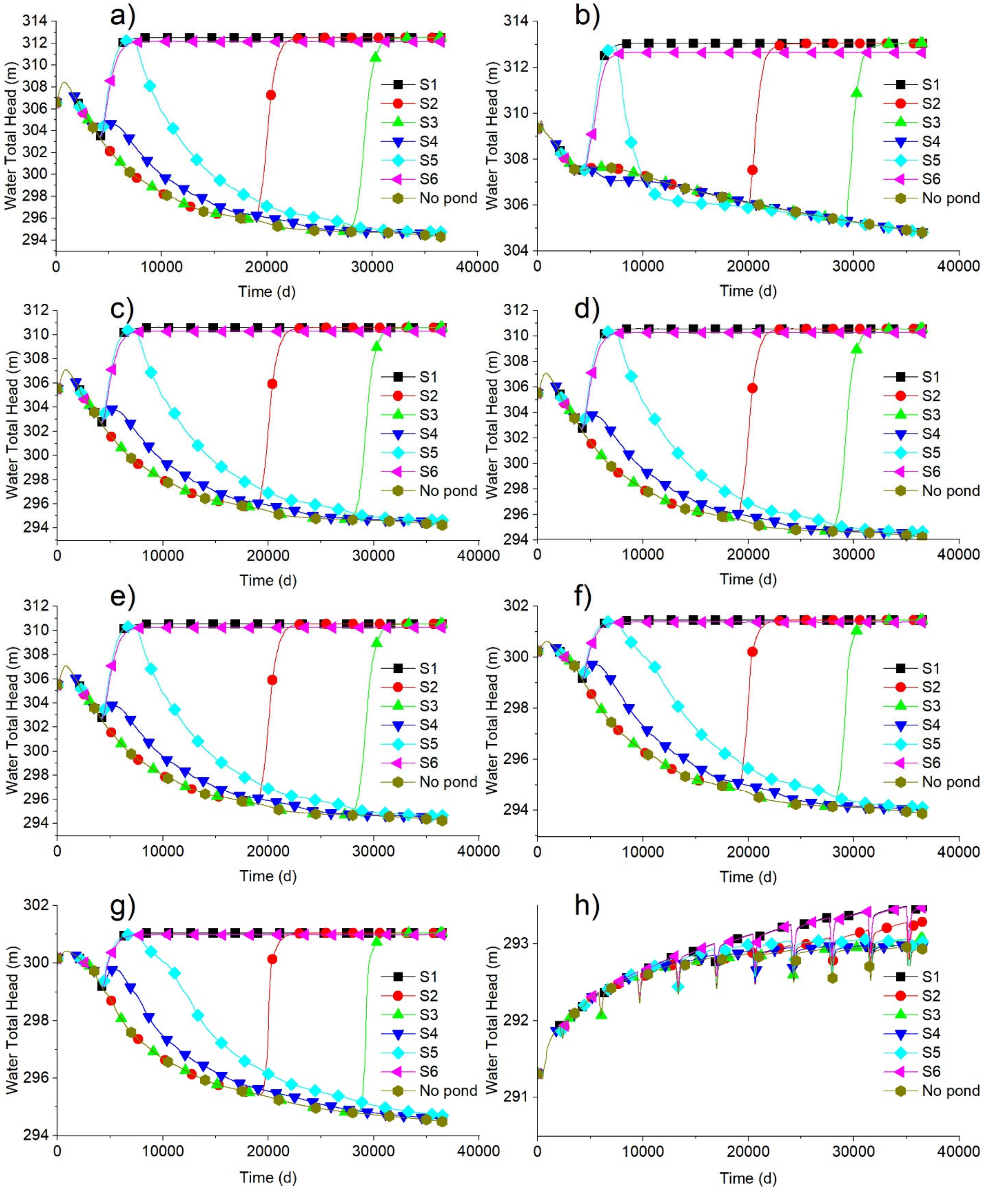


Figure 6-14: Total head over time for pond formation scenarios for a) Piezometer 1 b) Piezometer 2 c) Piezometer 3 d) Piezometer 4 e) Piezometer 5 f) Piezometer 6 g) Piezometer 7 h) Piezometer 8

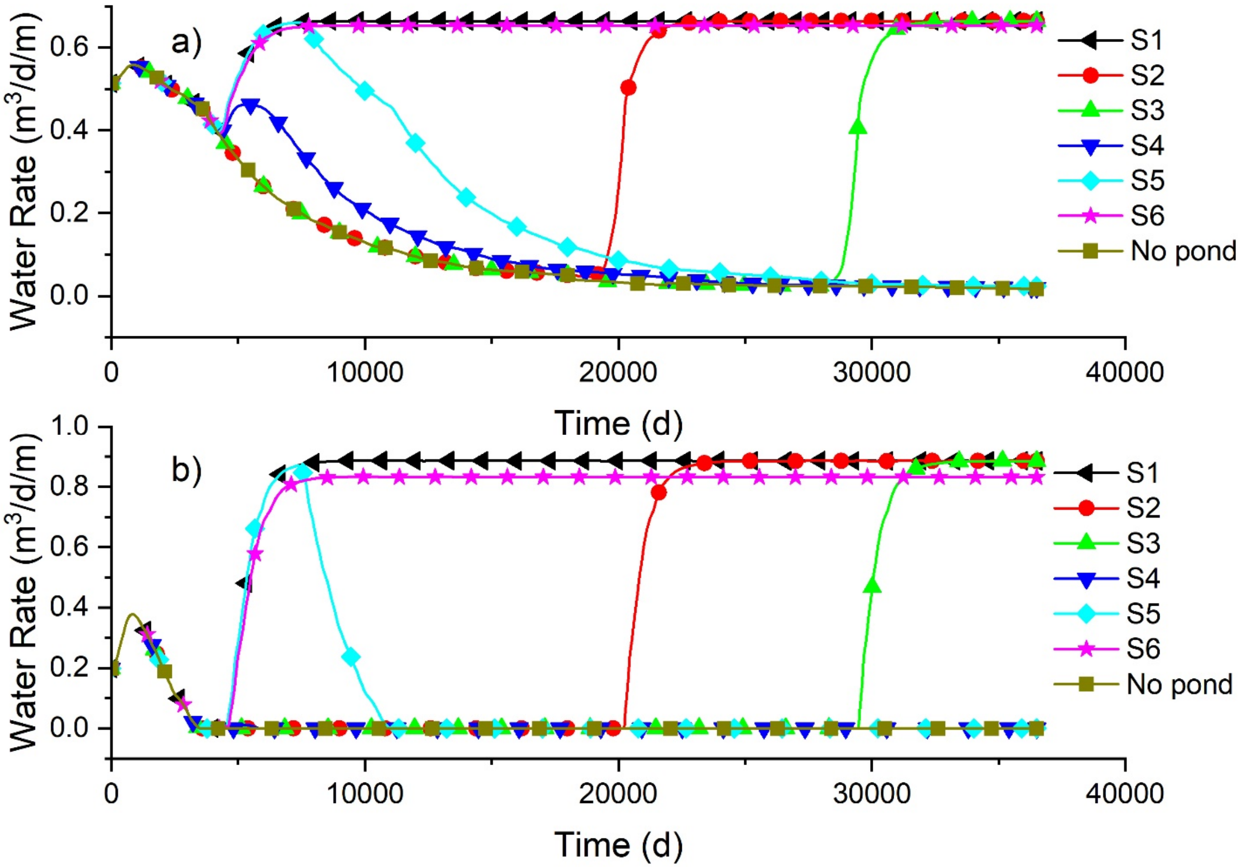


Figure 6-15: Drain outflows over time for pond formation scenarios for a) level 1 drains b) level 2 drains

Table 6-17: Maximum difference between scenario total head and no failure condition over model run time for all piezometers for pond formation scenarios

Legend	$\Delta H_{T(max)}$, t = 0 – 100 years		≤ 1 m		1-5 m		≥ 5 m	
Scenario ID	**Piezometer**							
	1	2	3	4	5	6	7	8
1	18.2	8.2	16.3	16.3	16.3	7.6	6.6	0.6
2	18.2	8.2	16.3	16.3	16.3	7.6	6.6	0.4
3	18.2	8.2	16.3	16.3	16.3	7.6	6.6	0.1
4	3.2	0.0	2.9	2.9	2.9	1.7	1.6	0.0
5	12.5	5.3	11.0	11.0	11.0	4.2	3.6	0.1
6	17.9	7.8	16.1	16.0	16.0	7.5	6.5	0.5

Table 6-18: Difference between scenario total head and no failure condition 1 year after scenario change all piezometers for pond formation scenarios

Legend	ΔH_T, t = 1 year after change		≤ 1 m		1-5 m		≥ 5 m	
Scenario ID	**Piezometer**							
	1	2	3	4	5	6	7	8
1	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0

Table 6-19: Difference between scenario total head and no failure condition 5 years after scenario change all piezometers for pond formation scenarios

Legend	ΔH_T, t = 5 years after change		≤ 1 m		1-5 m		≥ 5 m	
Scenario ID	**Piezometer**							
	1	2	3	4	5	6	7	8
1	8.4	2.7	7.3	7.3	7.3	2.6	2.2	0.0
2	8.3	0.0	7.3	7.3	7.3	3.9	3.3	0.0
3	7.9	0.0	6.9	6.9	6.9	3.7	2.0	0.0
4	2.8	-0.2	2.6	2.6	2.6	1.4	1.3	0.0
5	8.4	2.7	7.3	7.3	7.3	2.6	2.2	0.0
6	7.9	2.2	6.8	6.8	6.8	2.5	2.1	0.0

Table 6-20: Difference between scenario total head and no failure condition 10 years after scenario change all piezometers for pond formation scenarios

Legend	ΔH_T, t = 10 years after change		≤ 1 m		1-5 m		≥ 5 m	
Scenario ID	**Piezometer**							
	1	2	3	4	5	6	7	8
1	12.4	5.3	10.9	10.9	10.9	4.1	3.5	0.0
2	17.1	6.7	15.3	15.3	15.2	7.0	5.8	0.0
3	17.4	7.3	15.6	15.6	15.6	7.3	6.3	0.0
4	2.8	-0.5	2.6	2.6	2.6	1.6	1.5	0.0
5	12.4	5.3	10.9	10.9	10.9	4.1	3.5	0.0
6	12.1	4.9	10.6	10.6	10.6	4.0	3.5	0.0

6.2.2.5.3 Downstream Slope Erosion

It is expected that erosion will occur on a reclaimed and closed tailings facility over time as it is geomorphically altered from external forces (i.e., from precipitation, vegetation, wind). This may be especially true in the oil sands where the structures are constructed using highly erodible sand. As erosion is an expected external process, the impact of erosion on the phreatic surface was investigated. The erosion scenarios were guided using Slingerland (2019), which investigated erosion of a similar oil sands dam using a Landscape Evolution Model (LEM). Slingerland (2019) conducted a 200-year simulation on the TSF and showed that the majority of changes on the downstream slopes occurred in the first 60 years where large gullies developed and progressed retrogressively inward through the dam (Slingerland 2019). The LEM showed gullies develop along the bottom half of the downstream slopes initially, which was attributed to the higher water content in the soil in this area, accumulation of water, and a concentration of flow (Slingerland 2019). In some cases, gullies were found to be up to 20 m deep and one was notably 1250 m long and reached back into the central tailings storage area (Slingerland 2019).

Erosion scenarios were modelled by altering the geometry at specific time frames to mimic the removal of material. The model simulated significant erosion events resulting in a major gulley occurring at a moment in time (i.e., from an extreme event) rather than very small amounts of erosion over large time scales due to model capabilities. The erosion scenarios modelled are outlined in Table 6-21. Scenario 1 considers a 10 m deep gully fully forming at 10 years in the lower half of the downstream slope and remaining stable for the duration of the model run time. The LEM results from Slingerland (2019) that showed a 10 m gully formed in the toe berm of a similar oil sands dam at 10 years was used to guide this scenario. It should be noted that Slingerland (2019) showed that this erosion gully eroded further (>15 m) over the following years; however, this scenario focussed on the initial 10 m deep gully to evaluate the response of the phreatic surface. Similarly, Scenario 2 considers the formation of a 10 m gully forming by year 10; however, the erosion was imposed more slowly over time (2 m occurring every 2 years). This modelling scenario was specifically chosen to evaluate if any changes to the phreatic surface in Scenario 1 were a response to the modelling conditions rather than erosion.

Erosion Scenarios 3 and 4 were selected to evaluate if erosion on the upper half of the downstream slope had an impact on the phreatic surface. As with Scenarios 1 and 2, a 10 m deep gully forming at 10 years (Scenario 3) and over 10 years (Scenario 4) were modelled to evaluate if phreatic surface changes were due to modelling conditions or in response to erosion. It is expected that a gully would form in the upper portion of the downstream slope following the extension of a gully in the lower portion moving upwards as indicated by Slingerland (2019). This was found to be accompanied by the deposition of material in the lower portion following erosion from the upper portion (Slingerland 2019). However, for the purposes of this modelling, erosion in the upper and lower portion of the downstream slope were decoupled to evaluate the impact on the phreatic surface. The erosion in the upper portion of the downstream slope was selected to occur at 10 years (rather than closer to 50 years) as the phreatic surface in the dam is higher at 10 years and may represent a more critical point for evaluating impacts from erosion.

Table 6-21: Erosion scenarios

Scenario ID	Scenario Description
1	10 m deep gully at 10 years in lower half of downstream slope
2	10 m deep gully forms over 10 years (2 m every 2 years) in lower half of downstream slope
3	10 m deep gully at 10 years in upper half of downstream slope
4	10 m deep gully forms over 10 years (2 m every 2 years) in upper half of downstream slope

The different modelling scenarios were assessed based on the piezometer total heads over time (Figure 6-16), drain outflows over time (Figure 6-17), and the final phreatic surface after 100 years (Figure C-32 to Figure C-35 in Appendix C: Seepage Modelling). The base case where erosion does not occur is also provided on Figure 6-16 and Figure 6-17. Figure 6-18 and Figure 6-19 show a comparison between the base case with no erosion and each of the 4 scenarios for the total heads and drain outflows, respectively. The maximum total head difference between the scenarios and the base case where no erosion has occurred was also evaluated and is summarized in Table 6-22. The results of the modelling show a minimal impact on the phreatic surface in response to erosion on the downstream slope.

For Scenarios 1 and 2, Piezometer 6 fluctuates for a short period of time following formation of the 10 m deep gully as shown in Figure 6-16. The formation of the 10 m deep gully results in the removal of material below the elevation of Piezometer 7 for Scenarios 1 and 2. Significant impacts are seen at Piezometer 8 following erosion for Scenarios 1 and 2 compared to the other piezometers as shown in Figure 6-16 and Figure 6-18. This fluctuation is attributed to the removal of soil from the toe resulting in a more significant impact to the total head from the infiltration boundary condition (fluctuates in response to climatic factors). The maximum total head difference for Piezometer 8 is -1.4 m and -1.5 m for Scenarios 1 and 2, respectively. In comparison, the maximum total head difference for the other piezometers for Scenarios 1 and 2 is less than 1 m. For the drain outflows, the level 1 drain outflows fluctuates following erosion for Scenarios 1 and 2 as shown in Figure 6-17 and Figure 6-19. For Scenario 2, Figure 6-17 shows that the level 2 drain starts running dry before the no erosion base case. Scenarios 1 and 2 were conducted to evaluate the impact of modelling the erosion event as happening instantaneously versus over a period of time. Minor differences were encountered between the two approaches.

For Scenarios 3 and 4, little to no impact was experienced in the total heads at the piezometer locations or in the drain outflows compared to the no erosion base case as shown in Figure 6-16 to Figure 6-19. As with Scenarios 1 and 2, Scenario 3 and 4 were conducted to evaluate the impact of modelling the erosion event as happening instantaneously versus over a period of time. No differences were encountered between the two approaches.

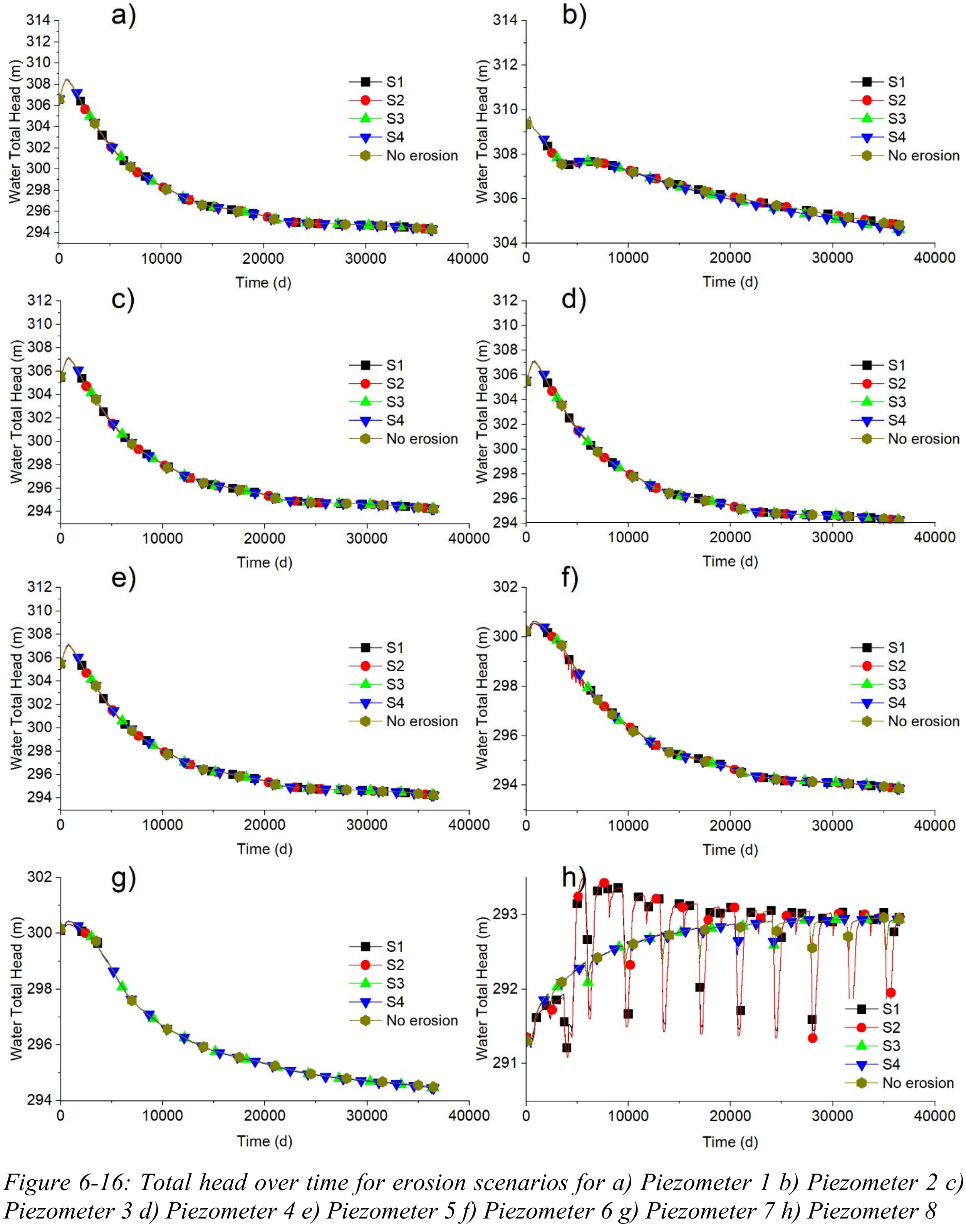


Figure 6-16: Total head over time for erosion scenarios for a) Piezometer 1 b) Piezometer 2 c) Piezometer 3 d) Piezometer 4 e) Piezometer 5 f) Piezometer 6 g) Piezometer 7 h) Piezometer 8

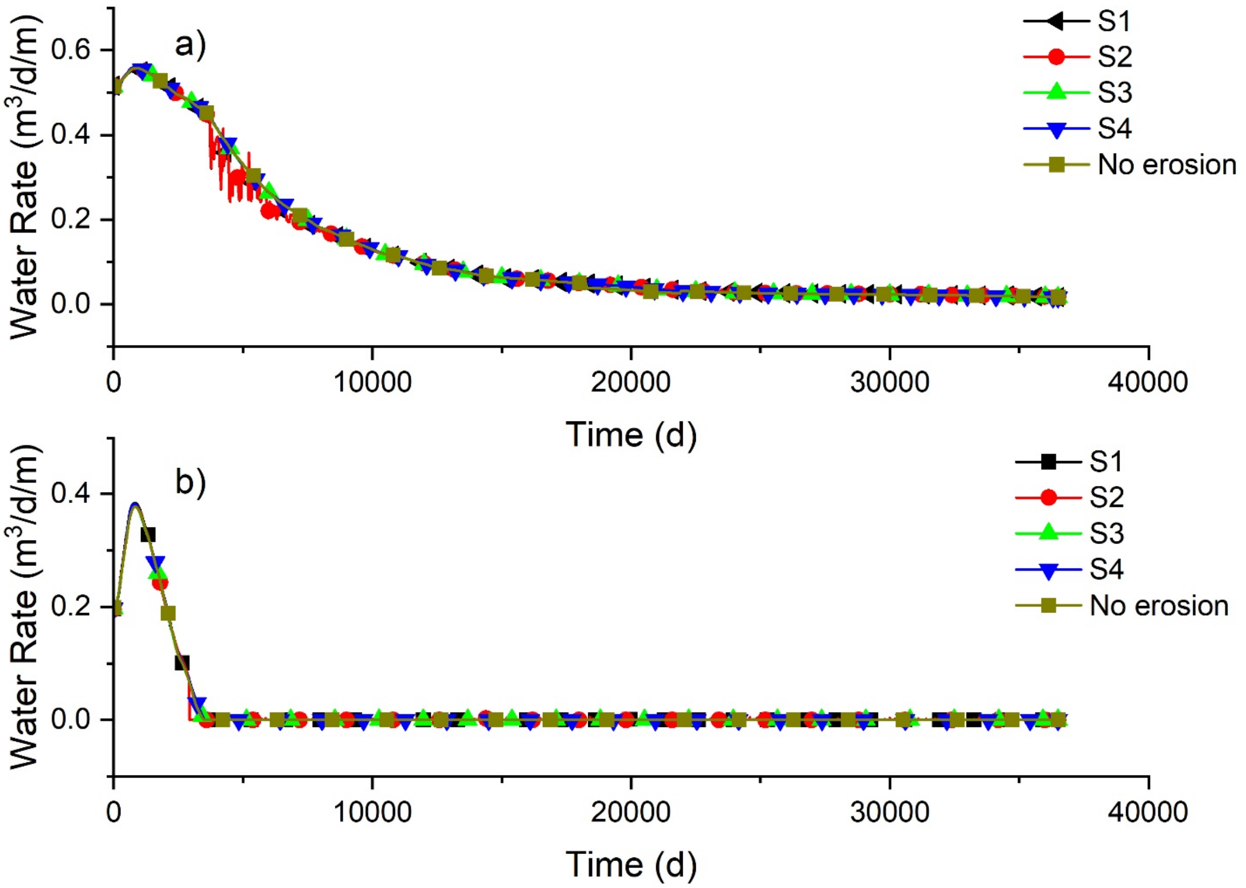
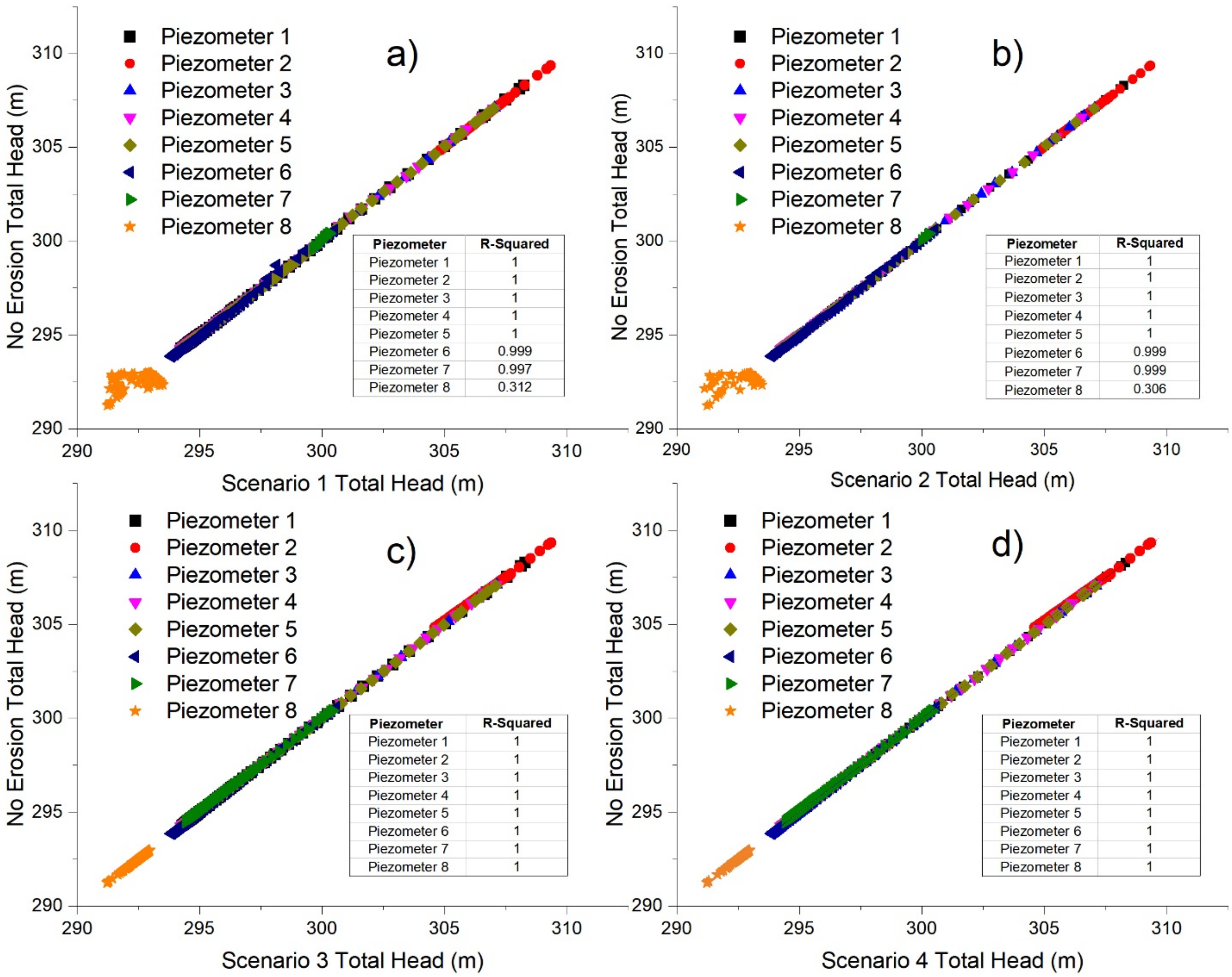


Figure 6-17: Drain outflows over time for erosion scenarios for a) level 1 drains b) level 2 drains



a)

Piezometer	R-Squared
Piezometer 1	1
Piezometer 2	1
Piezometer 3	1
Piezometer 4	1
Piezometer 5	1
Piezometer 6	0.999
Piezometer 7	0.997
Piezometer 8	0.312

b)

Piezometer	R-Squared
Piezometer 1	1
Piezometer 2	1
Piezometer 3	1
Piezometer 4	1
Piezometer 5	1
Piezometer 6	0.999
Piezometer 7	0.999
Piezometer 8	0.306

c)

Piezometer	R-Squared
Piezometer 1	1
Piezometer 2	1
Piezometer 3	1
Piezometer 4	1
Piezometer 5	1
Piezometer 6	1
Piezometer 7	1
Piezometer 8	1

d)

Piezometer	R-Squared
Piezometer 1	1
Piezometer 2	1
Piezometer 3	1
Piezometer 4	1
Piezometer 5	1
Piezometer 6	1
Piezometer 7	1
Piezometer 8	1

Figure 6-18: Total head for no erosion compared to a) Scenario 1 b) Scenario 2 c) Scenario 3 d) Scenario 4

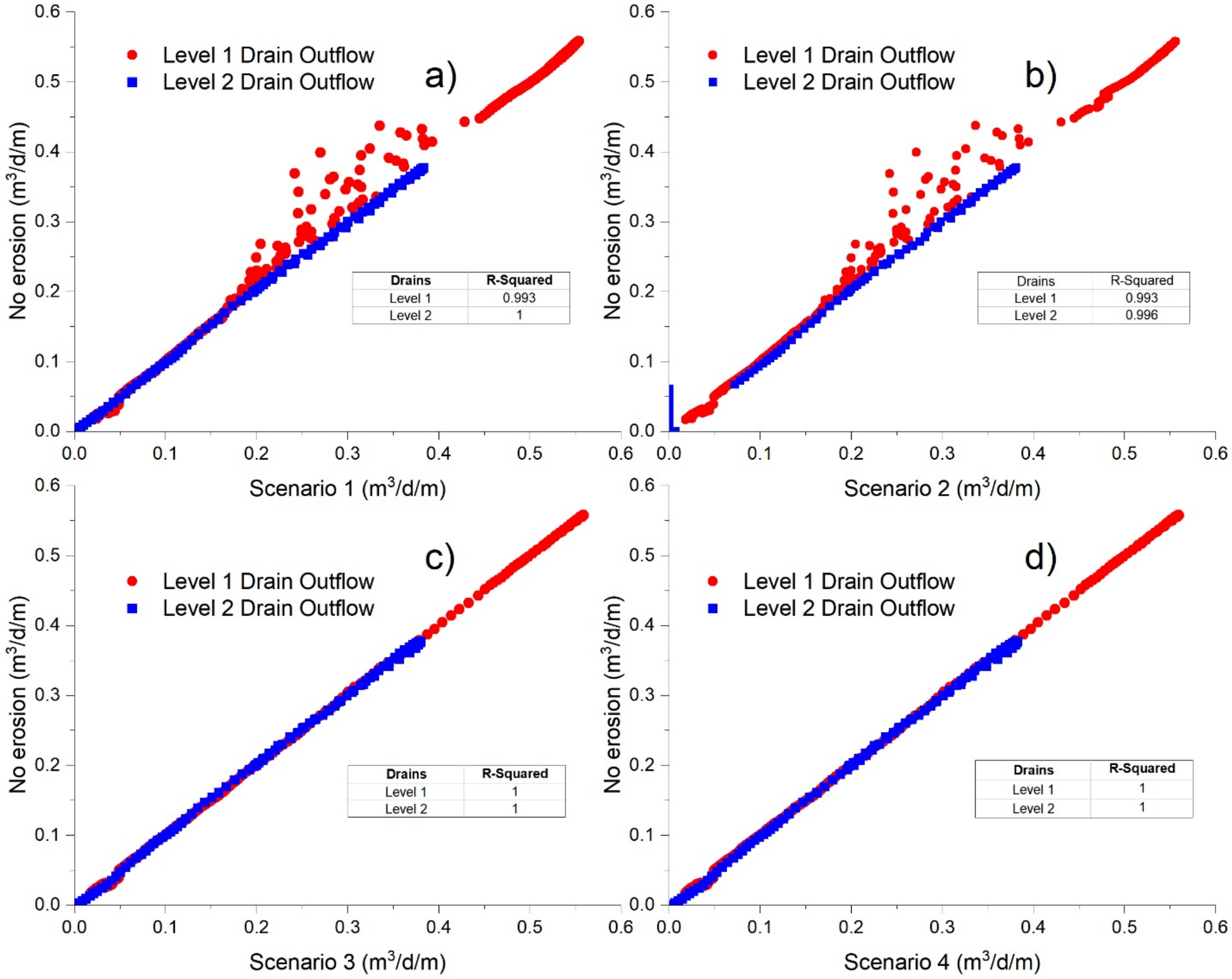


Figure 6-19: Drain outflows for no erosion compared to a) Scenario 1 b) Scenario 2 c) Scenario 3 d) Scenario 4

Table 6-22: Maximum difference between scenario total head and no failure condition over model run time for all piezometers for erosion scenarios

<table>
<tr><th>Legend</th><th colspan="2">$\Delta H_{T(max)}$,
t = 0 – 100 years</th><th colspan="2">≤ 1 m</th><th colspan="2">1-5 m</th><th colspan="2">≥ 5 m</th></tr>
<tr><td rowspan="2">Scenario ID</td><td colspan="8">Piezometer</td></tr>
<tr><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td><td>6</td><td>7</td><td>8</td></tr>
<tr><td>1</td><td>-0.1</td><td>0.0</td><td>-0.1</td><td>-0.1</td><td>-0.1</td><td>-0.7</td><td>-</td><td>-1.4</td></tr>
<tr><td>2</td><td>-0.1</td><td>0.0</td><td>-0.1</td><td>-0.1</td><td>-0.1</td><td>-0.7</td><td>-</td><td>-1.5</td></tr>
<tr><td>3</td><td>0.0</td><td>-0.2</td><td>0.0</td><td>0.0</td><td>0.0</td><td>0.0</td><td>0.0</td><td>-0.1</td></tr>
<tr><td>4</td><td>0.1</td><td>-0.2</td><td>0.1</td><td>0.1</td><td>0.1</td><td>0.0</td><td>0.0</td><td>-0.1</td></tr>
</table>

6.2.2.5.4 Climate Change

It is common practice to use historic climate information when conducting long-term analysis (Ferguson et al. 2009, KCB 2018), as done in simulations in Sections 6.2.2.5.1 to 6.2.2.5.3. However, this is changing as regulations move towards expecting operators to account for long-term failure modes that may not be present during operations and develop risk profiles that account for the uncertainties in predicting the future, including climate change. Due to the potential impact on the phreatic surface, climate change scenarios were investigated to determine if the results were significant enough to warrant using climate projections (especially at a preliminary design level). It should be noted that this modelling considers the impact of climate change on the overall phreatic surface and does not evaluate the impact of climate change on other failure mechanisms or pathways (i.e., covers that may be used on the TSF or the progression of erosion).

To account for climate change, global climate models (GCMs) can be used to provide information regarding long-term changes to annual and seasonal precipitation, season length, air temperature, etc. (IPCC 2014). GCMs allow for climate change projections to be conducted at a coarse spatial scale (typically over a 300 km grid) (Lane et al. 2007, Kuo et al. 2014). Finer-scale models can be generated by combining the GCM with regional topography and climate characteristics (Lane et al. 2007, Kuo et al. 2014). GCMs use time dependent scenarios of greenhouse gas emissions and atmospheric concentrations, air pollutant emissions, and land use, referred to as Representative Concentration Pathways (RCPs) (IPCC 2014). There are four RCPs representing different emission scenarios, including: stringent mitigation of emissions (RCP 2.6), two intermediate scenarios (RCP 4.5 and RCP 6.5), and minimal mitigation of emissions (RCP 8.5) (IPCC 2014).

The climate change projections for the seepage modelling were developed using global emission scenarios generated by the Intergovernmental Panel for Climate Change (IPCC) (IPCC 2014). Two scenarios were conducted to evaluate the impact of climate change to the year 2100, which represents the time period that climate change projections are available in the greatest detail. The climate change scenarios were compared to a base case that used historic climate information. The scenarios are outlined in Table 6-23, and are based on two GCMs (CSIRO-Mk2-6-0 and IPSL-CM5A-LR) and one RCP (RCP 8.5). RCP 8.5 was selected to evaluate how the most extreme emissions scenario would impact the phreatic surface. Temperature and precipitation data were attained for the GCMs from ClimateData.ca from the CMIP5 climate model datasets, which were downscaled and bias-adjusted using the BCCAQv2 method (McKenney et al. 2011, ClimateData.ca 2022). This allowed for daily maximum temperature, minimum temperature, and precipitation to be attained for the GCMs and RCPs. The daily maximum and minimum temperature was converted into an hourly temperature using Equation 6-7 from GEO-SLOPE International Ltd. (2020), which assumes that the minimum and maximum temperature occur at 1:00 and 13:00, respectively. Historical data were used for the remaining climatic data required for the LCI boundary condition (relative humidity, snow depth, albedo, wind speed, solar radiation).

$$T_a = \frac{T_{max} + T_{min}}{2} + \frac{T_{max} - T_{min}}{2} \cos\left[2\pi\left(\frac{t-13}{24}\right)\right] \tag{6-7}$$

Where: T_a is the hourly air temperature, T_{max} is the maximum temperature, T_{min} is the minimum temperature, and *t* is the time in hours since 00:00:00.

Table 6-23: Climate change scenarios

Scenario ID	Scenario Description
1	CSIRO-Mk2-6-0 RCP 8.5
2	IPSL-CM5A-LR RCP 8.5

The different modelling scenarios were assessed based on the piezometer total heads over time (Figure 6-20), drain outflows over time (Figure 6-21), and the final phreatic surface after 100 years (Figure C-36 to Figure C-37 in Appendix C: Seepage Modelling). The base case where climate change does not occur is also provided on Figure 6-20 and Figure 6-21. The maximum total head difference between the scenarios and the base case where no climate change has occurred was also evaluated and is summarized in Table 6-24. The results of the modelling show a minimal impact on the phreatic surface in response to the integration of climate change into the LCI boundary condition.

For Piezometers 1, 3, 4, 5, 6, and 7, there is a minimal difference between the no climate change base case and the climate change scenarios as shown in Figure 6-20. This is also clear by Table 6-24, which shows that the maximum total head difference between the no climate change base case and the two scenarios is less than 0.5 m for Piezometers 1, 3, 4, 5, 6, and 7. The most substantial differences between the no climate change base case and the scenarios can be seen in Piezometer 2 and 8. For Piezometer 2, the tip elevation of the piezometer is at 310.6 m, and the phreatic surface is below the tip. Consequently, the total head variation in Figure 6-20 is attributed to suction (negative porewater pressures). Other scenarios have shown that Piezometer 8 (installed in the berm) is impacted the most substantially by climate. As a result, the variation of Scenarios 1 and 2 from the no climate change base case near Piezometer 8 is attributed to fluctuations in response to climatic factors from the climate change models.

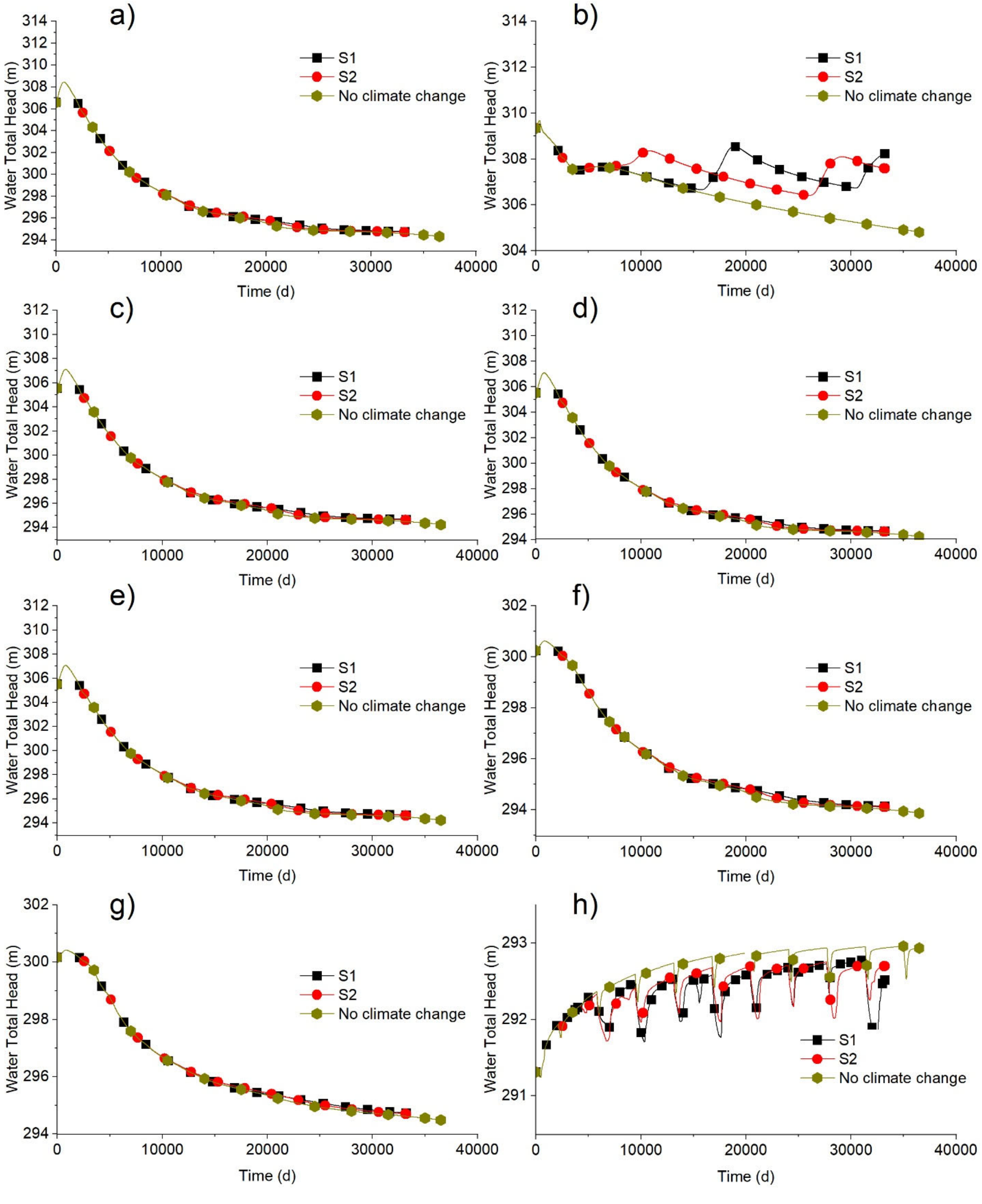


Figure 6-20: Total head over time for climate change scenarios for a) Piezometer 1 b) Piezometer 2 c) Piezometer 3 d) Piezometer 4 e) Piezometer 5 f) Piezometer 6 g) Piezometer 7 h) Piezometer 8

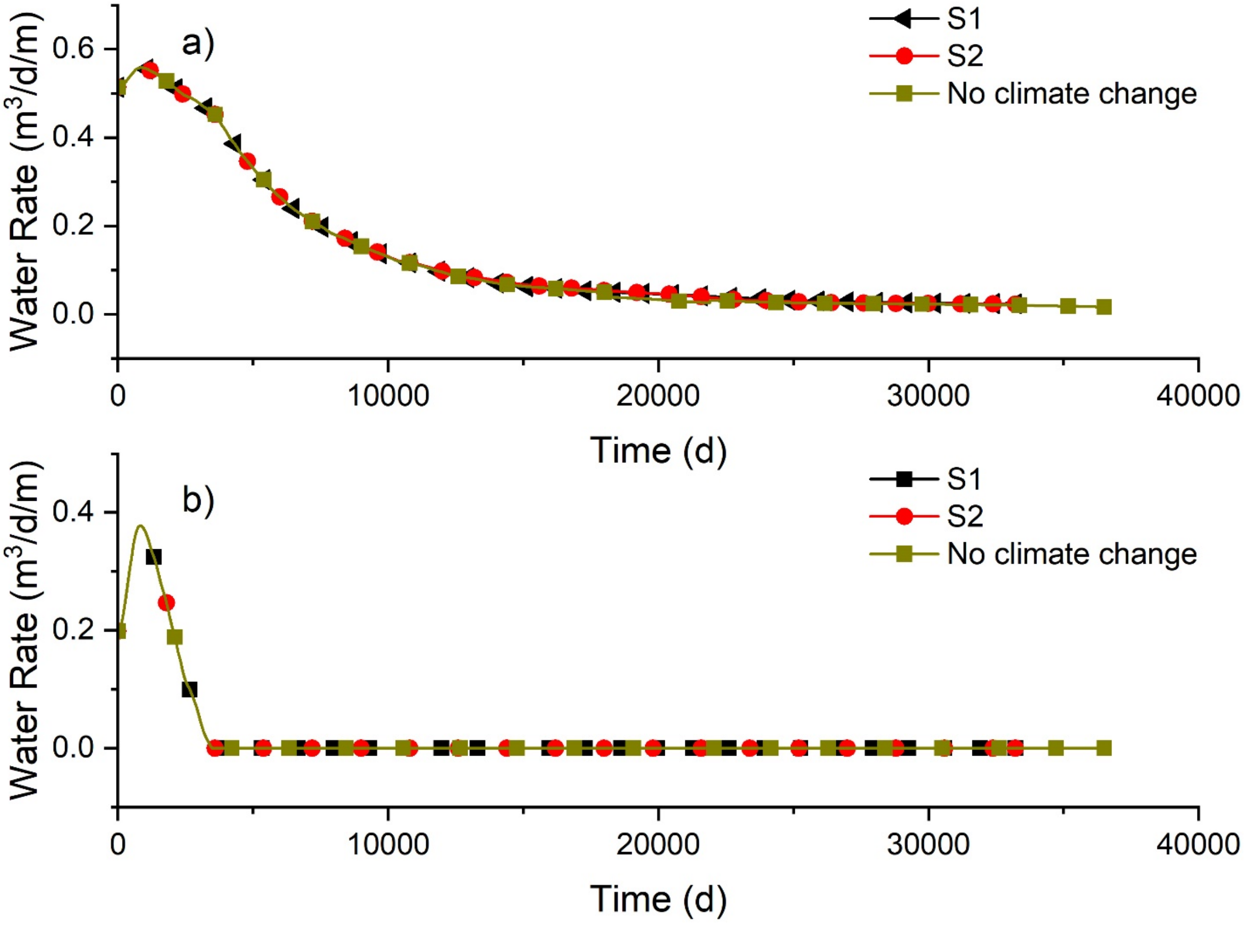


Figure 6-21: Drain outflows over time for climate scenarios for a) level 1 drains b) level 2 drains

Table 6-24: Maximum difference between scenario total head and no failure condition over model run time for all piezometers for climate change scenarios

Legend	$\Delta H_{T(max)}$, t = 0 – 100 years		≤ 1 m		1-5 m		≥ 5 m	
Scenario ID	**Piezometer**							
	1	2	3	4	5	6	7	8
1	0.5	2.4	0.4	0.4	0.4	0.3	0.2	-1.0
2	0.4	2.8	0.3	0.3	0.3	0.2	0.1	-0.9

6.3 Discussion

The impact of different potential changes to the phreatic surface of a case study dam were investigated using transient seepage modelling with the intent of demonstrating how a modelling tool could be used to reduce uncertainty in risk management. The risk management tool developed in Section 4 and applied to a case study site in Section 5 acknowledges the significance of the long-term evolution of the phreatic surface in response to external factors (climate change) or serviceability failures that may occur in the dam (i.e., drain failure). It is commonly assumed that the phreatic surface of a reclaimed tailings dam will decrease over time; however, these assumptions need to be supported by literature from other sites, field performance, and modelling projections due to the importance of the phreatic surface on the stability of the facility. To aid in this, long-term modelling was conducted as a tool to help understand how the phreatic surface in a tailings facility may evolve in response to external changes. This approach is a method that can be used to understand uncertainty associated with assumptions and aid in managing risk. To demonstrate this, the risk assessment conducted in Section 5.1.3.3.1 that evaluated the risk associated with particulate clogging of the level 2 drains was re-assessed following the completion of the seepage modelling. This work is detailed in Section 6.3.1. The seepage modelling work was also used to develop a framework for assessing the long-term evolution of the phreatic surface as outlined in Section 6.3.2.

A detailed review of literature on closed tailings dams showed that industry needs to be conducting further research into long-term TSF behaviour, while publishing industry data of historical dams that have been closed. Pushing forward in this direction will aid in informing long-term risk management decisions. A review of closed TSFs in BC showed that some facilities did show signs that the phreatic surface was decreasing over time. However, it would be greatly beneficial to industry to show how these phreatic surfaces have evolved over time in comparison to projections made for the facility.

Steady state seepage modelling was conducted to calibrate the material properties. However, steady state seepage modelling is only able to calibrate transmissivity (hydraulic conductivity) and cannot be used to calibrate the specific storage (SWCC), which should be calibrated using transient modelling. Unfortunately, closure of the TSF had not been completed at the time of modelling so the SWCCs were not able to be calibrated using transient modelling. Instead, a scenario analysis using different SWCCs was conducted to evaluate the impact of different curves on the overall model conclusions. The results showed that the various scenarios resulted in similar model conclusions and long-term trends. It is worth noting that the hydraulic conductivity curves and SWCCs for the tailings sand are very steep, which can make convergence difficult.

Following the completion of the SWCC scenarios, the response of the phreatic surface in the dam to different potential changes over time were evaluated, including: drain failure, ponds forming on the reclamation surface, downstream slope erosion, and climate change. For each of these changes, multiple scenarios were evaluated. The results from each of these groups of changes impacted the phreatic surface of the dam differently and can be used to inform and guide risk management decisions, including monitoring and maintenance schedules, where applicable. The generalized impact to the phreatic surface from the different changes is summarized in Table 6-25.

Table 6-25: Generalized impact to phreatic surface from different model changes

Model Changes	**Generalized Impact to Phreatic Surface**
Drain failure	• Influenced by location of phreatic surface at time that failure occurs • Results in an increase in phreatic surface if the initial phreatic surface is above the drain at time of failure
Pond formation on reclamation surface	• Substantial impact in phreatic surface in response to pond formation regardless of when the pond forms following closure • Short duration ponds do not have a significant impact on the long-term phreatic surface
Downstream slope erosion	• Negligible impact on phreatic surface
Climate change	• Negligible impact in phreatic surface

The phreatic surface increased with drain failure when the phreatic surface was above the drain. This has important implications for guiding maintenance plans during periods when drain performance is critical to controlling the phreatic surface. For example, the results showed that the level 2 drain failure does not impact the phreatic surface following 10 years as the phreatic surface is sufficiently low (Scenario 2 in Figure 6-12). Consequently, maintenance of the level 2 drains may be more important in the first 10 years, especially when there is the potential for the level 1 and level 2 drains to fail together (Scenario 7 in Figure 6-12). This is discussed further in Section 6.3.1.

A pond forming on the reclamation surface was modelled at different points in time, remaining for different points of time, and with different depths. All scenarios showed a substantial impact on the phreatic surface in response to the pond formation. It should be noted that there are limitations of the modelling approach as it is expected that the formation of a pond would be accompanied by settlement and a corresponding change in material properties. This was beyond the scope of this work. However, the general trend showed that there needs to be a careful evaluation of the impact of a pond forming on the reclamation surface, especially for closure plans that are designed to have wetlands incorporated into the reclamation surface.

Downstream slope erosion did not have an impact on the phreatic surface in the model. It is not known at this time if this is a limitation of approaching this in 2D, which does not consider the width of the gully. This could be evaluated using a 3D seepage model. Additionally, erosion features commonly develop during operations on the downstream slope. These events could be used to evaluate the porewater pressure response to the erosion event and aid in making long-term predictions of the expected behaviour of the phreatic surface to erosion events. Such an exercise can be used to 'build a story' to support or disprove modelling predictions.

The implementation of climate change resulted in minor changes in the phreatic surface with the most substantial changes seen near Piezometer 8, which is attributed to climatic factors. Overall, the long-term trends remained generally the same. Consequently, it may be appropriate to use historical data sets for the LCI boundary condition in the early planning stages.

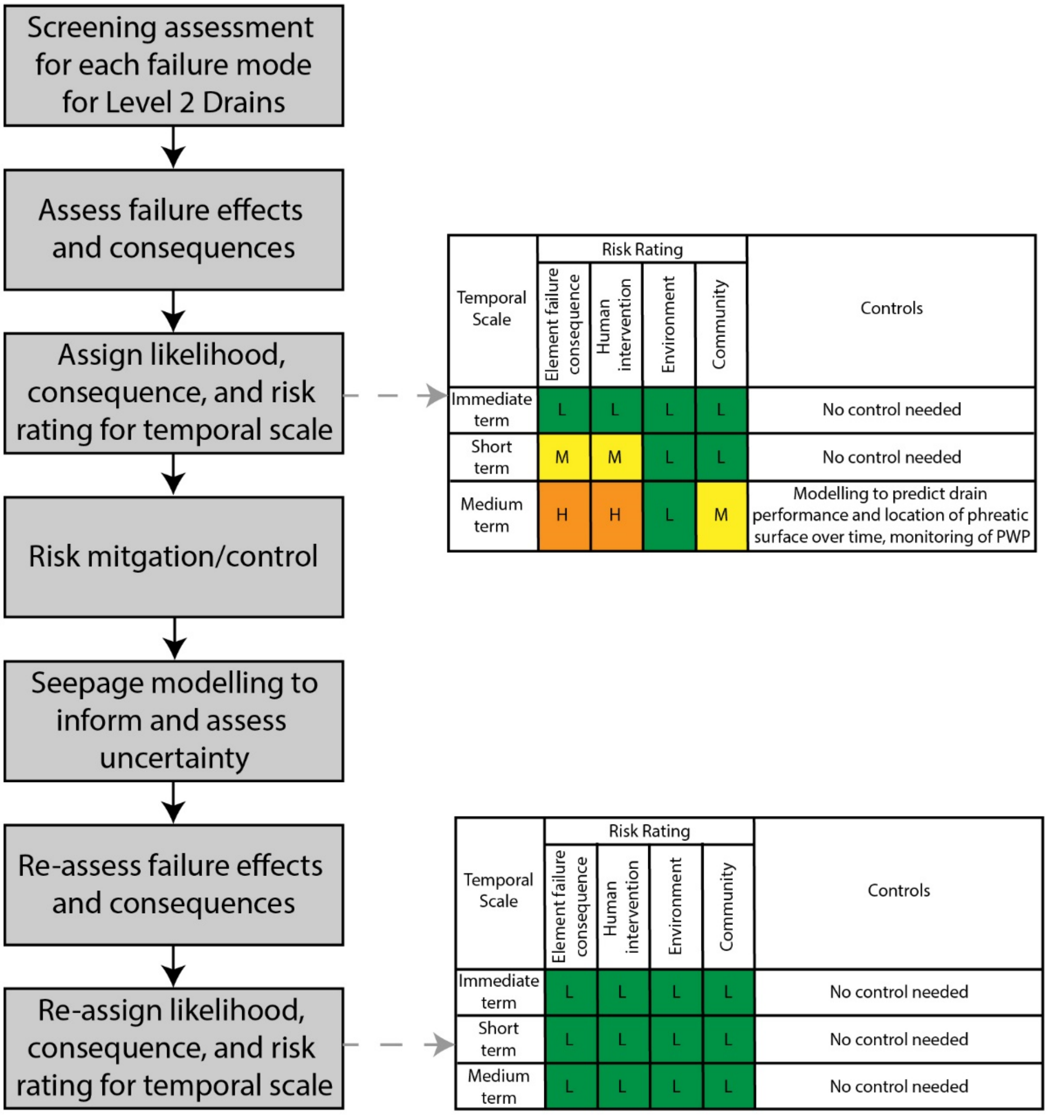
6.3.1 Updated Level 2 Drains Risk Assessment

Section 5 implemented the G-FMEA framework to a case study oil sands site to demonstrate its application, which included an assessment of potential failure modes for individual elements. Following this step, two failure modes were selected to demonstrate how the likelihood, consequence, and risk rating may be assigned for different temporal scales. This included an assessment of the particulate clogging of the level 2 drains as shown in Table 5-3. At the time that the risk assessment was conducted, no seepage modelling had been completed. As such, there was uncertainty associated with the risk assessment. One of the suggested controls was modelling to predict the location of the phreatic surface over time to evaluate if the consequence or likelihood ratings could be adjusted with an increase in understanding of how the phreatic surface may evolve. The amended risk assessment based on the seepage modelling is provided in Table 6-26, and the workflow showing the process of completing and updating the risk assessment for the particulate clogging of the level 2 drains is provided in Figure 6-22.

The seepage modelling of drain failure in Section 6.2.2.5.1 showed that failure of the level 2 drains at 10 years and beyond (short-term and medium-term temporal scales) had no impact on the phreatic surface as the phreatic surface was already predicted to be below the level 2 drain by that point in time. Consequently, there was a drop in the consequence ratings for the short-term and medium-term scenarios to the lowest level of 'slight'. Failure of the level 2 drains at 5 years before the phreatic surface drops below the level 2 drains was also investigated. For this scenario, there was a maximum increase in the total head of 0.971 m above the no failure condition near the Piezometer 7 location (Table 6-12). This increase should be compared to historical behaviour and trigger levels set for the facility. Despite the increase, the phreatic surface does decrease following failure. Combined with an anticipated site presence in the first 10 years following tailings dam closure, a 'slight' consequence rating was assigned for all the categories for the immediate-term temporal scale. The assigned likelihood ratings for the different temporal scales were not altered from the original risk assessment. The alteration of the consequence ratings for the different categories results in a low-risk rating for all categories for all temporal scales (element failure consequence, human intervention, environment, and community).

Table 6-26: Amended immediate-term, short-term, and medium-term risk assessments for particulate clogging of level 2 drains

Temporal Scale	**Likelihood**	**Consequences**				**Risk Rating**				**Controls**
		Element failure consequence	**Human Intervention**	**Environment**	**Community**	**Element failure consequence**	**Human Intervention**	**Environment**	**Community**	
Immediate term	Very rare	Slight	Slight	Slight	Slight	L	L	L	L	No control needed
Short term	Rare	Slight	Slight	Slight	Slight	L	L	L	L	No control needed
Medium term	Possible	Slight	Slight	Slight	Slight	L	L	L	L	No control needed



Temporal Scale	Risk Rating				Controls
	Element failure consequence	Human intervention	Environment	Community	
Immediate term	L	L	L	L	No control needed
Short term	M	M	L	L	No control needed
Medium term	H	H	L	M	Modelling to predict drain performance and location of phreatic surface over time, monitoring of PWP

Temporal Scale	Risk Rating				Controls
	Element failure consequence	Human intervention	Environment	Community	
Immediate term	L	L	L	L	No control needed
Short term	L	L	L	L	No control needed
Medium term	L	L	L	L	No control needed

Figure 6-22: Workflow for updating risk assessment of particulate clogging of level 2 drains

It is important to note that this updated risk assessment does not consider combined failure modes. For example, Section 6.2.2.5.1 also investigated the impact of the level 1 and level 2 drains failing simultaneously after 5 years. This scenario had a substantial impact on the total heads and the drain outflows (a maximum total head difference between the scenario and the no failure base case of 17.437 m near Piezometer 7 as shown in Table 6-12). Further, Section 6.2.2.5.2 investigated the impact of ponds forming on the reclamation surface. This assessment showed that the pond formation resulted in the phreatic surface rising above the level 2 drains again (regardless of the point in time that the pond forms). This would result in a very different risk assessment than the one presented in Table 6-26. The G-FMEA does evaluate the impact of a consequence of a failure on another element in the dam to serve as a trigger, but does not account for combined failure modes. While the G-FMEA does not explicitly represent these combined scenarios, they can be projected and incorporated, such that a risk assessment is conducted for them.

6.3.2 Framework for Assessing Long-term Evolution of the Phreatic Surface

Understanding the long-term evolution of the seepage system in a closed tailings dam is important to managing the long-term risk as it contributes greatly to the potential for failure modes to develop. Seepage modelling allows practitioners to develop an understanding of how the phreatic surface of a tailings dam may evolve over time and use this information to inform risk decisions, especially with relation to failure mode development (e.g., change in phreatic surface leading to a change in mean effective stress and the potential for static liquefaction). As shown in Section 6.3.1, seepage modelling can be used to update risk assessments by reducing uncertainty. While a useful tool, seepage modelling should be supported by field data and confirmation of behaviour. Figure 6-23 shows how data can be collected and used to support seepage modelling to increase the level of confidence in the model conclusions, which then aids in risk management and the goal of de-registration.

Figure 6-23 provides a list of data that can be collected during preliminary design (before any construction has occurred), operations, and closure to inform the initial long-term modelling. As the life cycle of the facility progresses, data should be continuously collected and used to update the model, as required. Further, ongoing monitoring and data collection following closure allows for seepage model predictions to be compared to field data. As this process continues, the risks associated with the facility can be re-assessed (for example, using the G-FMEA tool as in Section 6.3.1) and the design can be adapted, as needed.

The data to be collected includes three main categories, including: climate data, material properties, and piezometer and drain response to specific events. The climate data are important to determining infiltration to establish the upper boundary condition for the tailings dam. Data from nearby climate stations can be used; however, climate can vary greatly over small distances and as such, site specific climate stations are recommended, where available. Material properties to be collected include the hydraulic conductivity and SWCC. As shown in Section 6.2.2.5.4, climate change scenarios had a minor impact on the model results for the case study. Consequently, climate change may not need to be integrated into the seepage model for this case study site at the preliminary design stage but should always be integrated into final design predictions.

Material properties should be determined throughout the life cycle of the facility. At the preliminary design stage, this may be based on site investigation data or from nearby sites (i.e., for the tailings materials), if available. As the life cycle of the tailings dam proceeds, material properties should be assessed on an ongoing basis to allow for the model to be updated. For example, it is possible that material properties may change over time following reclamation and closure due to processes such as settlement or the degradation of dewatering aids, such as polymers. While there is staff on site in the active management stage these properties should be closely monitored. This information can be used to update and inform the model as it may have an impact on the anticipated long-term behaviour. This process also allows for further calibration of the transient model to mitigate issues associated with SWCC calibration.

The last set of data that should be collected includes piezometer and drain response to specific events. It is expected that most tailings dams will have monitoring programs to evaluate performance. During operations, monitoring programs can be used to aid in informing the validity of long-term seepage predictions by evaluating the response of the dam to external changes. For example, Section 6.2.2.5.3 showed that the phreatic surface was not substantially impacted by erosion on the downstream slope in the seepage model. Such a prediction could be validated through field observations during operations, especially on large sand dams where erosion gullies form often. Following reclamation and closure, piezometer and drain responses can be used to compare the expected behaviour to the actual behaviour, which will be an essential step to creating a story for de-registration to the regulator. Again, during this stage of the life cycle, the behaviour in response to specific events can aid in validating the model predictions – such as with ponds forming on the reclamation surface, which showed a substantial increase in the phreatic surface.

Using the data collected during design, operations, and reclamation/closure, long-term seepage modelling can be conducted. Recommended seepage modelling includes a base case long-term evolution mode and a scenario analysis (drain failure, pond formation, climate change, and downstream slope erosion). If material properties are noted to be changing during closure, the model must be updated and re-evaluated. As shown in Figure 6-23, it is expected that the ability of the model to predict real-world performance would increase as the dam moves through its life cycle and additional data are collected to inform and update the model. Figure 6-23 shows the potential difference from real world conditions decrease over time as additional information is gathered. Examples of data that can be used to improve the accuracy of the model are provided in Figure 6-23.

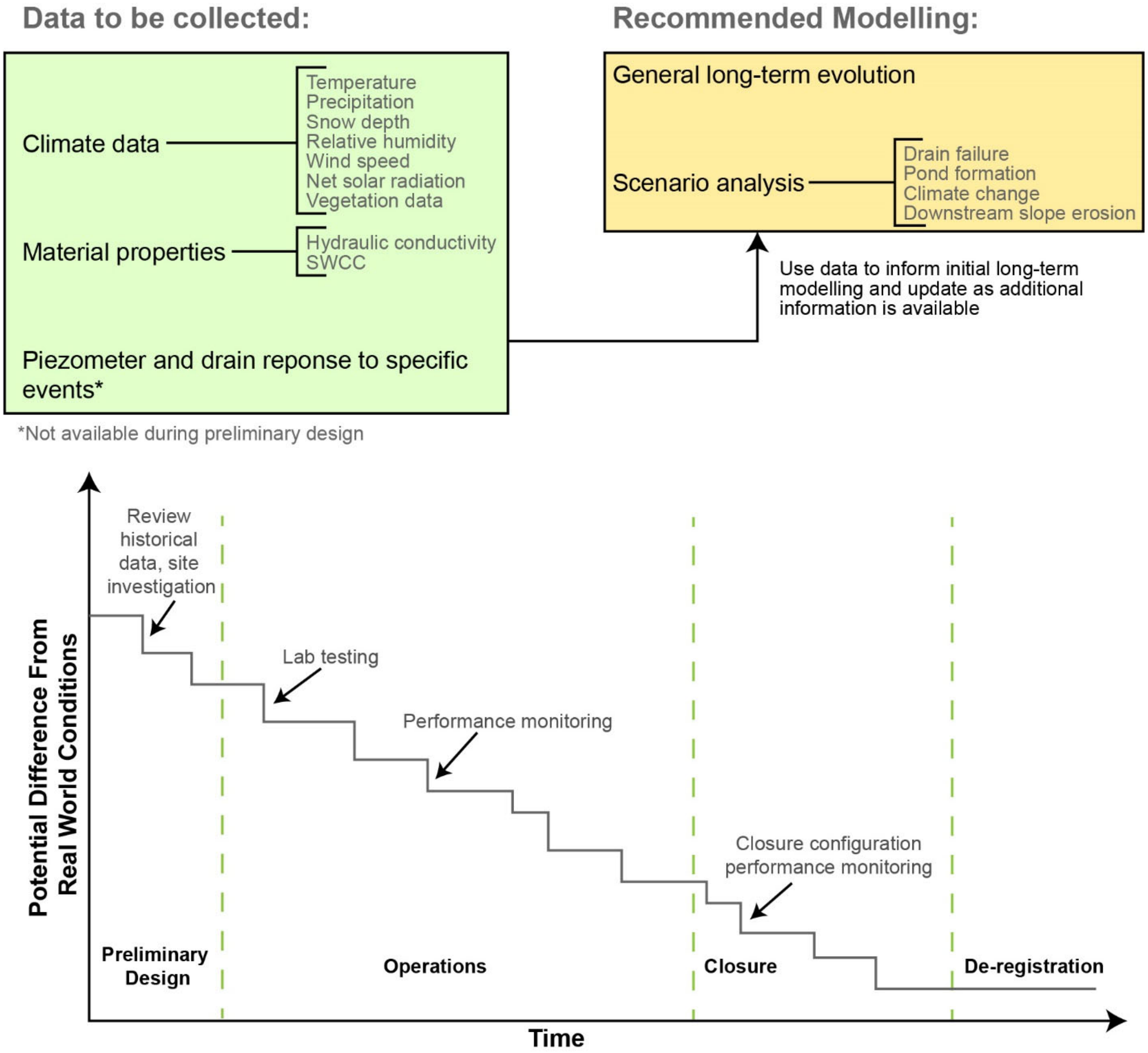


Figure 6-23: Framework for long-term seepage modelling

Long-term seepage modelling can be used to help guide monitoring and maintenance plans, which can be anchored back to the observational method or an adaptive management framework (both of which are forms of risk management). It is worth a reminder that the observational method and adaptive management frameworks both require contingency plans for scenarios where the facility is not behaving as expected, which long-term seepage modelling can help with. As an example, Section 6.3.2 showed that a pond forming on the reclamation surface resulted in a substantial increase in the phreatic surface, regardless of the point in time that it happened at. Scenario 4 investigated the impact of a 1.0 m pond forming at year 10 and remaining for only 1 year. In this scenario, the phreatic surface increased rapidly, but did not rise above the initial condition (Figure 6-14). In contrast, the pond remained for 10 years in Scenario 5 and the phreatic surface rose substantially above the initial condition before lowering following the removal of the pond (Figure 6-14). This may suggest that a 1-year maintenance schedule (combined with regular monitoring) is required to respond to the formation of any ponds on the reclamation surface to prevent the phreatic surface from rising above the initial condition (if the initial condition is deemed to be concerning from a stability perspective). The schedule could be amended as more is learned about the dam's behaviour in closure and compared to the seepage modelling predictions. As with anything in closure, this requires a realistic evaluation of the custodial transfer scenario. The process of using long-term seepage modelling to guide monitoring and maintenance plans is all a part of the process of continuously learning and creating a 'story' to build a comprehensive case towards de-registration.

6.4 Summary and Conclusions

Long-term seepage modelling was conducted on a case study oil sands tailings dam to investigate how the phreatic surface of a tailings dam may evolve over time in response to various factors. The objective of this was to illustrate a method that could be used to reduce uncertainty in the G-FMEA. Rises in the phreatic surface can be critical to the development of failure modes in the tailings dam. The seepage modelling showed that the phreatic surface has the potential to rise in response to different events, including the formation of ponds on the reclamation surface and drain failure. The predicted rise should be compared to historical piezometer levels as a way of assessing how critical the change in the phreatic surface may be to the potential for a failure mode to develop.

The seepage modelling was used to update the risk assessment conducted on the level 2 drains in Section 5.1.3.3.1. This showed that the consequences of the level 2 drains failing decreased resulting in a decrease in the corresponding risk ratings. Ultimately, seepage modelling can be used as a tool to understand complex processes and reduce uncertainty to manage the risk.

Long-term seepage modelling requires data to be collected during design, operations, and closure/reclamation, including climate data, material properties, and piezometer and drain outflows. These data can be used to inform the model and update it as additional information is available. Over time, it is expected that the accuracy of the prediction will increase as more data is collected and used to update the model.

Seepage modelling represents one tool that can be used to reduce uncertainty in long-term behaviour in the effort to de-register tailings dams and can be accompanied by other methods, such as LEM to understand the geomorphology. These tools allow practitioners to forecast complex processes and employ engineering judgement in risk management decisions. The confidence in these tools may be increased over time through the comparison of model predictions to field data.

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7 CONCLUSIONS, CONTRIBUTIONS, AND RECOMMENDATIONS

7.1 Conclusions

The overall purpose of this research, as discussed in Chapter 1, was to develop a framework to support determining and assessing the long-term risks associated with tailings dams in Alberta for coal and oil sands mines as they transition into a landform. This work evaluated the state of knowledge on the long-term physical performance of tailings dams and demonstrated the significant uncertainty associated with the closure phase of a tailings dam. A risk management tool was developed, referred to as the Generalized Failure Modes Effects Analysis (G-FMEA) framework, to support the process of dam de-registration for external tailings facilities in Alberta through the identification of hazards of a tailings dam using an element approach. Application of the G-FMEA framework to a case study oil sands tailings dam was completed to demonstrate the application of the framework. Seepage analysis on the case study oil sands tailings dam was conducted to show how modelling tools can be used to support the process of risk management by reducing uncertainty. Overall, the work developed and applied a method for evaluating and reducing uncertainty with tailings dam closure through the use of risk management.

The overall research purpose was achieved through five objectives, as discussed in Chapter 1. The research objectives were addressed throughout the previous chapters, and the conclusions are discussed below:

Synthesize available information on the physical performance of tailings dams undergoing closure in Canada.

Available information on the physical performance of tailings dams was evaluated in Chapters 2, 3, and 6. This involved a comprehensive literature review, interviews with industry professionals, and a review of published dam safety reports from British Columbia for closed tailings storage facilities. The review showed that there is a knowledge gap regarding long-term dam evolution and significant uncertainty associated with long-term tailings dam behaviour. This can be mitigated through comprehensive risk management practices. Additional research needs to be conducted into the long-term behaviour of tailings dams, specifically with regard to the mobility of tailings and liquefaction potential. Industry needs to publish case studies on closed tailings dams and how they have behaved in comparison to the anticipated, projected behaviour. These elements will be essential to conducting long-term risk management.

Identify the broad potential failure modes and largest uncertainties associated with closure of tailings dams in Alberta, based on polling opinions of industry professionals.

One of the key elements to the development of the G-FMEA was the identification of hazards, triggers, failure modes, and uncertainties associated with closure of tailings dams. In Chapter 3, an interview protocol was developed to aid in this effort and the results of the interviews were presented. This process allowed for hazards, triggers, and failure modes to be categorized for different elements of the dam and emphasized the importance of dam evolution processes. Ultimately, the interviews emphasized a lack of consensus amongst practitioners regarding long-term dam evolution, which clearly showed the significant uncertainty associated with the long-time frame of tailings dam closure. This uncertainty is a primary reason why comprehensive risk management practices for tailings dam closure should be developed and integrated into practice, ideally at the outset of design.

Develop a risk-based tool to aid decision-making for tailings dam closure strategies and assessment, based on the widely applied failure modes effects analysis (FMEA) method (referred to as the Generalized-FMEA (G-FMEA)).

In Chapter 4, a risk management tool, referred to as the G-FMEA framework, was developed. The G-FMEA framework aims to address the objective: How should geotechnical risks associated with an external tailings facility in Alberta be managed in the long term to achieve an acceptable closure plan, such that the facility is able to be de-registered as a dam? The developed G-FMEA framework takes an element approach to conducting the FMEA and establishes the relationship between different elements through a block diagram. This process requires an assessment of serviceability failure of the individual elements and an understanding of the impact of the failure of an element on the rest of the system. The G-FMEA includes four individual charts for the drainage system, foundation, dam body, and landform, which includes a reasonably comprehensive list of element specific failure modes, triggers/causes, screening assessment questions, and failure effects. The G-FMEA framework requires the risk assessment to be conducted at four different points in time as a way of accounting for dam evolution processes, including the immediate term, short term, medium term, and long term. A risk matrix was developed for use with the G-FMEA, which includes a likelihood rating table, consequence rating table, and risk rating table. The developed risk matrix considered and integrated the known pitfalls associated with risk matrices into the development. Risk matrices should be colour coded through the process of meaningful engagement with stakeholders. Consequently, the final risk matrix was not colour coded; however, guidance was developed on how to colour code the risk matrix. The developed G-FMEA framework provides a systematic method to assess the risks following closure of tailings dams. It aims to provide an actionable tool that is consistent with the requirements of the Global Industry Standard on Tailings Management and Manual 019 from the Alberta Energy Regulator to support the process of de-registration. The G-FMEA evaluates the potential of a closure plan to support de-registration. An important element to the process of de-registration will be evaluating if the proposed closure plan aligns with what is being promised. It is essential that the closure plan, and any changes made following the G-FMEA, align with the agreed upon design basis memorandum.

Illustrate the application of the G-FMEA for a typical tailings dam in Alberta to provide an example application for practitioners.

In Chapter 5, the G-FMEA framework was applied to a case study oil sands dam to illustrate how the framework could be used in practice. The case study oil sands dam was broken down into subsystems and individual elements within each of those subsystems using a block diagram. Each element was assessed using the appropriate G-FMEA chart to determine applicable failure modes. Two example failure modes (particulate clogging of the level 2 drains and surface erosion of the berm) were selected to demonstrate how the risk matrix could be used to assign risk ratings for the different consequence categories. Risk ratings were assigned at different temporal scales to demonstrate how the risk could change over time. For both of the failure modes, the risk rating increases as the temporal scale increases (from immediate term to long term). This is partially attributed to the increasing uncertainty over time. Various tools, such as modelling, can be used to reduce the uncertainty in long-term predictions and aid in informing risk decisions. Completing the full G-FMEA allows the closure plan to be assessed based on the residual risk and thus allows the potential for de-registration to be assessed.

Demonstrate how the phreatic surface in a tailings dam may evolve over time using seepage modelling to illustrate a method that could be used to reduce uncertainty in the G-FMEA.

Chapter 6 explored the evolution of the phreatic surface in a case study oil sands tailings dam as a way of reducing uncertainty in the G-FMEA. Long-term seepage modelling was conducted on the tailings dam to evaluate how the phreatic surface responded to various factors, including drains failing, the formation of ponds on the reclamation surface, erosion on the downstream slope, and climate change. The results of the seepage modelling showed that the phreatic surface has the potential to rise in the long term in response to different events, including the failure of drains and ponds forming on the reclamation surface. The results of the seepage modelling were used to update the risk assessment conducted on the level 2 drains in Section 5 to demonstrate how modelling may be used to understand complex processes and reduce uncertainty. The resulting updated risk ratings decreased due to a decrease in the consequences associated with the level 2 drains failing. The seepage modelling was used to develop a framework for guidance for conducting long-term seepage modelling that included a list of data that should be collected to support the modelling. As more is learned about the dam over time, the model can be updated and improved. It is expected that the accuracy of the prediction will increase over time as the quality of the data improves. This work demonstrated how seepage modelling can be used to forecast complex processes to reduce uncertainty and inform risk management decisions.

7.2 Key Contributions

The following are key contributions from this research to the state of practice of long-term risk management of tailings dams. The chapter(s) where the contribution was presented, and the applicable research objective is provided in parentheses.

- The state of knowledge of long-term behaviour of tailings dams in Canada was synthesized (Chapter 2, 3, and 6; Objective 1).
- Aggregated tailings dam closure industry experience related to changing failure modes, closure challenges, development of hazards and triggers, impact of recent tailings dam failures, long-

term monitoring and surveillance, potential closure scenarios, and risk communication to aid in supplementing the identified knowledge gap associated with the long-term behaviour of tailings dams (Chapter 3; Objective 1 and 2).

- Developed a comprehensive hazard and trigger list for tailings dam failure following closure (Appendix B: Hazard Mapping; Objective 2 and 3).
- Developed a comprehensive risk management tool for long-term risk management of tailings dams to support the process of de-registration. Risk assessment is a requirement for DCA plans according to Manual 019 from the AER (Chapter 4; Objective 3).
- Identified long-term potential failure modes, triggers/causes, and failure effects for individual elements of tailings dam subsystems (Chapter 4; Objective 3).
- Recommended different temporal scales for conducting long-term risk assessments that are anchored to different periods of management of the tailings dam (Chapter 4; Objective 3).
- Developed a risk matrix, including a likelihood rating table, consequence rating table, and risk rating table. This was accompanied by guidance steps for colour coding a risk matrix with the input of stakeholders (Chapter 4; Objective 3).
- Demonstrated how the risk management tool could be used for a case study site and how this can be used to support de-registration (Chapter 5; Objective 4).
- Demonstrated how to conduct a detailed sensitivity analysis of a steady state seepage model and showed how the model output changes in response to different model changes (Chapter 6; Objective 5).
- Evaluated an alternative to using an LCI BC on a 2D model (Chapter 6; Objective 5).
- Demonstrated how to evaluate different SWCCs for inclusion in seepage modelling when transient model calibration is not possible (Chapter 6; Objective 5).
- Determined the impact of different long-term changes (drains failing, ponds forming on the reclamation surface, downstream slope erosion, and climate change) on the phreatic surface using seepage modelling (Chapter 6; Objective 5).
- Demonstrated how a modelling tool could be used to reduce the uncertainty in the G-FMEA (Chapter 6; Objective 5).
- Developed a framework for assessing long-term seepage evolution (Chapter 6; Objective 5).

7.3 Recommendations for Future Research

This research focused on the development of risk management tools in Alberta for the long-term management of external tailings facilities following closure. There is a need for further research into the long-term behaviour of tailings dams to aid in risk management, and the risk management tool could be expanded. The following is recommended for future research to advance the long-term risk management of tailings dams:

- Expand the G-FMEA framework to account for other jurisdictions and other configurations of tailings facilities (i.e., in-pit facilities).
- The G-FMEA framework was developed to account for technical geotechnical risks. The framework should be expanded or adjusted to incorporate methodology to manage and account for the human factors that contribute to failure (where human factors "…range from: the way we review evidence, make decisions and approach risk; unconscious social pressures; error; work cultures, whether dam safety management systems, company cultures or educational/mentoring; to preventing complacency and remaining vigilant" (Philip 2021)).
- The G-FMEA framework was limited to evaluating geotechnical risks. Custodial transfer of tailings dams will require the dam to be physically, chemically, ecologically, and socially stable. The framework should be expanded to integrate other disciplines to support the process of custodial transfer. Alternatively, it could be combined with other risk management tools.
- The G-FMEA did not provide explicit guidance for the aggregation of risks. Additional guidance on this should be developed. For example, guidance should be developed on how to use the risk matrix if all of the hazards are green (or green or yellow). Does the aggregation of all of these risks represent an intolerable risk?
- While the G-FMEA evaluates the impact of a consequence of a failure on another element in the dam to serve as a trigger, it does not account for combined failure modes. This limitation should be evaluated further to consider if it can be integrated into the framework explicitly.

- The G-FMEA framework should be accompanied by a level-of-confidence framework to evaluate the degree of uncertainty in an assigned risk rating. This research is currently underway by another researcher at the University of Alberta.
- A key element discussed during the interviews by interviewees was the uncertainty associated with the custodial transfer scenario for mining sites – will walk-away closure be possible? Unfortunately, there have been very few examples of successful walk-away closure globally where a tailings dam is reclaimed and transferred back to the regulating body thus relieving the operator of ongoing responsibilities. Overall, the research showed that walk-away closure scenarios may not be possible for many tailings dams due to the large number of failure modes, aggregation of failure modes, climate change, interaction between failure modes, associated long time frames, changing understanding of failure mechanisms as the dam evolves, changing societal and regulatory expectations, and the fact that many dams were not built with long-term considerations. In such scenarios, mechanisms must be developed to support long-term risk management by the mining company or the regulator. It is important that a practical and realistic view of the long-term care of the facility is developed now, such that it can be planned for. Further research is needed to evaluate alternative custodial transfer scenarios to support the long-term monitoring and maintenance of facilities that are not able to achieve walk-away closure. This will be key to successful risk management.
- Long-term seepage modelling is a useful tool to understanding complex processes. This work will be strengthened by comparison to field data for case study sites.
- Two-dimensional seepage modelling was conducted. Three-dimensional seepage modelling should be conducted to evaluate if the model conclusions from the downstream toe erosion were an artifact of approaching the problem in two-dimensions.
- The impact of the phreatic surface on the evolution of failure modes in the tailings dam should be evaluated. For example, how does drain failure increasing the phreatic surface impact the liquefaction susceptibility and the potential for embankment failure?

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Appendix A: Supplementary Information for G-FMEA

A.1 Discussion on Changing Probability

The probability of failure of the system may change over time as it requires consideration of the probability of failure of each individual failure mode. With respect to design, the probability of failure can be used to capture uncertainty in input parameters when predictive tools are used (Baecher and Christian 2003). For example, if the undrained shear strength of a soil is estimated from cone penetration testing, the probability of failure can be determined based on the distribution of the calculated factor of safety values based on the established undrained shear strength distribution. This application of the probability of failure does not have meaning in the context of tailings dam closure. Instead, the probability of failure is associated with uncertainty in determining deterioration of elements of the dam over time and changes to the frequency and effects of external triggers over time.

Ultimately, this is the reason why it is important to evaluate risk over time. The probability of failure of a particular failure mode may increase, decrease, or plateau over time as depicted in Figure 4-1. Consequently, as the probability of failure of one failure mode increases, another one may decrease. These considerations are important as the sum of the probability of failure of each failure mode for each element will determine the probability of failure of the system. Consider four failure modes (i=1, 2, 3, 4) and their probability of failure over time as shown in Figure A-1. Then, at any given time, the probability of failure of the system will be the combined probability of failure of each element of the system. This process is further complicated by the level of uncertainty or degree of confidence associated with a failure mode over time. For example, failure modes that may be triggered by extreme events or climate change may have a higher degree of uncertainty than foundation failure modes that are generally expected to have a decreasing risk over time as shown in Figure A-2. Decreasing foundation risk over time may be due to consolidation effects increasing the shear strength with time and performance of the structure reducing epistemic uncertainty associated with the closure analysis. The reliance of the probability of failure of the system on changing probabilities of failure and uncertainties over time of individual failure modes and elements emphasizes the importance of evaluating long-term tailings dam risk. Further, it could be argued that an FMEA should be conducted on a tailings dam as a whole as breaking the facility down into individual elements and conducting an FMEA for each element is too cumbersome. However, due to the changing uncertainty and probability of failure over time, it is important to take the time to break the system down into elements and conduct the FMEA in this manner. As such, the Generalized FMEA involves assessing the risk rating for failure modes of individual dam elements as opposed to the facility as a whole.

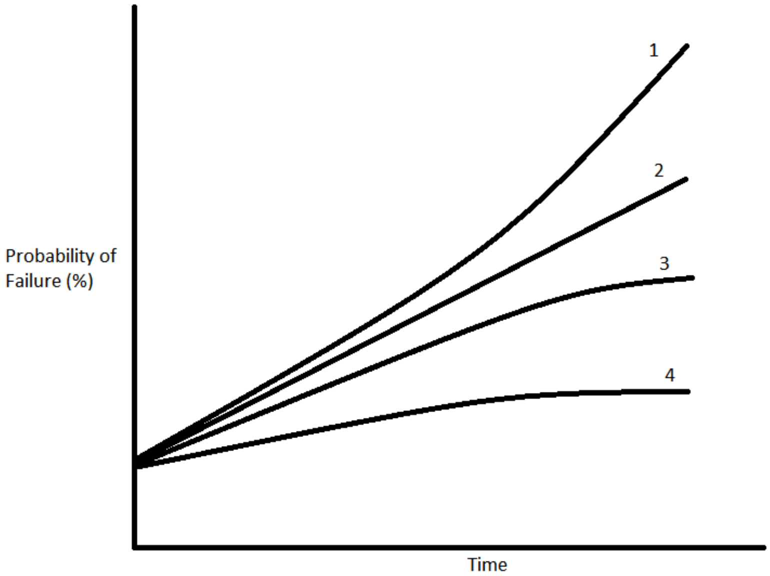

Figure A-1: Changing probability of failure with time for four failure modes

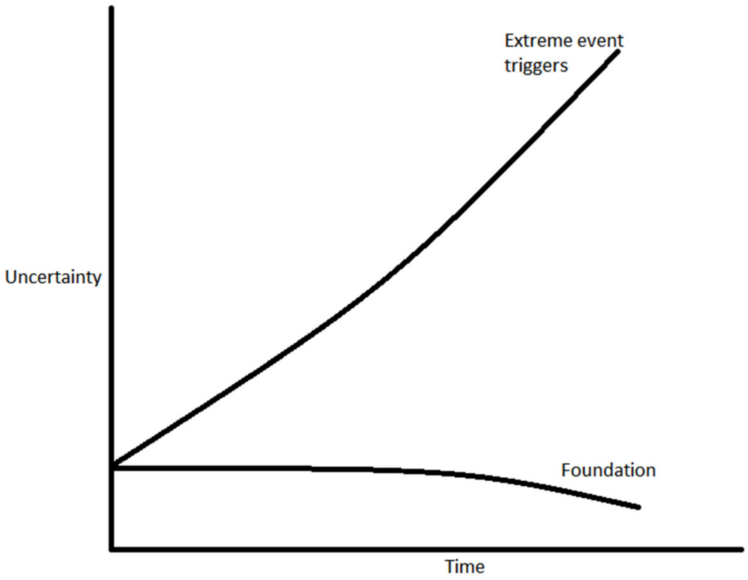

Figure A-2: Changing uncertainty over time for different failure modes

A.2 Inclusion of Temporal Scales

As discussed, the Generalized FMEA incorporates time by doing a short-term, medium-term, and long-term assessment of risk for each dam element using a risk matrix. This section defines the time frames to be used for the short-term, medium-term, and long-term assessments. Determination of the time frames requires consideration of what the overall time frame is for closure (i.e., what are we practically designing for). Evaluation of this is done using the following points: geological context, nuclear repository industry, Uranium Mill Tailings Remedial Action (UMTRA) Surface project, the current databases that are relied on in the industry (often less than 100 years), and our ability to forecast the future. Ultimately, this has resulted in the use of 1000 years for the overall temporal scale to be considered. However, if specific projects or the regulatory framework requires larger or shorter time frames, the current methodology is meant to provide the flexibility to adjust those time frames.

A.3 Geological Context

Determination of reasonable time frames for design requires consideration of the geological context. The current geological period is the Quaternary, which began about 2.6 million years ago (Woodward 2014). The current epoch is the Holocene epoch, which was preceded by the Pleistocene epoch (Bowen and Gibbard 2007, Woodward 2014). The Quaternary period is characterized by periods of severe cold climate, referred to as glacials, and periods of warmer climate, referred to as interglacials (Woodward 2014). The shift from a glacial to an interglacial period is characterized by the retreat of large ice sheets (Woodward 2014). During the most recent glacial period, most of Canada was covered by the Laurentide and Cordilleran ice sheets with the Laurentide ice sheet reaching its maximum extent around 22,000 years ago (Woodward 2014). The retreat of these ice sheets and the transition to an interglacial period resulted in the formation of large glacial lakes and ultimately impacted the geology that the majority of engineers work with today from a design perspective. In consideration of the extreme changes that occur from a geological perspective during glaciation and the risks associated with tailings dams, it is not practical for a tailings dam closure design life to extend to time periods that incorporate glacial periods.

A.4 Nuclear Repositories

In contrast to the tailings dam industry, nuclear repositories, which are designed to hold the radioactive waste produced from nuclear power plants, are expected to safely contain the waste for tens of thousands of years and beyond (even up to one million years) to protect the public and the environment (Ontario Power Generation 2011, STUK 2013, Tosoni et al. 2017). These repositories pose significant risk as the waste can contain radionuclides with half-lives of hundreds of thousands of years (Tosoni et al. 2017). In this case, the associated risks necessitate time frames that are expected to include glaciation and extreme geological change. Considering the geological context and the time frames used for design of nuclear repositories, it was concluded that design time frames in the order of 10,000 years or longer are not representative of the conditions required for assessment of tailings dams as glaciation would effectively rework the geomorphology at regional scales.

A.5 Uranium Mill Tailings Remedial Action Surface Project

Another industry that can be evaluated to determine appropriate time frames for short-term, medium-term, and long-term risk assessment is the uranium industry in the United States with the UMTRA project. The goal of the United States Department of Energy's UMTRA project was to remediate 22 inactive uranium-ore processing sites following Congress passing the Uranium Mill Tailings Radiation Control Act (UMTRCA) in 1982 (Task Committee on Low-Level Radioactive Waste Management of the Technical Committee on Nuclear Effects 1986, Mathes 1999, DOE

2017). UMTRA aims to employ remedial action to isolate and stabilize uranium tailings to prevent misuse by humans and release by environmental forces (DOE 1991). Ultimately, this is to reduce radon emissions and exposure to gamma radiation. While this industry differs from that of tailings dams in the oil sands and coal industries, the ultimate goal of this program is to limit risk to future generations. The UMTRA program aims for long-term stabilization and control of uranium mill tailings using controls that are designed to be effective for 1000 years where reasonably achievable with a minimum required performance of 200 years (Task Committee on Low-Level Radioactive Waste Management of the Technical Committee on Nuclear Effects 1986, DOE 1991, Mathes 1999, IAEA 2004). In order to meet these design life objectives, the designs should use passive controls that require minimal maintenance and repair (Task Committee on Low-Level Radioactive Waste Management of the Technical Committee on Nuclear Effects 1986). It should be noted that rock erosion protection was typically chosen over a vegetative cover as it was easier to show that it could withstand environmental forces with limited maintenance for 1000 years (Mathes 1999). Further, UMTRCA made the federal government permanent custodian over the disposal cells (Mathes 1999). As the permanent custodian, the federal government (Department of Energy) selected a conservative approach to meet long-term stability that had limited maintenance requirements (Mathes 1999). Mathes (1999) noted that:

> *"The EPA standards resulted in a consistent approach to cleanup and containment, but this consistency resulted in the deployment of remedies that were not necessarily cost effective at all sites. Thus, from a 'business' standpoint, less aggressive remedies might have been used if a risk-based standard had been the regulatory basis. However, risk and risk perception are often different, and less aggressive remedies might not have been as durable and might not have been as publicly acceptable. Because communities became more involved and knowledgeable over the life of the Project, it would have been difficult to implement remedies that would have been perceived as not being equally protective."*

UMTRA provides a useful comparison of practical time frames for closure to the tailings dam industry and should be considered in determining the time frames for short-term, medium-term, and long-term risk assessment.

A.6 Current Databases Used in Industry

Closing a tailings dam requires a comprehensive design, which involves inputs that are typically based on historical databases, including precipitation and climate data. The issue with this is that the databases may be limited in terms of the number of years of recorded data (often no more than 100 years). For example, the Government of Canada has historical climate data for weather stations across Canada. The database provides climate data, including temperature and precipitation data, as far back as 1840 depending on the station; however, many weather stations have limited records. For example, Fort McMurray has a weather station with daily temperature data as far back as 1944 (Government of Canada 2019). Further, the closest weather station to a site may be a significant distance away. This introduces additional uncertainty.

These historical records of climate data provide an important and essential step to the long-term design of tailings dams. However, this is complicated by climate change, which is expected to impact hydrology and result in changes to the annual precipitation and the ratio of water resources from rain, snow, or extreme events (NRCAN 2008, MEND 2011). As a result, a climate change model must be incorporated into the design. The issue with this is that climate change models are only considered reliable up to the year 2100, and even this is debatable. Predictions are available to the year 2500, but have a high degree of uncertainty associated with them (IPCC 2014).

Further, as noted during the interviews discussed in Section 3, loss of knowledge over time is a major challenge to closure especially with the potential of changing custodial care of a site. Due to this, many participants of the interviews noted that data management is extremely important for closure to avoid loss of knowledge over time. The reality is that many tailings dams globally are already facing this issue, particularly in cases where a site has changed ownership many times or the tailings dam is very old. Ultimately, the hope is that data management practices have improved sufficiently that this is not a problem in the future. However, given technological advances, this can be hard to predict.

Designing for closure is inherently difficult as the global trajectory is towards a closure landscape design life of 1000 years (ICOLD Tailings Dam Committee 2013). The short historical record associated with many of the databases used in industry and the reliability of climate change models beyond 2100 contributes greatly to this difficulty and introduces uncertainty into long-term design.

As a result, this uncertainty should be considered during the development of the FMEA with respect to the long-time frame.

A.7 Ability to Forecast the Future

As discussed, the global expectation for closure design is for a 1000-year design life. Designing for such a time frame is difficult due to a number of factors already discussed, including limitations of prediction tools and historical records. It is further complicated by our inherent inability to accurately forecast the future as human beings. We need to pause to consider what 1000 years really means – what did Alberta look like 1000 years ago, what did Canada look like, what did society look like? Confederation occurred in Canada in 1867, and Alberta only became a province in 1905. Effectively, Canada, as we know it, did not exist 1000 years ago. Within the last decade, we have seen technology advance at an increasing rate – something that is expected to continue. Society is not stagnant. Ultimately, this impacts a designer's ability to accurately forecast the future and incorporate this into design.

A.8 Discussion

The following conclusions can be made:

- Time frames in excess of 10,000 years are not appropriate for application in the mining industry, but are suited for systems in environments that have not seen substantial changes in such time frames; such as underground nuclear waste repositories in tectonically inactive areas. This industry requires consideration of these time frames given that glacial periods may impact the stability of the deposit. In the mining industry, glacial periods are expected to change the geology and effectively bury the tailings dam.
- The global expectation for tailings dam closure is 1000 years. This is also reflected by the UMTRA project where the facilities are designed to be effective for 1000 years where reasonably achievable with a minimum required performance of 200 years (Task Committee on Low-Level Radioactive Waste Management of the Technical Committee on Nuclear Effects 1986, DOE 1991, Mathes 1999, IAEA 2004). With consideration of this, the maximum time frame selected for the Generalized FMEA tool is 1000 years. All risk assessments conducted for the 1000-year time frame should include careful consideration

of uncertainties associated with current databases, climate change predictions, and our ability to forecast the future.

- Further discussion is needed to determine appropriate time frames for the short time frame and medium time frame.

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Appendix B: Hazard Mapping

B.1 Hazard Mapping

The hazard mapping exercise was conducted using the interview results and literature resources. Table B-1 is intended to provide a detailed list of potential hazards and triggers that may develop at a tailings over time. This exercise contributed greatly to the developed of the G-FMEA charts. A source that contributed greatly to the development of the hazard and trigger list was McKenna (2002) who developed a list of failure modes, triggers, activities, and risks that may be present at a variety of landforms on a mine site.

Table B-1: Potential hazards and triggers

Category	**Hazard/Trigger**	
Animals	Beaver dams	
	Burrowing animals in the dam (i.e., gophers)	
	Denning of bears	
	Herds of animals	
Environmental forces	Avalanche	
	Avulsion and flooding	
	Climate change	
	Coal fire	
	Desiccation	
	Downslope creep (solifluction)	
	Drought	
	Erosion	Animal induced erosion
		Bank erosion
		Crest erosion
		Gullies
		Rill erosion
		Road/trail deterioration
		Slope erosion
		Sheet erosion
		Shoreline erosion
		Spring sapping
		Toe erosion
		Wind erosion and deposition
	Explosion	
	Fire	
	Frost action (freeze/thaw)	
	Glacial advance	
	Ice movement	
	Ice storm	
	Icing	
	Isostatic rebound	
	Meteorite	
	Micro-climate change	

Category	Hazard/Trigger	
	Migrating dunes	
	Permafrost creation/destruction	
	Precipitation (including extreme events)	
	Seismicity	
	Spontaneous combustion	
	Tornado	
	Volcanism	
	Wind event (including extreme events)	
Humans	Blasting	
	Changing downstream or upstream populations	
	Defaulting owner/change in ownership	
	Excavation of dam	
	Excessive cost	
	Firefighting	
	Future activities	Construction activities, including road construction and general traffic
		Cultivation
		Infrastructure development
		Logging
		Remining
		Road/trail deterioration
		Third party use
		Upstream land use
	Ignorance	
	Management system failures	
	Rapidly applied load increment, including construction activities at an accelerated rate	
	Regulation changes	
	Vandalism, sabotage, terrorism, human malfeasance	
	War	
Material and Dam Specific	Aging of Sands	
	Beach encroachment and slimes deposition	
	Cementation/decementation	
	Change in saturation	
	Concrete degradation	
	Consolidation/settlement	
	Cracking	
	Creep - consolidation	
	Culvert evolution	
	Decant evolution	
	Differential settlement	
	Drains and filters evolution	
	Erosion protection evolution	
	Infilling of water body	
	Insufficient beach length	
	Liners/geosynthetics	
	Liquefaction potential of beach above water deposit	
	Liquefaction potential of beach below water deposit	
	Loose layers	
	Loss of strength	
	MFT Lens	
	Permeability	
	Pipes	

Category	Hazard/Trigger
	Radioactivity
	Saturated/desaturation of sands
	Salt accumulation/salt pan
	Sinkholes
	Slipoff failures
	Slope changes
	Slumps
	Soil chemistry
	Solution feature collapse
	Strain incompatibility
	Strain weakening
	Transition of drained to undrained behaviour
	Transition zones
	Weak layers
	Wetting of materials
Seepage and water movement	Artesian pressures
	Breakwater damage
	Catastrophic outflow of water from other source
	Concentrated tailings discharge from one location for an extended period
	Diversion dams/ditches failure
	Drainage system evolution
	Excessive settlement
	Fan deposition
	Fluctuating water levels
	Herds of animals
	High seepage gradients
	Increase in pond water level or creation of new ponds
	Infilling of water body
	Infiltration
	Leachates
	Loss of freeboard
	Perched water table development
	PWP and phreatic surface change
	Seepage
	Seepage breakout on face of dam
	Upstream diversion ditches
	Wave action
Spillways	Beaver dam blockage
	Algae
	Buoyancy in sand channels
	Debris Blockages
	Denning of bears
	Differential settlement
	Excessive vegetation
	Failure of erosion control measures
	Icing
	Log jam
	Sedimentation
Stress changes	Beaver activity
	Loading or removing support/confinement
	Precipitation events
	Steepening of the slope

Category	Hazard/Trigger
	Toe erosion
Surrounding environment	Debris flow
	Grazing/cultivation
	Landslide
	Pipeline break
	Retrogressive failure
	River movement
	Slipoff failures
	Slumps
	Spalling
	Undermining
Vegetation	Loss of diversity
	Road/trail deterioration
	Vegetation growth
	Vegetation loss
	Vegetation undercut by gullies

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Appendix C: Seepage Modelling

C.1 Calibration and Sensitivity Analysis

Table C-1: Calibration sensitivity analysis

ID #	Scenario Description	Level 1 Drain (L/s)	Level 2 Drain (L/s)	Piezometer Residuals								ME	MAE	RMSE
				1	2	3	4	5	6	7	8			
1	Initial model	83.00	45.72	4.01	0.53	1.67	1.37	2.65	-1.04	0.42	-2.22	0.92	1.74	2.07
2	BC: Drains modelled using a zero pressure head at a single point	83.74	44.60	4.06	0.57	1.72	1.42	2.70	-0.96	0.49	-2.08	0.99	1.75	2.08
3	BC: Drains modelled using a water rate=0 m^3/s and a potential seepage face at a single point	83.74	44.60	4.06	0.57	1.72	1.42	2.70	-0.96	0.49	-2.08	0.99	1.75	2.08
4	BC: Increase infiltration rate to crest (800 mm/year)	131.51	260.01	14.39	12.92	10.28	9.98	11.24	1.27	2.35	-1.74	7.59	8.02	9.46
5	BC: Decrease infiltration rate to crest (200 mm/year)	82.01	41.40	3.68	0.29	1.41	1.11	2.39	-1.10	0.38	-2.23	0.74	1.58	1.90
6	BC: Increase infiltration rate to crest (600 mm/year)	84.03	50.11	4.34	0.93	1.92	1.63	2.91	-0.99	0.46	-2.22	1.12	1.92	2.25
7	BC: Decrease infiltration rate to crest (100 mm/year)	81.49	39.19	3.52	0.18	1.28	0.98	2.26	-1.13	0.36	-2.24	0.65	1.49	1.82
8	BC: Increase infiltration to cell sand (300 mm/yr)	83.71	48.77	4.16	0.72	1.80	1.51	2.79	-1.01	0.45	-2.22	1.03	1.83	2.16
9	BC: Decrease infiltration to cell sand (75 mm/yr)	82.66	44.18	3.94	0.73	1.60	1.31	2.58	-1.06	0.41	-2.23	0.91	1.73	2.04
10	BC: Decrease infiltration to cell sand (40 mm/yr)	82.49	43.48	3.91	0.43	1.57	1.27	2.55	-1.07	0.40	-2.23	0.85	1.68	2.01
11	BC: Increase infiltration to berm (1 mm/yr)	83.04	45.77	4.02	0.53	1.67	1.38	2.65	-1.04	0.42	-1.19	1.06	1.61	1.96
12	BC: Increase infiltration to berm (10 mm/yr)	83.21	45.85	4.02	0.54	1.67	1.38	2.65	-1.04	0.42	2.64	1.53	1.79	2.13
13	Fine tailings increase k_{sat} by a factor of 10	96.74	111.79	8.12	5.12	4.94	4.64	5.98	-0.30	0.96	-2.10	3.42	4.02	4.73
14	Fine tailings decrease k_{sat} by a factor of 10	32.95	0.00	-4.48	-0.17	-5.38	-5.68	-4.39	-4.05	-2.38	-2.56	-3.64	3.64	4.02
15	Fine tailings increase k_{sat} by a factor of 5	94.00	98.09	7.42	4.39	4.35	4.05	5.32	-0.45	0.85	-2.12	2.98	3.62	4.23
16	Fine tailings decrease k_{sat} by a factor of 5	47.84	0.00	-2.40	-0.14	-3.58	-3.88	-2.59	-3.03	-1.37	-2.47	-2.43	2.43	2.68
17	Fine tailings decrease k_{sat} by a factor of 2	73.82	12.68	1.33	-0.38	-0.44	-0.73	0.55	-1.55	0.04	-2.30	-0.43	0.91	1.15
18	Fine tailings anisotropy increase by a factor of 10	95.97	107.86	7.91	4.89	4.77	4.48	5.75	-0.34	0.93	-2.11	3.29	3.90	4.58

ID #	Scenario Description	Level 1 Drain (L/s)	Level 2 Drain (L/s)	Piezometer Residuals								ME	MAE	RMSE
				1	2	3	4	5	6	7	8			
19	Fine tailings anisotropy decrease by a factor of 10	34.47	0.00	-4.25	-0.16	-5.19	-5.48	-4.20	-3.93	-2.27	-2.55	-3.50	3.50	3.87
20	Fine tailings anisotropy decrease by a factor of 2	74.07	13.46	1.39	-0.36	-0.39	-0.68	0.60	-1.53	0.05	-2.30	-0.40	0.91	1.15
21	BBW below pond increase k_{sat} by a factor of 5	85.11	55.00	4.65	1.46	2.17	1.87	3.15	-0.93	0.50	-2.21	1.33	2.12	2.45
22	BBW below pond decrease k_{sat} by a factor of 5	72.79	9.96	1.07	-0.46	-0.64	-0.94	0.35	-1.60	0.00	-2.31	-0.57	0.92	1.15
23	BBW below pond decrease k_{sat} by a factor of 2	79.26	30.53	2.84	-0.07	0.75	0.45	1.73	-1.26	0.27	-2.26	0.31	1.20	1.52
24	BBW below pond increase k_{sat} by a factor of 2	84.52	52.08	4.48	1.13	2.03	1.73	3.01	-0.96	0.48	-2.21	1.21	2.00	2.33
25	BBW below pond anisotropy increase by a factor of 10	85.27	55.70	4.69	1.51	2.20	1.91	3.19	-0.92	0.50	-2.21	1.36	2.14	2.47
26	BBW below pond anisotropy decrease by a factor of 10	73.59	9.79	1.13	-0.44	-0.59	-0.88	0.40	-1.56	0.04	-2.30	-0.52	0.92	1.14
27	BAW and Cell Sand increase k_{sat} by a factor of 10	163.52	0.00	-7.24	-0.96	-7.85	-8.15	-6.86	-5.50	-3.84	-2.61	-5.38	5.38	5.92
28	BAW and Cell Sand decrease k_{sat} by a factor of 10	12.42	23.29	13.39	11.24	9.37	9.07	10.33	0.97	2.06	-1.83	6.82	7.28	8.59
29	BAW and Cell Sand increase k_{sat} by a factor of 5	275.20	114.94	-3.23	-0.59	-4.10	-4.40	-3.11	-2.62	-0.84	-2.42	-2.66	2.66	2.96
30	BAW and Cell Sand increase k_{sat} by a factor of 2	140.93	7.82	0.50	-0.77	-1.11	-1.41	-0.12	-1.73	-0.10	-2.32	-0.88	1.01	1.25
31	BAW and Cell Sand decrease k_{sat} by a factor of 5	22.09	35.14	11.09	8.60	7.39	7.09	8.35	0.36	1.51	-1.97	5.30	5.79	6.87
32	BAW and Cell Sand decrease k_{sat} by a factor of 2	47.28	50.35	7.47	4.51	4.43	4.13	5.41	-0.42	0.87	-2.12	3.04	3.67	4.29
33	BAW anisotropy increase by a factor of 10	83.23	46.02	4.17	0.16	1.76	1.47	2.76	-1.03	0.43	-292.60	-35.36	38.05	103.47
34	BAW anisotropy decrease by a factor of 10	81.53	40.35	2.55	2.84	0.90	0.64	1.99	-1.13	0.37	-2.24	0.74	1.58	1.81
35	Cell Sand anisotropy increase by a factor of 10	77.35	51.83	3.80	0.39	1.45	1.16	2.43	-1.39	0.12	-2.55	0.68	1.66	2.01
36	Cell Sand anisotropy decrease by a factor of 10	74.09	53.80	4.43	0.93	2.15	1.86	3.15	-0.27	1.18	-1.45	1.50	1.93	2.29
37	Cell Sand anisotropy decrease by a factor of 5	81.38	46.87	4.24	0.73	1.91	1.61	2.90	-0.66	0.78	-1.55	1.24	1.80	2.14
38	BAW increase k_{sat} by a factor of 10	89.84	69.56	0.92	-1.27	0.52	0.22	1.50	-0.66	0.67	-2.16	-0.03	0.99	1.15
39	BAW decrease k_{sat} by a factor of 10	43.66	0.00	4.66	4.89	-2.10	-2.32	-0.88	-3.30	-1.63	-2.49	-0.40	2.78	3.08
40	BAW increase k_{sat} by a factor of 5	88.81	67.09	1.66	-0.81	0.95	0.65	1.92	-0.72	0.63	-2.17	0.26	1.19	1.32

ID #	Scenario Description	Level 1 Drain (L/s)	Level 2 Drain (L/s)	Piezometer Residuals								ME	MAE	RMSE
				1	2	3	4	5	6	7	8			
41	BAW decrease k_{sat} by a factor of 5	65.81	0.00	5.01	3.87	-0.27	-0.52	0.88	-1.99	-0.33	-2.18	0.56	1.88	2.50
42	Cell Sand increase k_{sat} by a factor of 10	138.76	0.00	-2.92	-0.29	-6.93	-7.18	-5.80	-5.80	-4.12	-2.69	-4.47	4.47	5.00
43	Cell Sand decrease k_{sat} by a factor of 10	12.42	23.29	13.39	11.24	9.37	9.07	10.33	0.97	2.06	-1.83	6.82	7.28	8.59
44	Cell Sand increase k_{sat} by a factor of 5	136.83	0.00	-1.40	-0.37	-4.87	-5.13	-3.79	-4.50	-2.84	-2.60	-3.19	3.19	3.56
45	Cell Sand decrease k_{sat} by a factor of 5	22.09	351.37	11.09	8.60	7.39	7.09	8.35	0.36	1.51	-1.97	5.30	5.79	6.87
46	Cell Sand increase k_{sat} by a factor of 2	132.79	0.00	1.63	-0.27	-1.15	-1.33	-0.03	-1.95	-0.30	-2.35	-0.72	1.13	1.38
47	Starter Dyke and Berm increase k_{sat} by a factor of 10	83.12	45.38	4.01	0.53	1.66	1.36	2.64	-1.05	0.42	-2.23	0.92	1.74	2.07
48	Starter Dyke and Berm decrease k_{sat} by a factor of 10	82.99	45.75	4.02	0.53	1.67	1.38	2.65	-1.04	0.42	-2.22	0.93	1.74	2.07
49	Starter Dyke and Berm increase k_{sat} by a factor of 100	84.22	42.04	3.92	0.47	1.57	1.27	2.55	-1.12	0.38	-2.28	0.85	1.69	2.02
50	Starter Dyke anisotropy increase to 1	83.01	45.71	4.01	0.53	1.67	1.37	2.65	-1.04	0.42	-2.26	0.92	1.75	2.08
51	Starter Dyke anisotropy decrease by a factor of 10	82.97	45.72	2.01	0.53	1.67	1.37	2.65	-1.04	0.42	-1.96	0.71	1.46	1.63
52	Berm anisotropy increase to 1	83.14	45.58	4.02	0.54	1.67	1.38	2.66	-1.04	0.43	-2.24	0.93	1.75	2.08
53	Berm anisotropy decrease by a factor of 10	83.00	45.72	4.01	0.53	1.67	1.37	2.65	-1.04	0.42	-2.16	0.93	1.73	2.06
54	Starter Dyke increase k_{sat} by a factor of 10	83.34	45.38	4.01	0.53	1.66	1.36	2.64	-1.05	0.42	-0.85	1.09	1.56	1.93
55	Starter Dyke decrease k_{sat} by a factor of 10	82.98	45.75	4.02	0.53	1.67	1.38	2.65	-1.04	0.42	-4.36	0.66	2.01	2.46
56	Berm increase k_{sat} by a factor of 10	82.89	45.71	2.01	0.53	1.67	1.37	2.65	-1.04	0.42	-4.37	0.41	1.76	2.13
57	Berm decrease k_{sat} by a factor of 10	83.03	45.72	4.01	0.53	1.67	1.37	2.65	-1.04	0.42	-0.86	1.10	1.57	1.94

Table C-2: Sensitivity analysis

ID #	Scenario Description	Level 1 Drain (L/s)	Level 2 Drain (L/s)	Piezometer Residuals								ME	MAE	RMSE
				1	2	3	4	5	6	7	8			
1	Initial model	35.99	13.80	0.94	-0.61	-0.12	-0.42	0.85	-1.24	0.27	-1.21	-0.19	0.71	0.81
2	BC: Drains modelled using a zero pressure head at a single point	36.65	13.10	1.10	-0.55	0.05	-0.25	1.02	-1.01	0.50	-0.83	0.00	0.66	0.76
3	BC: Drains modelled using a water rate=0 m3/s and a potential seepage face at a single point	36.65	13.10	1.10	-0.55	0.05	-0.25	1.02	-1.01	0.50	-0.83	0.00	0.66	0.76
4	BC: Increase infiltration rate to crest (800 mm/year)	38.47	23.97	2.32	-0.30	1.08	0.78	2.05	-0.93	0.49	-1.17	0.54	1.14	1.32
5	BC: Decrease infiltration rate to crest (200 mm/year)	34.57	8.89	0.17	-0.64	-0.77	-1.07	0.20	-1.41	0.14	-1.23	-0.58	0.70	0.85

ID #	Scenario Description	Level 1 Drain (L/s)	Level 2 Drain (L/s)	Piezometer Residuals								ME	MAE	RMSE
				1	2	3	4	5	6	7	8			
6	BC: Increase infiltration rate to crest (600 mm/year)	37.29	18.86	1.65	-0.33	0.51	0.21	1.48	-1.08	0.39	-1.19	0.21	0.85	1.00
7	BC: Decrease infiltration rate to crest (100 mm/year)	33.79	6.51	-0.21	-0.52	-1.09	-1.39	-0.12	-1.51	0.07	-1.24	-0.75	0.77	0.95
8	BC: Increase infiltration to cell sand (300 mm/yr)	36.83	14.31	1.31	-0.30	0.24	-0.06	1.21	-1.13	0.35	-1.20	0.05	0.73	0.88
9	BC: Decrease infiltration to cell sand (75 mm/yr)	35.55	12.22	0.75	-0.78	-0.30	-0.60	0.67	-1.29	0.23	-1.22	-0.32	0.73	0.81
10	BC: Decrease infiltration to cell sand (40 mm/yr)	35.34	11.48	0.66	-0.89	-0.38	-0.68	0.59	-1.32	0.21	-1.22	-0.38	0.74	0.83
11	BC: Decrease infiltration to berm (0 mm/yr)	35.96	13.75	0.94	-0.61	-0.12	-0.42	0.85	-1.24	0.27	-2.25	-0.32	0.84	1.05
12	BC: Increase infiltration to berm (10 mm/yr)	36.17	13.88	0.94	-0.61	-0.12	-0.42	0.85	-1.24	0.28	2.63	0.29	0.89	1.16
13	Fine tailings increase ksat by a factor of 10	46.26	61.04	6.65	3.19	4.80	4.49	5.74	-0.01	1.17	-1.04	3.12	3.39	4.08
14	Fine tailings decrease ksat by a factor of 10	21.29	0.00	-3.74	-0.15	-4.28	-4.58	-3.30	-3.08	-1.41	-1.39	-2.74	2.74	3.11
15	Fine tailings increase ksat by a factor of 5	43.58	48.34	5.30	1.73	3.63	3.33	4.59	-0.31	0.94	-1.09	2.27	2.61	3.13
16	Fine tailings decrease ksat by a factor of 5	21.29	0.00	-3.74	-0.15	-4.28	-4.58	-3.30	-3.08	-1.41	-1.39	-2.74	2.74	3.11
17	Fine tailings decrease ksat by a factor of 2	32.60	3.42	4.23	-0.46	-1.57	-1.87	-0.59	-1.64	-0.04	-1.26	-0.40	1.46	1.90
18	Fine tailings increase ksat by a factor of 2	39.94	28.04	2.86	-0.30	1.53	1.23	2.50	-0.82	0.57	-1.16	0.80	1.37	1.61
19	Fine tailings anisotropy increase by a factor of 10	45.93	59.39	6.51	3.01	4.68	4.37	5.63	-0.04	1.14	-1.04	3.03	3.30	3.98
20	Fine tailings anisotropy decrease by a factor of 10	21.69	0.00	-3.65	-0.15	-4.19	-4.49	-3.21	-3.03	-1.36	-1.38	-2.68	2.68	3.05
21	Fine tailings anisotropy decrease by a factor of 2	32.66	3.59	-0.74	-0.46	-1.55	-1.84	-0.57	-1.63	-0.03	-1.26	-1.01	1.01	1.18
22	Fine tailings anisotropy increase by a factor of 5	43.42	47.58	5.20	1.62	3.55	3.25	4.50	-0.33	0.93	-1.09	2.20	2.56	3.07
23	BBW below pond increase ksat by a factor of 5	36.95	17.43	1.48	-0.38	0.35	0.05	1.32	-1.12	0.36	-1.20	0.11	0.78	0.93
24	BBW below pond decrease ksat by a factor of 5	32.60	3.10	-0.80	-0.46	-1.60	-1.90	-0.63	-1.64	-0.03	-1.26	-1.04	1.04	1.21
25	BBW below pond increase ksat by a factor of 2	36.77	16.70	1.38	-0.42	0.26	-0.04	1.23	-1.14	0.35	-1.20	0.05	0.75	0.90
26	BBW below pond decrease ksat by a factor of 2	34.71	9.34	0.23	-0.66	-0.71	-1.01	0.26	-1.39	0.16	-1.23	-0.54	0.71	0.83

ID #	Scenario Description	Level 1 Drain (L/s)	Level 2 Drain (L/s)	Piezometer Residuals								ME	MAE	RMSE
				1	2	3	4	5	6	7	8			
27	BBW below pond increase anisotropy by a factor of 2	36.71	16.46	1.34	-0.43	0.23	-0.07	1.20	-1.15	0.35	-1.20	0.03	0.75	0.89
28	BBW below pond decrease anisotropy by a factor of 1.5	35.65	12.05	0.69	-0.66	-0.33	-0.63	0.64	-1.28	0.25	-1.22	-0.32	0.71	0.79
29	BBW below pond increase anisotropy by a factor of 6.66	36.95	17.44	1.48	-0.38	0.35	0.05	1.32	-1.12	0.36	-1.20	0.11	0.78	0.94
30	BAW increase ksat by a factor of 10	36.74	15.12	-1.31	-1.51	-1.46	-1.75	-0.47	-1.14	0.34	-1.20	-1.06	1.15	1.24
31	BAW decrease ksat by a factor of 10	32.02	2.40	5.35	4.35	0.32	0.07	1.43	-1.71	-0.09	-1.27	1.06	1.82	2.60
32	BAW increase ksat by a factor of 5	36.61	14.97	-0.93	-1.11	-1.20	-1.49	-0.22	-1.16	0.33	-1.20	-0.87	0.95	1.04
33	BAW decrease ksat by a factor of 5	34.01	7.80	4.15	1.93	0.66	0.38	1.70	-1.48	0.10	-1.24	0.78	1.46	1.88
34	BAW increase ksat by a factor of 2	36.32	14.50	-0.07	-0.76	-0.66	-0.96	0.31	-1.20	0.30	-1.21	-0.53	0.68	0.79
35	BAW decrease ksat by a factor of 2	35.43	12.27	2.22	-0.14	0.39	0.09	1.37	-1.31	0.23	-1.22	0.20	0.87	1.13
36	BAW anisotropy increase by a factor of 10	36.13	14.07	0.93	-1.24	-0.11	-0.40	0.89	-1.22	0.29	-1.21	-0.26	0.79	0.89
37	BAW anisotropy decrease by a factor of 10	36.07	13.60	0.74	0.18	-0.15	-0.45	0.82	-1.24	0.29	-1.21	-0.13	0.63	0.75
38	Cell Sand anisotropy increase by a factor of 10	34.05	15.83	0.66	-0.67	-0.39	-0.69	0.59	-1.50	0.01	-1.46	-0.43	0.74	0.88
39	Cell Sand anisotropy decrease by a factor of 10	32.02	17.60	1.52	-0.36	0.52	0.22	1.50	-0.57	0.90	-0.58	0.40	0.77	0.90
40	Cell Sand anisotropy decrease by a factor of 5	35.17	14.52	1.29	-0.45	0.25	-0.05	1.23	-0.91	0.58	-1.21	0.09	0.75	0.87
41	Cell Sand increase ksat by a factor of 10	51.07	0.00	-6.39	-0.19	-8.17	-8.45	-7.13	-6.13	-4.27	-1.61	-5.29	5.29	6.00
42	Cell Sand decrease ksat by a factor of 10	9.89	23.95	17.41	13.73	16.67	16.36	17.61	5.07	5.17	0.06	11.51	11.51	13.23
43	Cell Sand increase ksat by a factor of 5	50.90	0.00	-4.83	-0.18	-6.33	-6.62	-5.32	-4.93	-3.20	-1.52	-4.11	4.11	4.64
44	Cell Sand decrease ksat by a factor of 5	14.49	31.00	10.93	7.26	10.07	9.76	11.01	2.55	3.27	-0.48	6.80	6.92	7.96
45	Cell Sand increase ksat by a factor of 2	50.38	0.00	-1.70	-0.50	-2.89	-3.18	-1.90	-2.55	-0.90	-1.35	-1.87	1.87	2.07
46	Cell Sand decrease ksat by a factor of 2	22.43	26.38	4.12	0.34	3.15	2.84	4.10	-0.16	1.04	-1.06	1.80	2.10	2.60
47	Starter Dyke and Berm increase ksat by a factor of 10	36.08	13.48	0.92	-0.61	-0.14	-0.44	0.83	-1.26	0.26	-2.14	-0.32	0.83	1.02
48	Starter Dyke and Berm decrease ksat by a factor of 10	35.98	13.84	0.94	-0.61	-0.12	-0.42	0.85	-1.24	0.28	2.63	0.29	0.88	1.16
49	Starter Dyke and Berm increase ksat by a factor of 5	36.03	13.66	0.93	-0.61	-0.13	-0.43	0.84	-1.25	0.27	-2.03	-0.30	0.81	0.99
50	Starter Dyke and Berm decrease ksat by a factor of 5	35.98	13.83	0.94	-0.61	-0.12	-0.42	0.85	-1.24	0.28	1.47	0.15	0.74	0.86
51	Starter Dyke anisotropy increase to 1	35.99	13.80	0.94	-0.61	-0.12	-0.42	0.85	-1.24	0.27	-1.27	-0.20	0.71	0.82
52	Starter Dyke anisotropy decrease by a factor of 10	35.98	13.81	0.94	-0.61	-0.12	-0.42	0.85	-1.24	0.28	-0.93	-0.16	0.67	0.76
53	Berm anisotropy increase to 1	35.99	13.80	0.94	-0.61	-0.12	-0.42	0.85	-1.24	0.27	-1.22	-0.19	0.71	0.81

ID #	Scenario Description	Level 1 Drain (L/s)	Level 2 Drain (L/s)	Piezometer Residuals								ME	MAE	RMSE
				1	2	3	4	5	6	7	8			
54	Berm anisotropy decrease by a factor of 10	35.99	13.81	0.94	-0.61	-0.12	-0.42	0.85	-1.24	0.27	-1.29	-0.20	0.72	0.82
55	Starter Dyke increase ksat by a factor of 10	36.30	13.49	0.92	-0.61	-0.14	-0.44	0.83	-1.26	0.26	-0.39	-0.10	0.61	0.70
56	Starter Dyke decrease ksat by a factor of 10	35.96	13.84	0.94	-0.61	-0.12	-0.42	0.85	-1.24	0.28	-2.05	-0.29	0.81	1.00
57	Berm increase ksat by a factor of 10	35.87	13.80	0.94	-0.61	-0.12	-0.42	0.85	-1.24	0.27	-4.07	-0.55	1.07	1.60
58	Berm decrease ksat by a factor of 10	36.01	13.80	0.94	-0.61	-0.12	-0.42	0.85	-1.24	0.27	1.95	0.20	0.80	0.97

C.2 1D LCI to Generate Water Flux for 2D Model

To demonstrate the validity of using the 1D LCI and applying it to the 2D model as a water flux over time, the output was compared to a 2D model with a LCI boundary condition on the upper boundary. The models were run for 10 years. For the 1D/2D LCI scenario, two 1D cross-sections were created and assessed for 10 years. The two scenarios were compared based on the total heads of the piezometers, the level 1 and level 2 drain outflows, and the final phreatic surface over 100 years. The total heads over time for the two scenarios are provided in Figure C-1, and the drain outflows over time are provided in Figure C-2. The 2D LCI total head versus the 2D water flux total head are provided in Figure C-3, and the 2D LCI drain outflows versus the 2D water flux drain outflows are provided in Figure C-4. The final phreatic surface after 10 years for the 2D water flux using the 1D LCI and the 2D LCI are provided in Figure C-5 and Figure C-6, respectively. It should be noted that the figures use 1D to refer to the scenario where the 2D model using the water flux from the 1D LCI models and 2D to refer to the scenario where the LCI boundary condition is used in the 2D model. The output from the two different scenarios shows that they both follow the same trend over time. Based on the comparison, it is considered reasonable to use the water flux over time from the 1D LCI model as the upper boundary condition for the 2D model. While this technique would be deemed reasonable for the purposes of this modelling, non-convergence issues were experienced with the 1D LCI water flux approach when the model was extended to longer timescales. This was deemed to be due to the large variations in water flux over time combined with the steep volumetric water content and hydraulic conductivity functions of the tailings sand. In contrast, the LCI boundary condition for the 2D model did not experience non-convergence issues when extended to longer timescales. As a result, the full 2D LCI boundary condition will be used for this research, despite the longer run times.

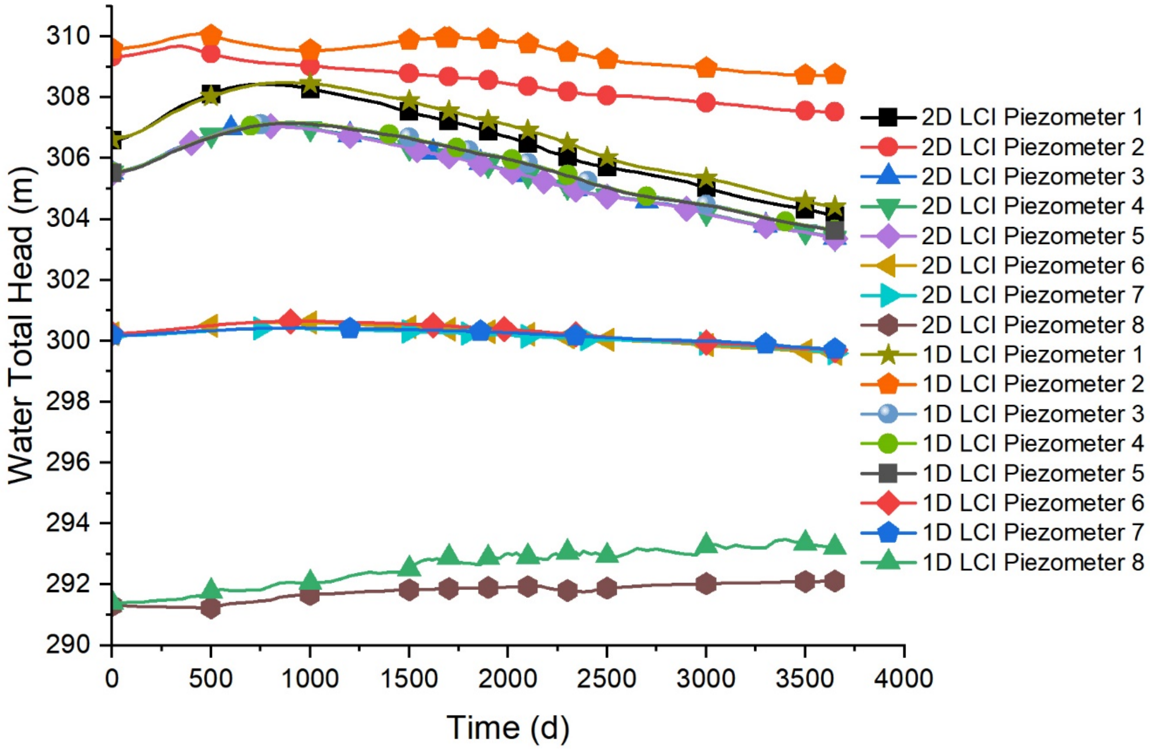


Figure C-1: Total head over time for 2D water flux (using 1D LCI) and 2D LCI

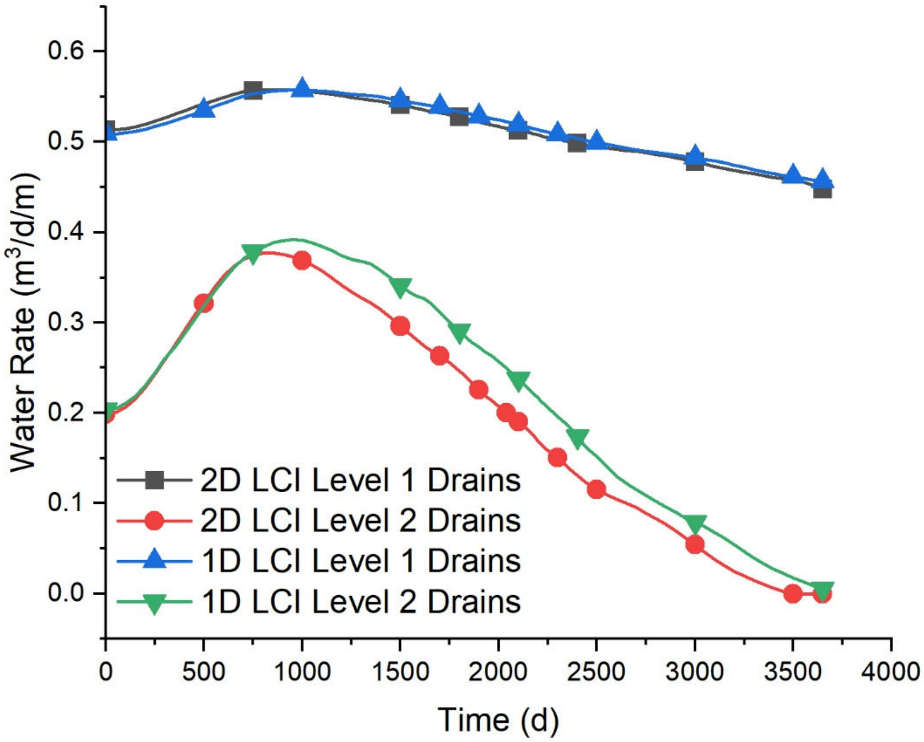
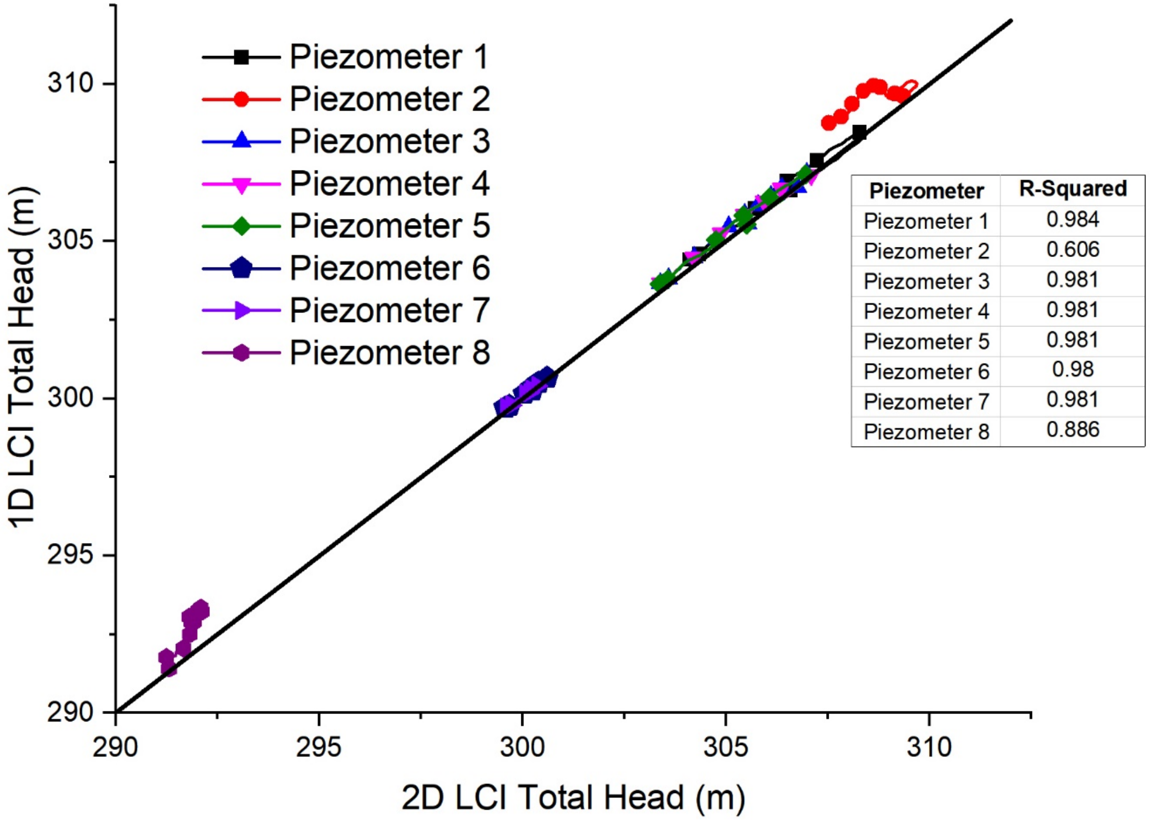


Figure C-2: Drain outflow over time for 2D water flux (using 1D LCI) and 2D LCI



Piezometer	R-Squared
Piezometer 1	0.984
Piezometer 2	0.606
Piezometer 3	0.981
Piezometer 4	0.981
Piezometer 5	0.981
Piezometer 6	0.98
Piezometer 7	0.981
Piezometer 8	0.886

Figure C-3: 2D LCI total head versus 2D water flux (using 1D LCI) total head with R-squared

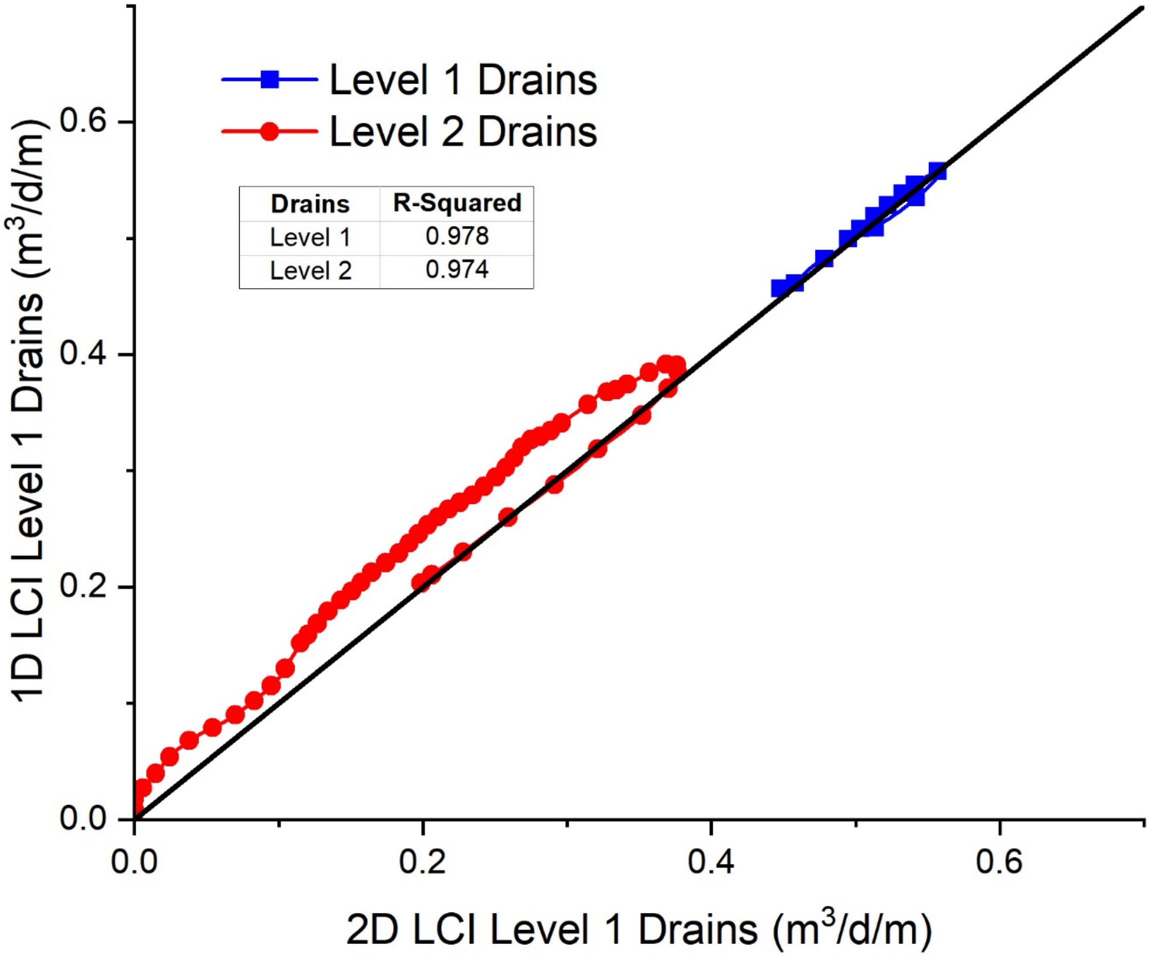


Figure C-4: 2D LCI drain outflows versus 2D water flux (using 1D LCI) drain outflows with R-squared

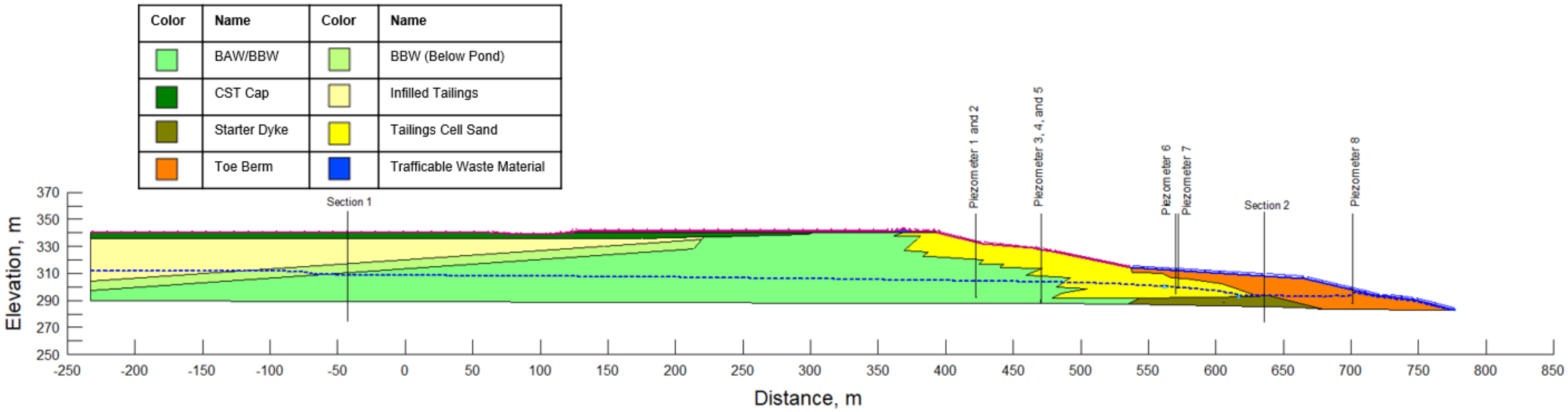


Figure C-5: Final phreatic surface after 10 years for 2D water flux using 1D LCI

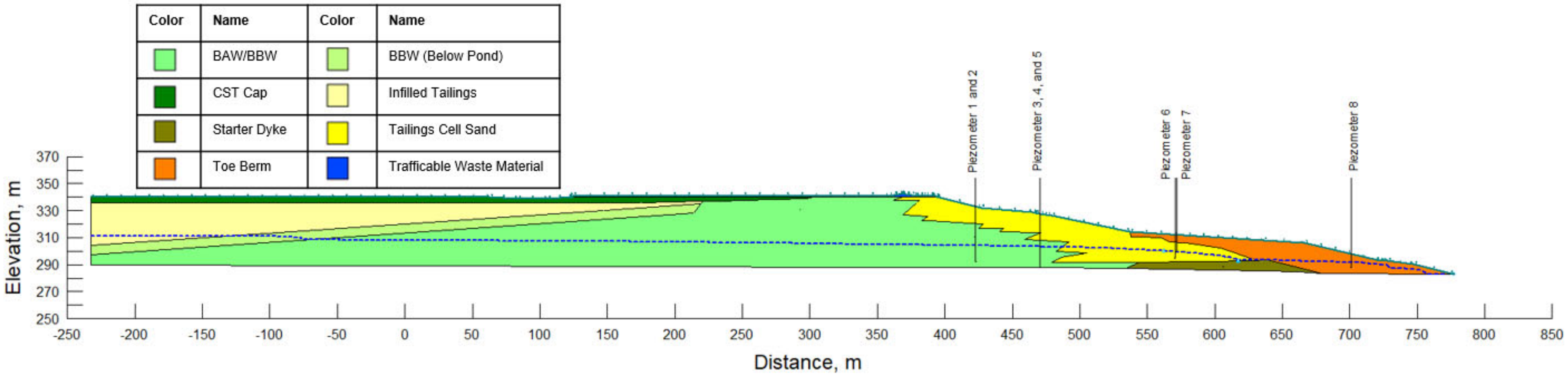


Figure C-6: Final phreatic surface after 10 years for 2D LCI

Convergence must be assessed on every model at completion. Figure C-7 to Figure C-9 shows an example of the checks completed on a 1D model for demonstration purposes. Figure C-7 shows the unconverged pressure head nodes versus time, which shows that there are no unconverged pressure head nodes over 100 years. This is a requirement for the solution to be deemed converged. Figure C-8 shows the hydraulic conductivity versus matric suction for the CST cap for the input function and the actual function used to obtain the solution. If the actual and input functions do not match, the solution has not converged. For this model, the functions match, which indicates convergence.

Figure C-9 shows the water balance error and cumulative change in domain water mass versus time for the domain. For a transient model, non-convergence can also express itself as an “inequality between the rate of change of the mass of water stored within the domain and the rate at which the water enters and leaves the domain” (GEO-SLOPE International Ltd. n.d.). This can be evaluated by comparing the water balance error (a mathematical by-product of non-convergence) to the cumulative change in mass of the water within the domain. As shown in Figure C-9, the water balance error is generally less than 2% of the cumulative change in domain water mass and is considered acceptable after 100 years. In general, water balance errors are a reflection of convergence. Convergence should be evaluated with consideration of the water balance error, other convergence measures, and engineering judgement to assess if a result is reasonable. It should be noted that the material property functions of the tailings sand in this research are quite steep. This means that small changes in the porewater pressures may result in larger water balance errors.

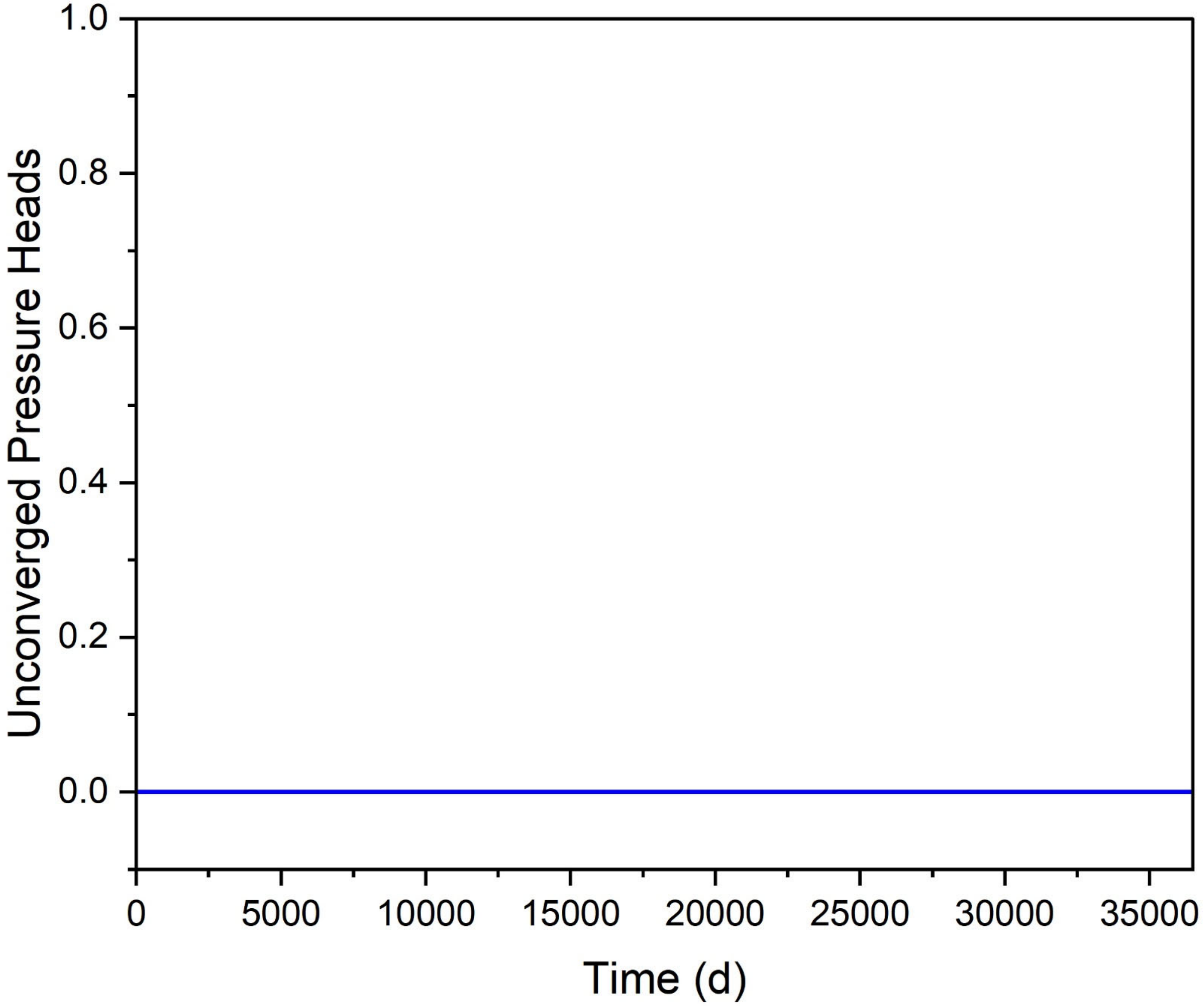


Figure C-7: Unconverged pressure nodes versus time for 1D model at Section 1 using TSB

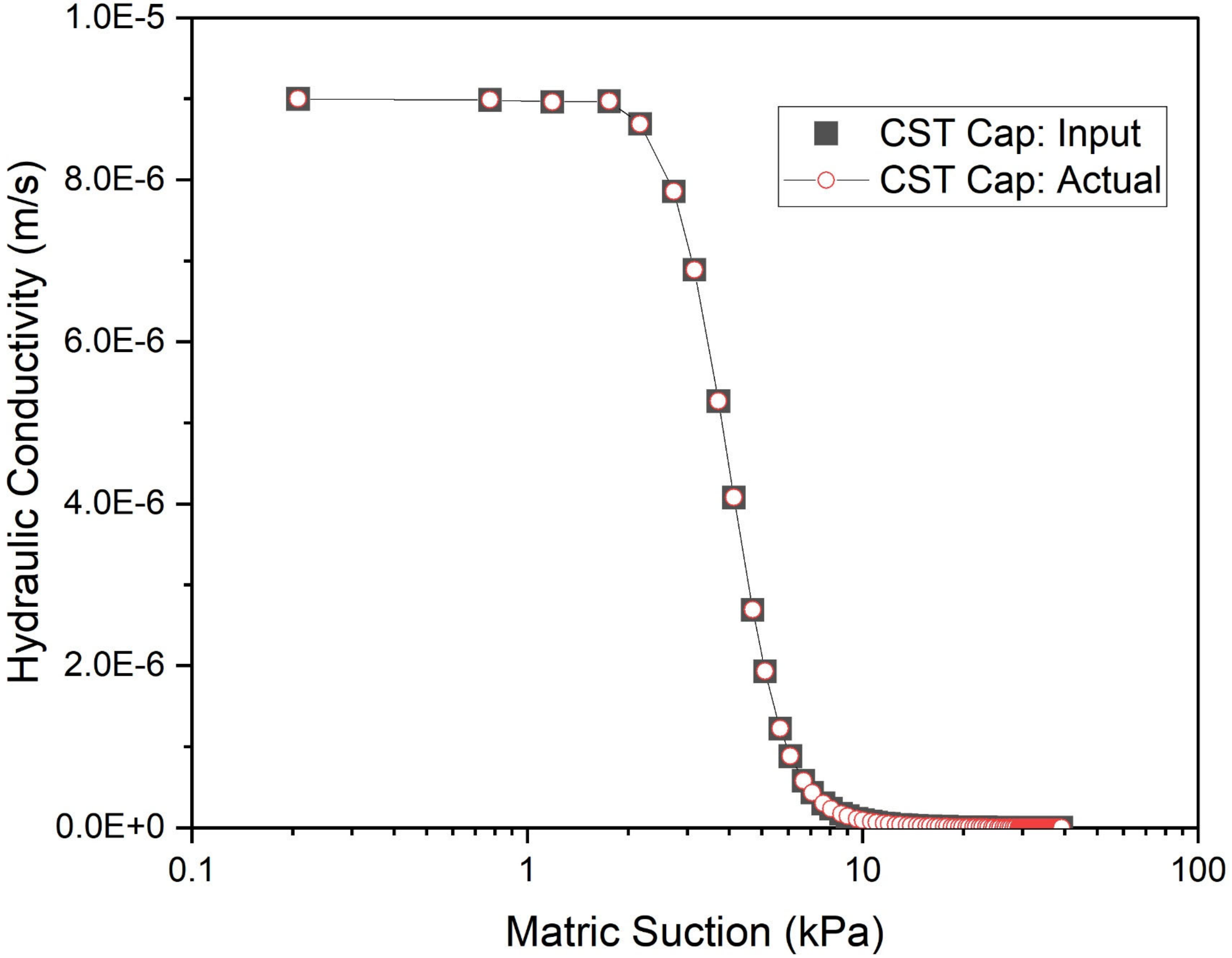


Figure C-8: Hydraulic conductivity versus time for output versus input function for 1D model at Section 1 using TSB

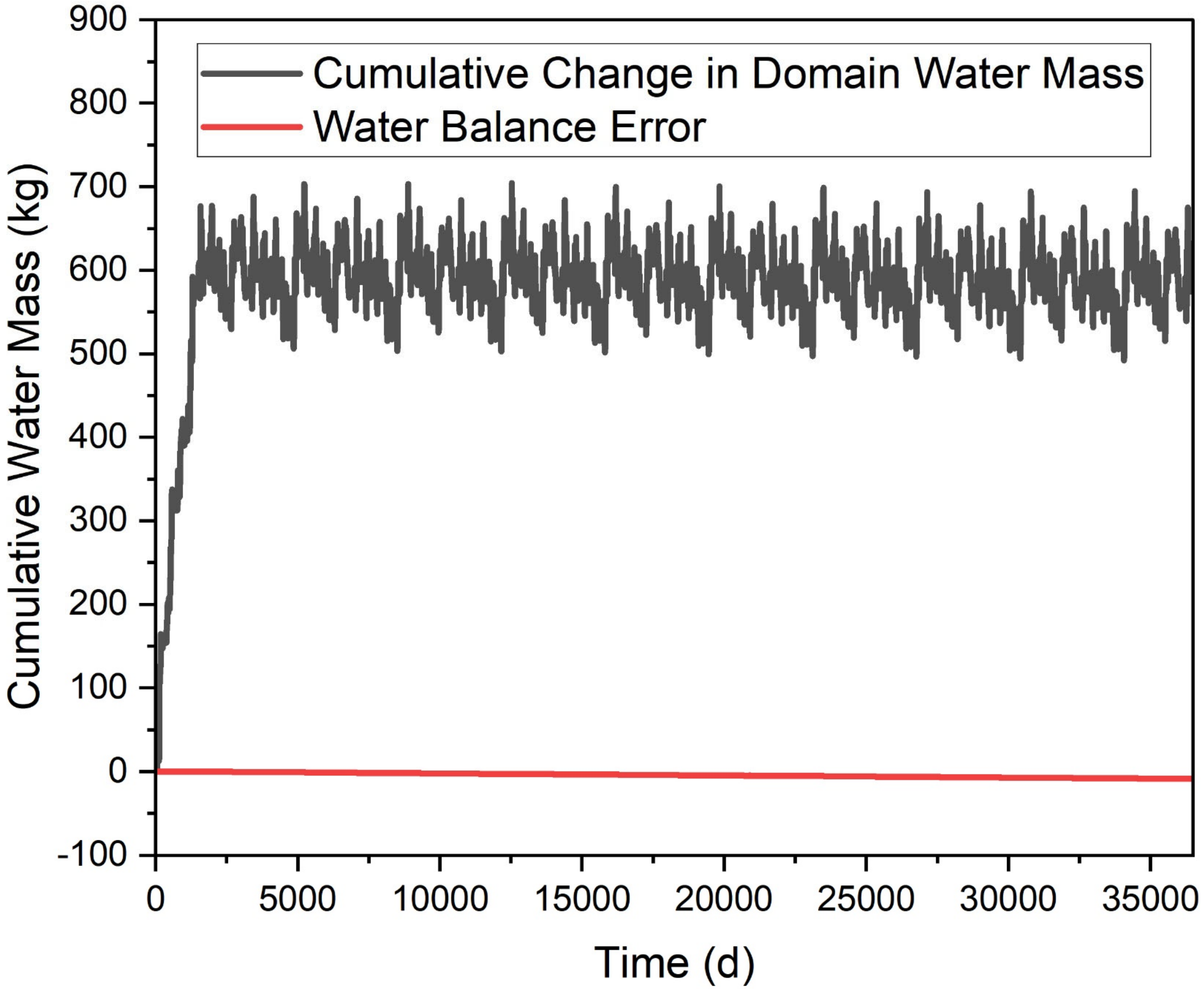


Figure C-9: Cumulative change in domain water mass and water balance error for 1D model at Section 1 using TSB

C.3 SWCC Scenario Cross-Sections

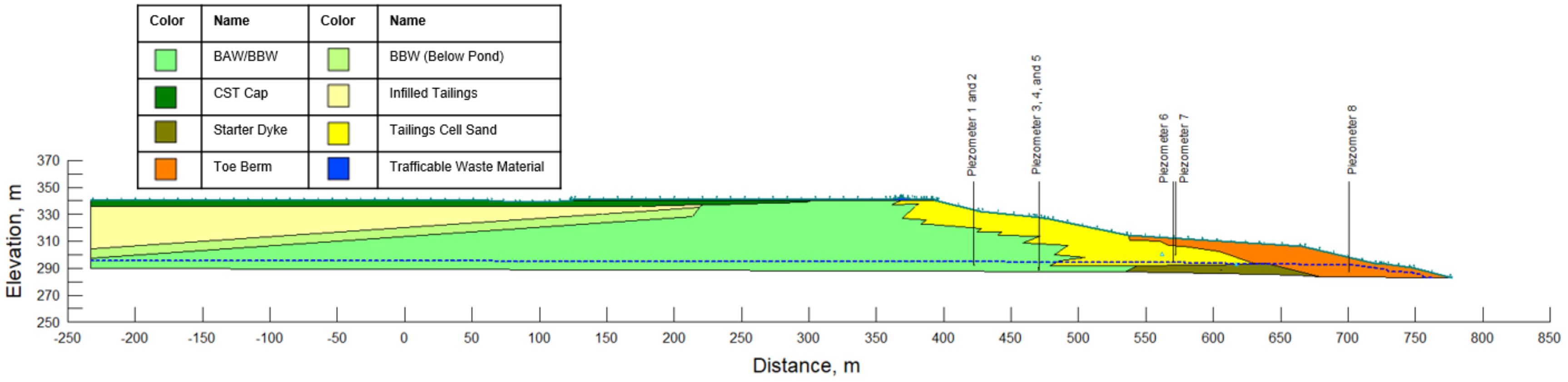


Figure C-10: SWCC comparison Scenario 1 TSA LOS1 final phreatic surface after 100 years

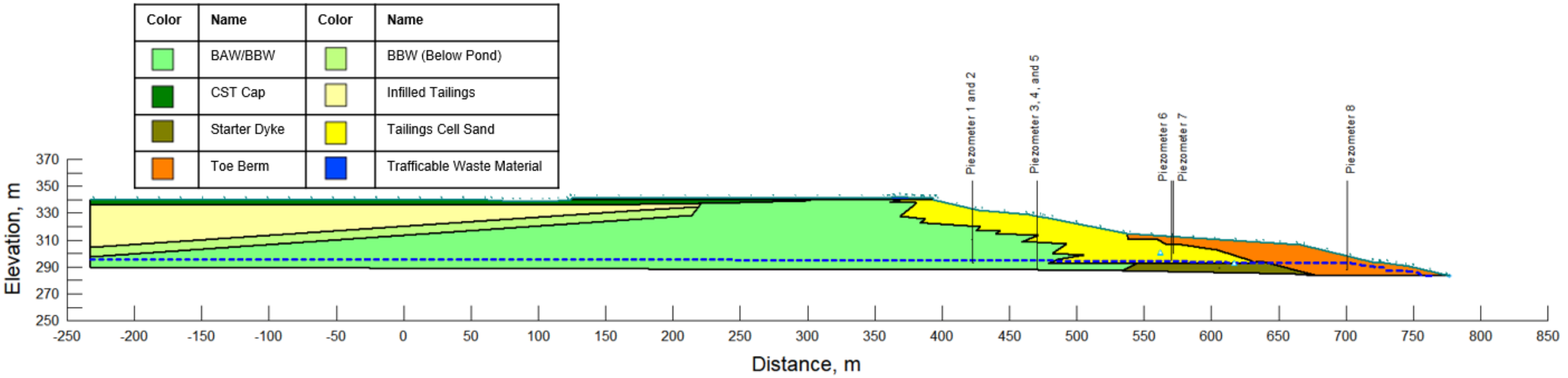


Figure C-11: SWCC comparison Scenario 2 TSA LOS2 final phreatic surface after 100 years

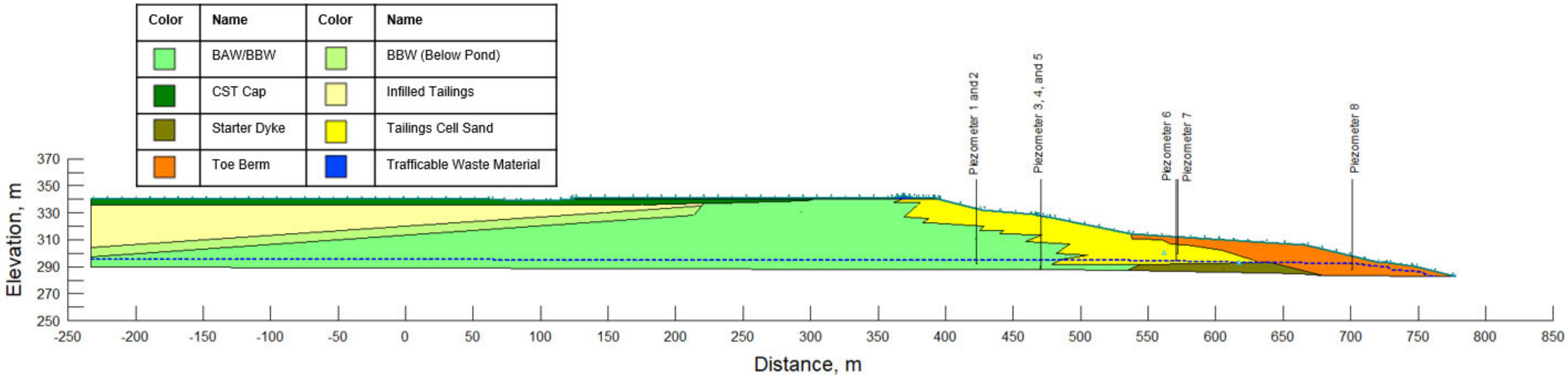


Figure C-12: SWCC comparison Scenario 3 TSA LOS3 final phreatic surface after 100 years

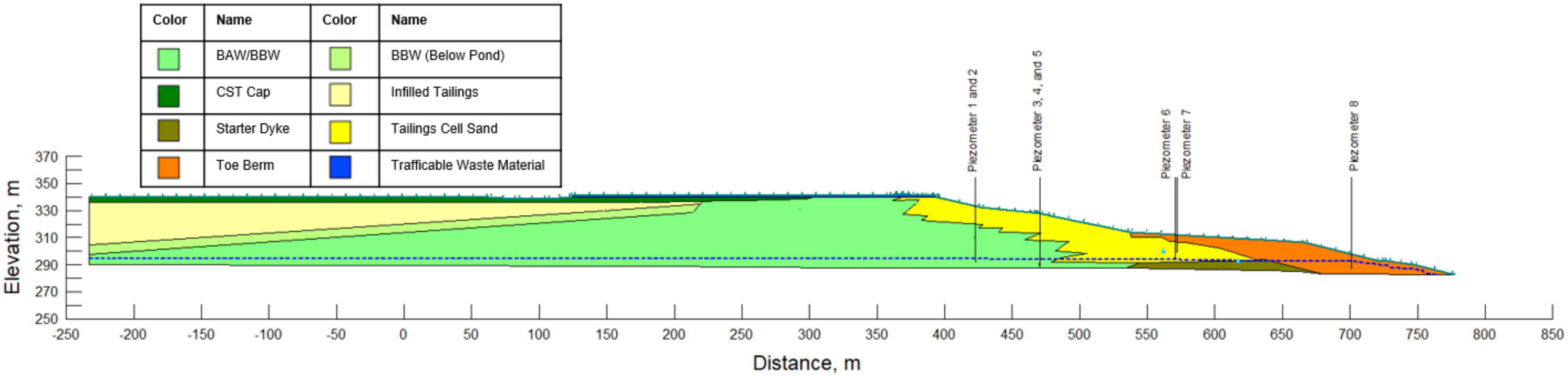


Figure C-13: SWCC comparison Scenario 4 TSB LOS1 final phreatic surface after 100 years

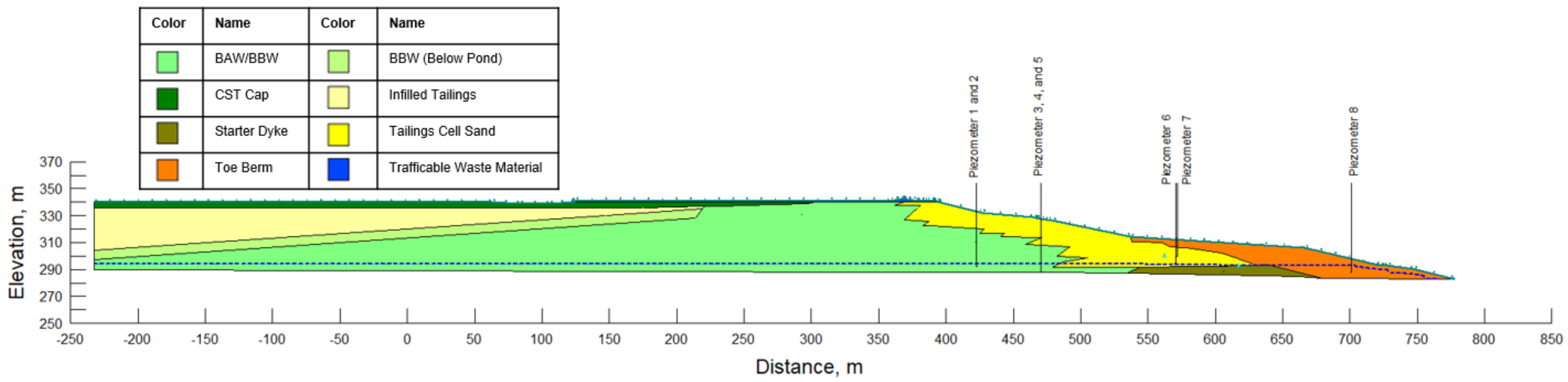


Figure C-14: SWCC comparison Scenario 5 TSB LOS2 final phreatic surface after 100 years

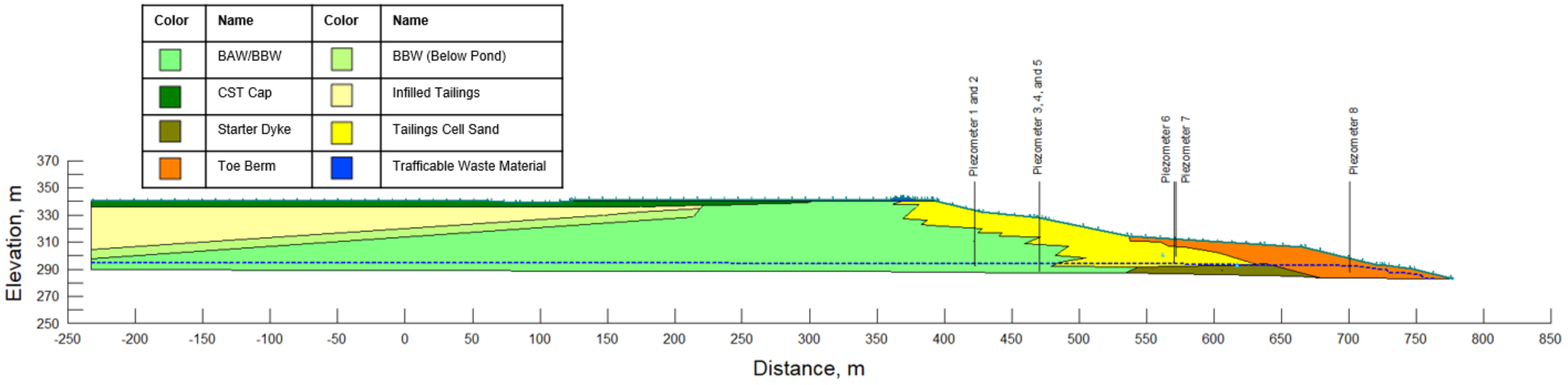


Figure C-15: SWCC comparison Scenario 6 TSB LOS3 final phreatic surface after 100 years

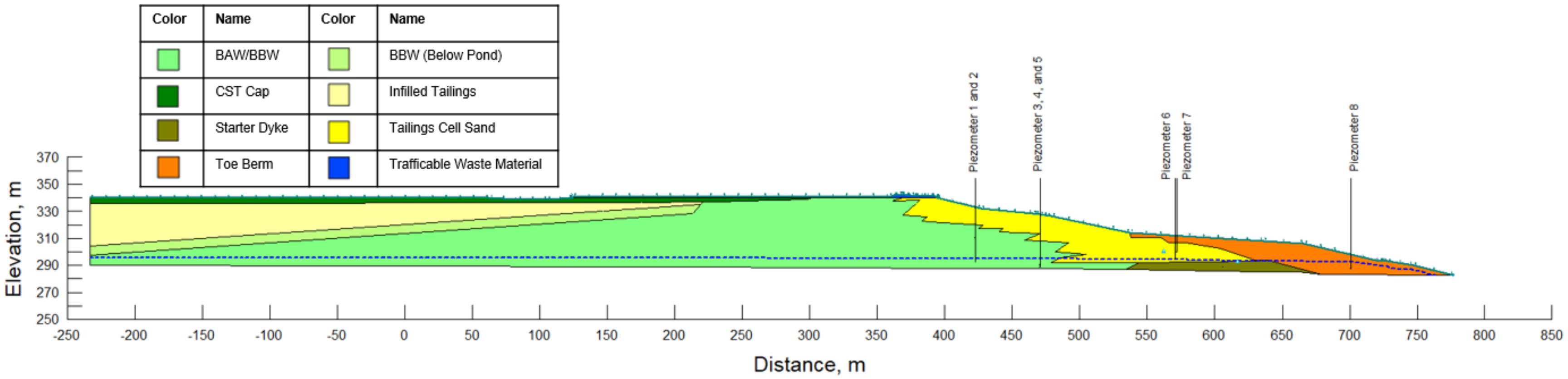


Figure C-16: SWCC comparison Scenario 7 TSC LOS1 final phreatic surface after 100 years

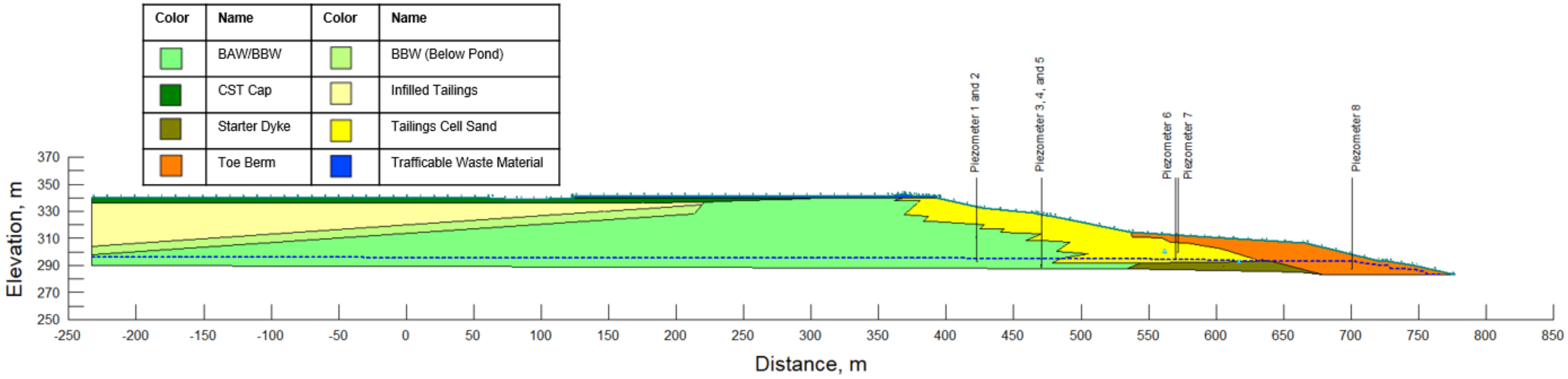


Figure C-17: SWCC comparison Scenario 8 TSC LOS2 final phreatic surface after 100 years

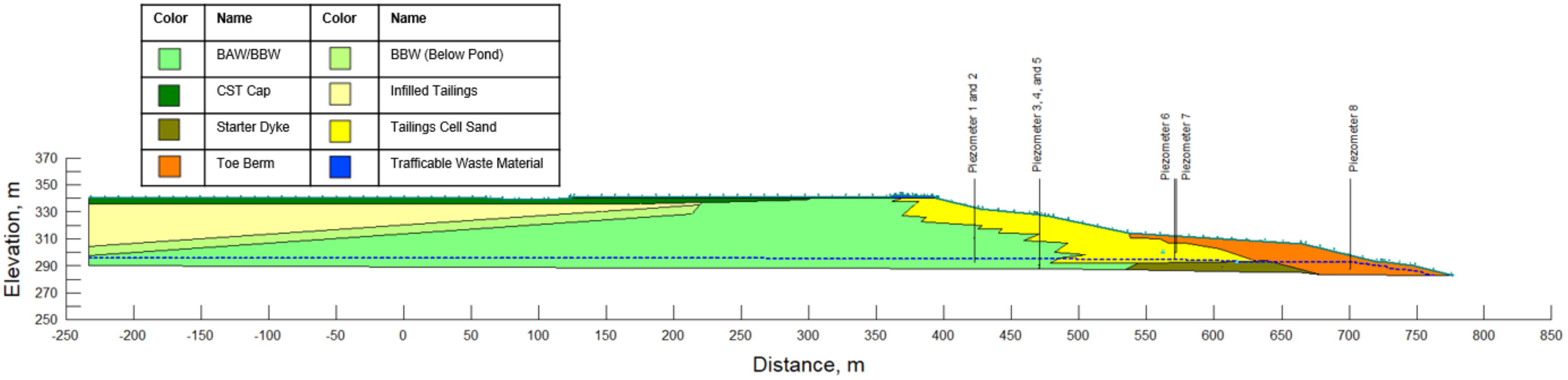


Figure C-18: SWCC comparison Scenario 9 TSC LOS3 final phreatic surface after 100 years

C.4 Transient Scenario Cross-Sections

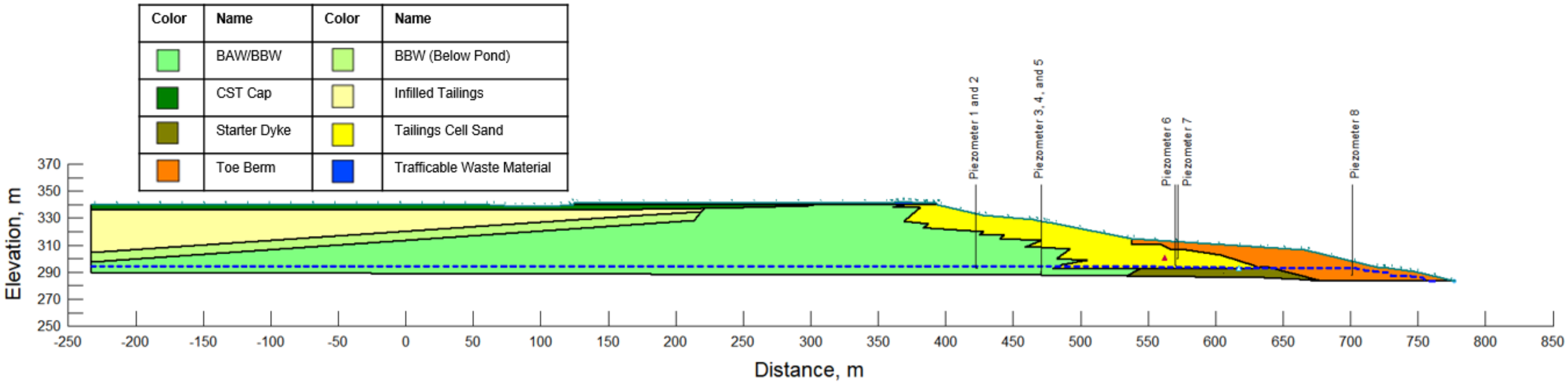


Figure C-19: Drain failure Scenario 1 final phreatic surface after 100 years

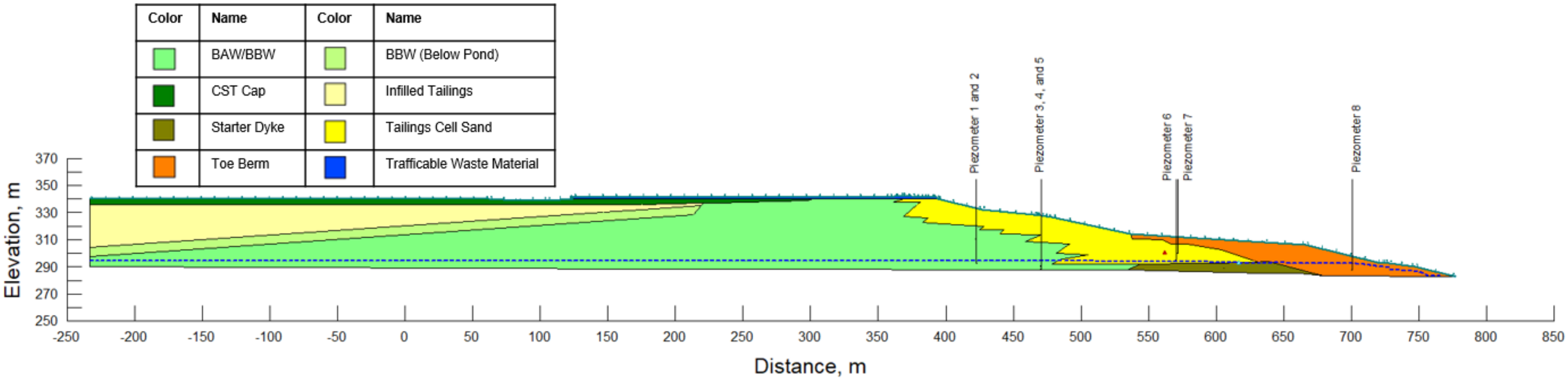


Figure C-20: Drain failure Scenario 2 final phreatic surface after 100 years

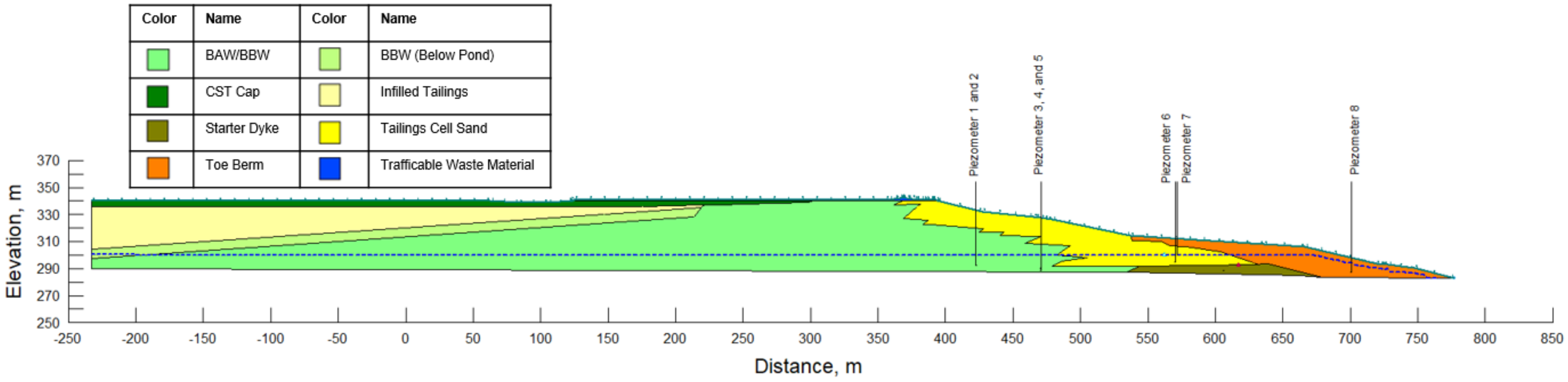


Figure C-21: Drain failure Scenario 3 final phreatic surface after 100 years

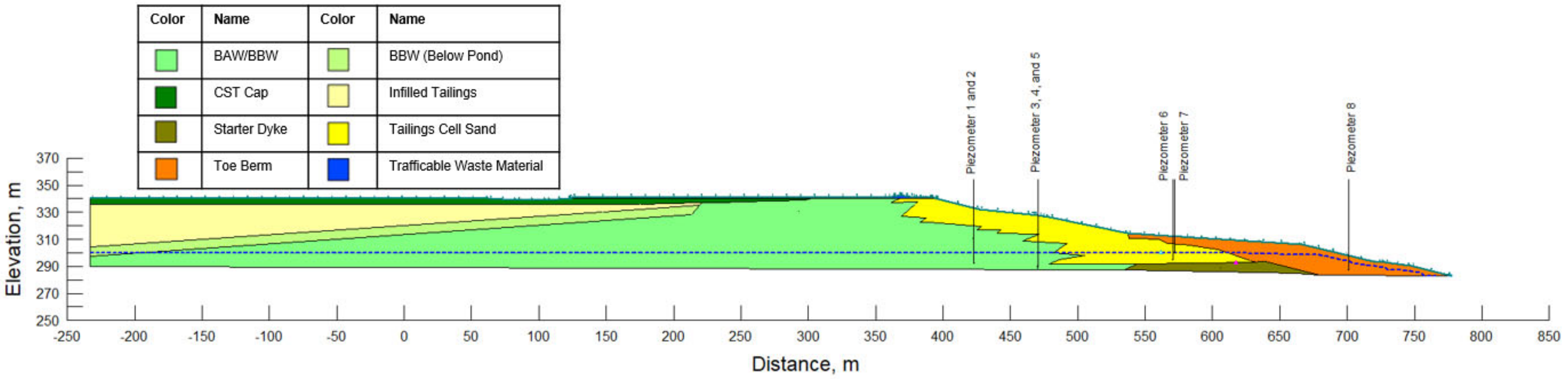


Figure C-22: Drain failure Scenario 4 final phreatic surface after 100 years

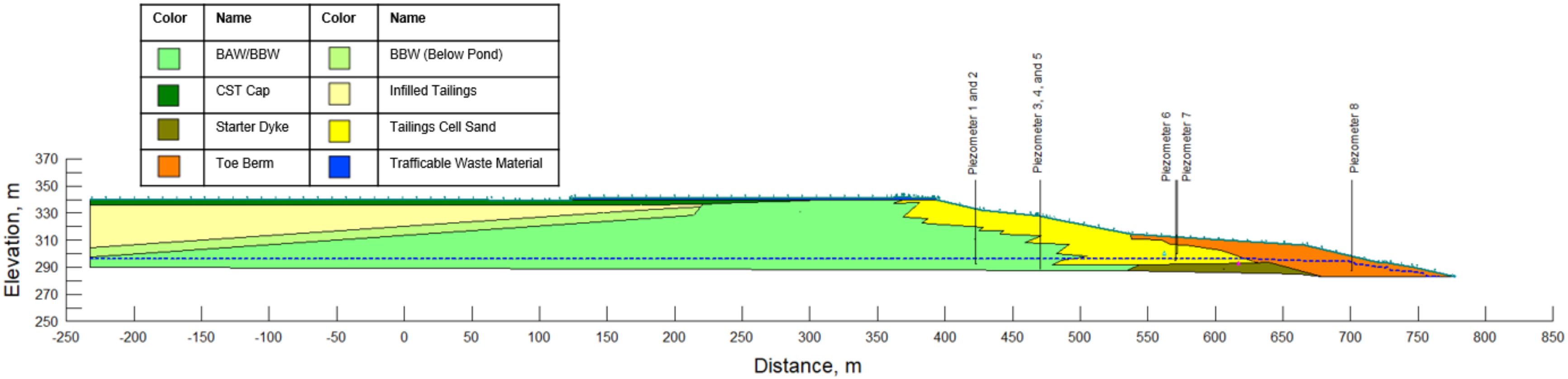


Figure C-23: Drain failure Scenario 5 final phreatic surface after 100 years

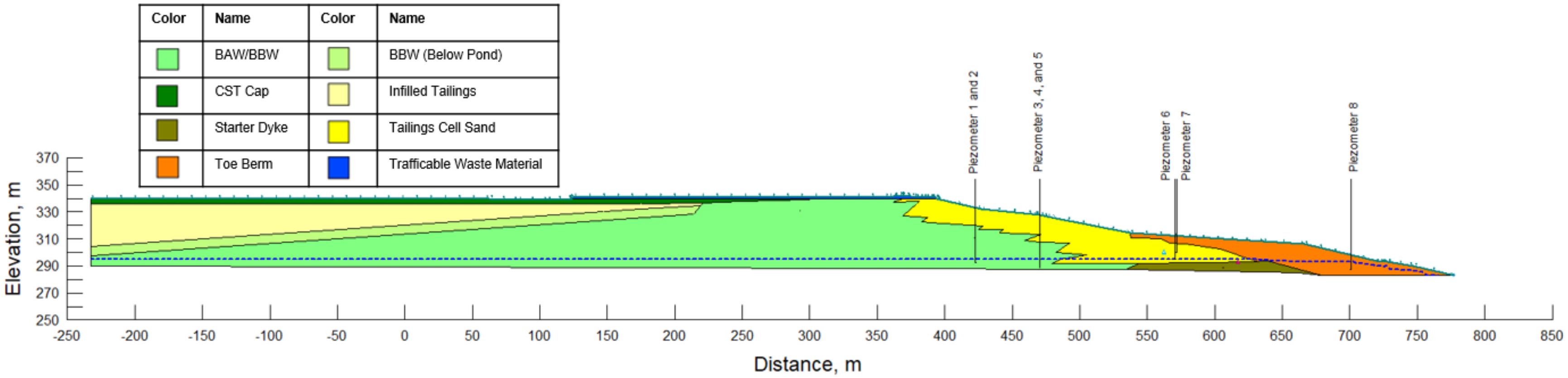


Figure C-24: Drain failure Scenario 6 final phreatic surface after 100 years

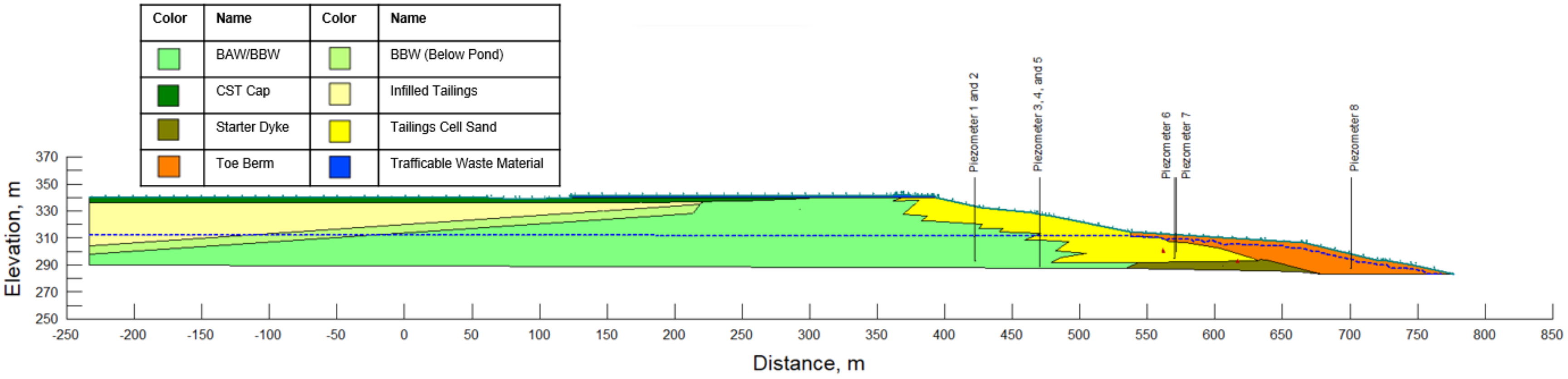


Figure C-25: Drain failure Scenario 7 final phreatic surface after 100 years

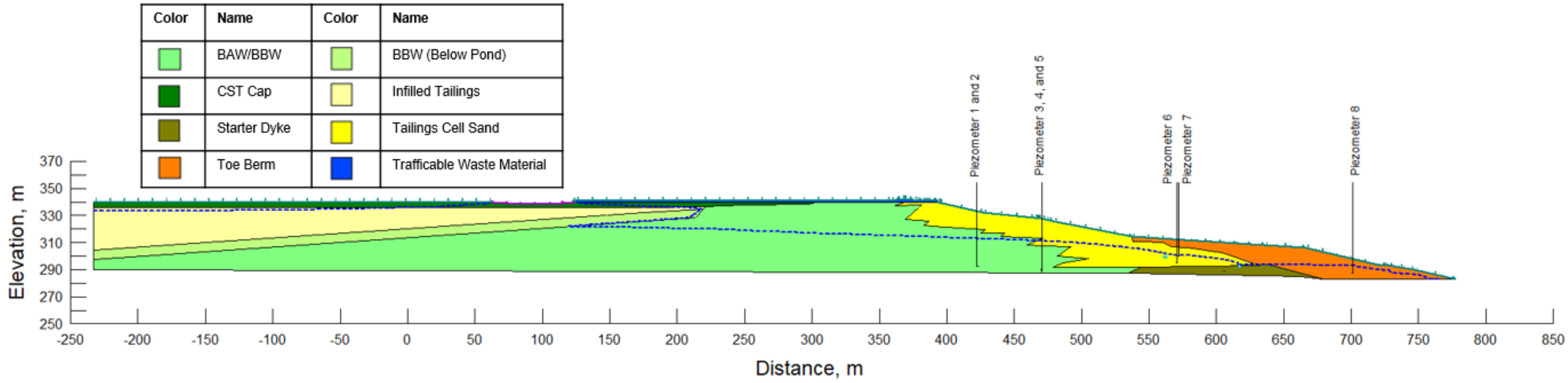


Figure C-26: Pond formation Scenario 1 final phreatic surface after 100 years

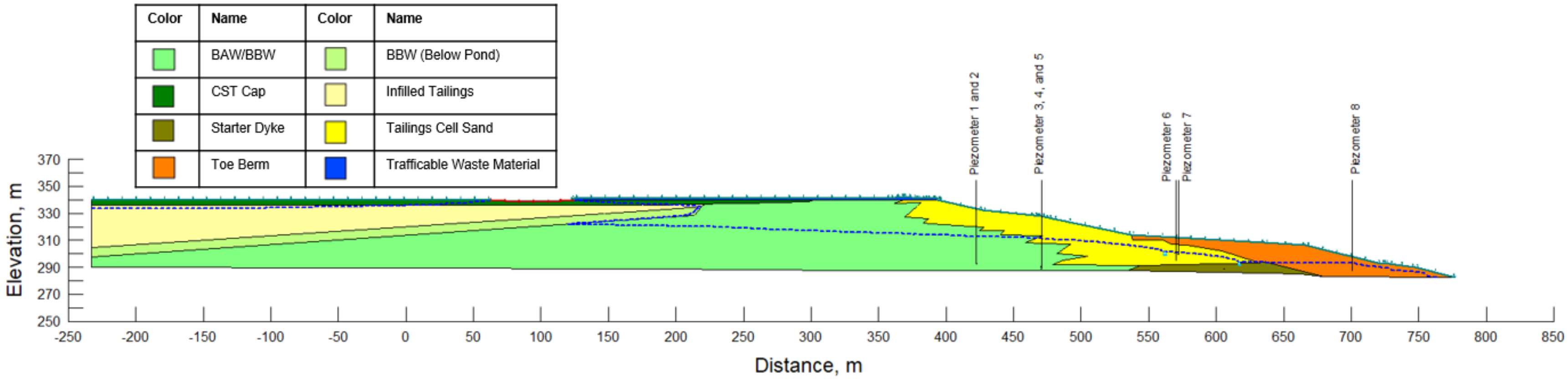


Figure C-27: Pond formation Scenario 2 final phreatic surface after 100 years

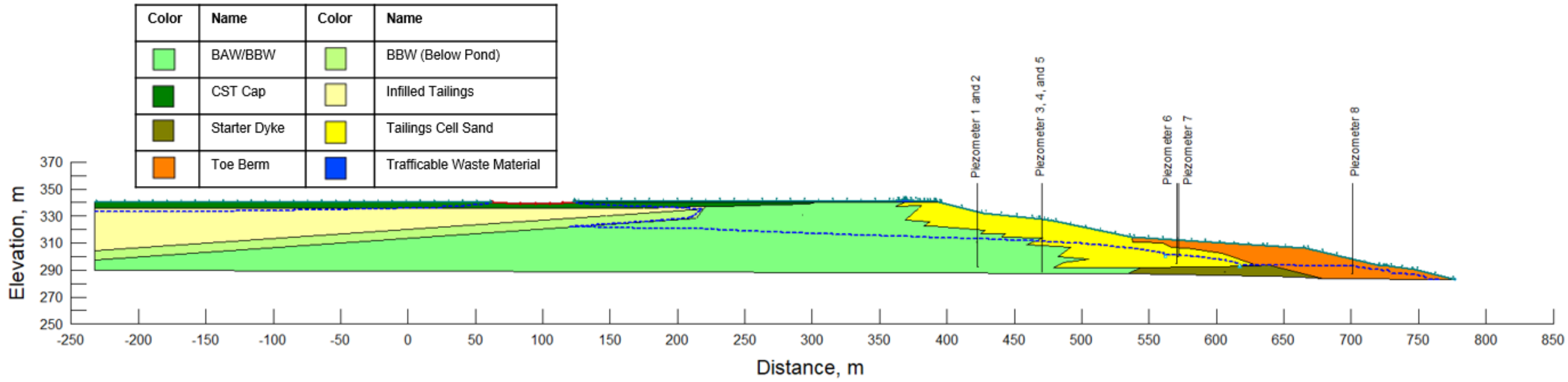


Figure C-28: Pond formation Scenario 3 final phreatic surface after 100 years

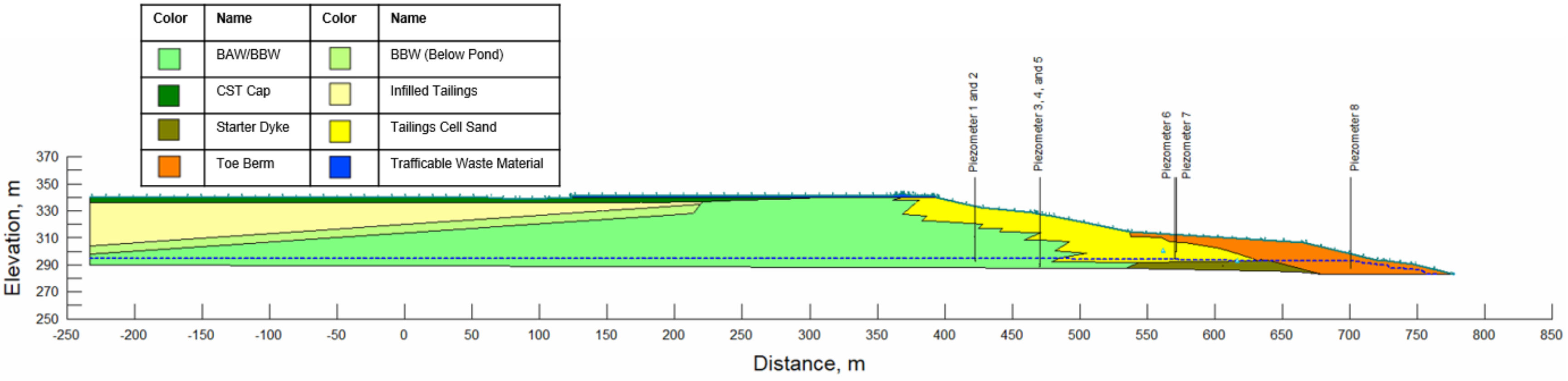


Figure C-29: Pond formation Scenario 4 final phreatic surface after 100 years

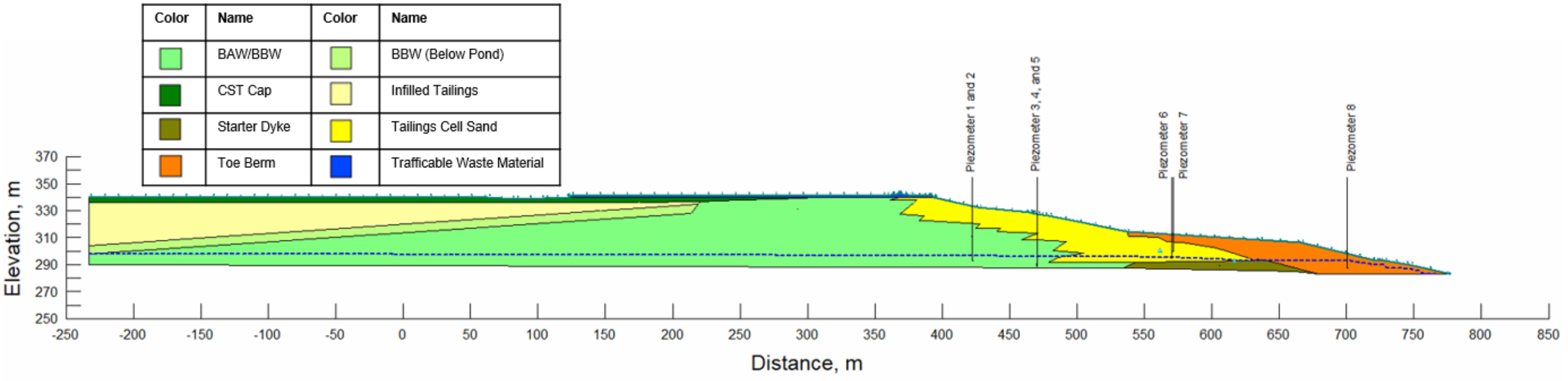


Figure C-30: Pond formation Scenario 5 final phreatic surface after 100 years

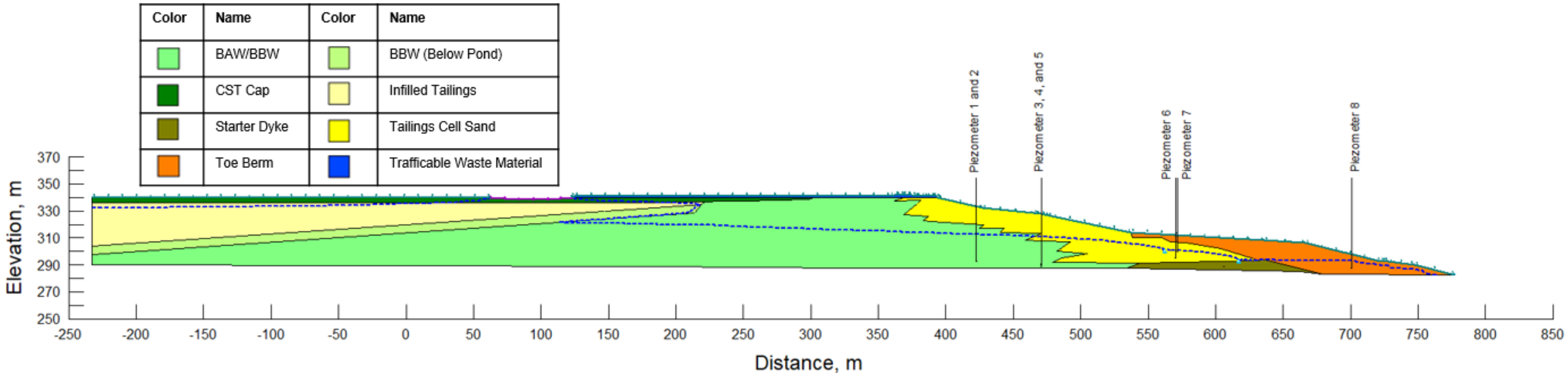


Figure C-31: Pond formation Scenario 6 final phreatic surface after 100 years

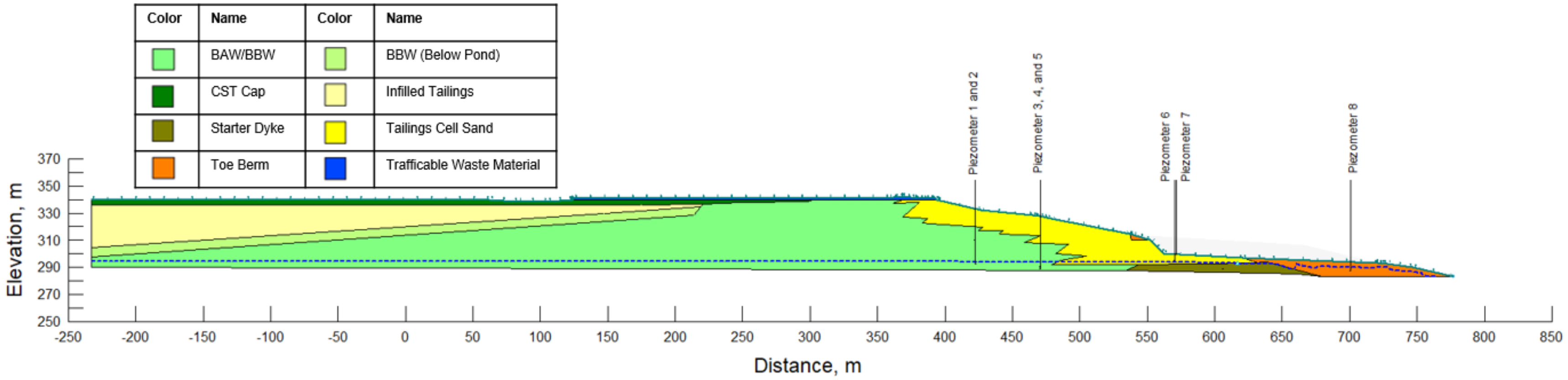


Figure C-32: Erosion Scenario 1 final phreatic surface after 100 years

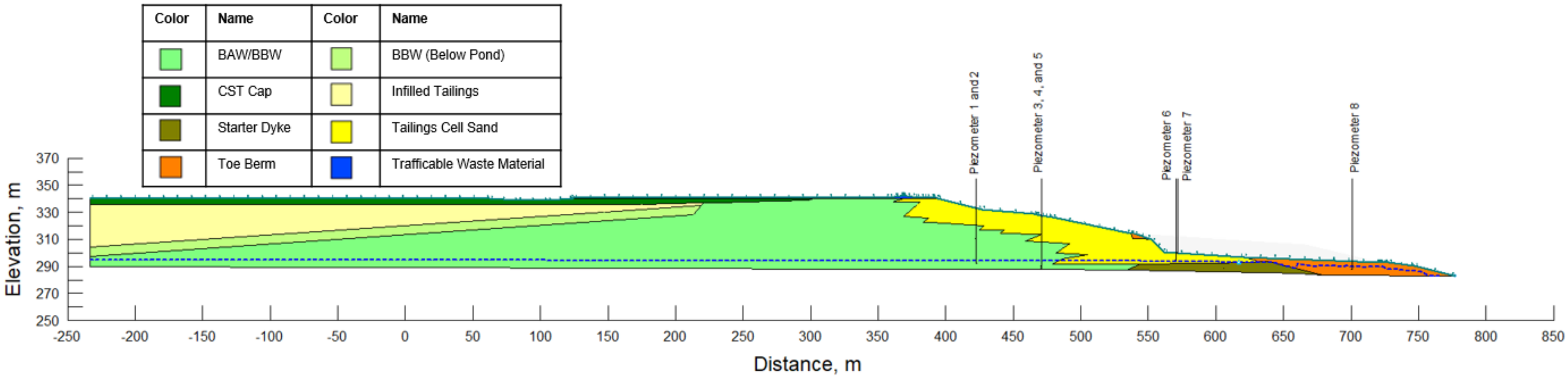


Figure C-33: Erosion Scenario 2 final phreatic surface after 100 years

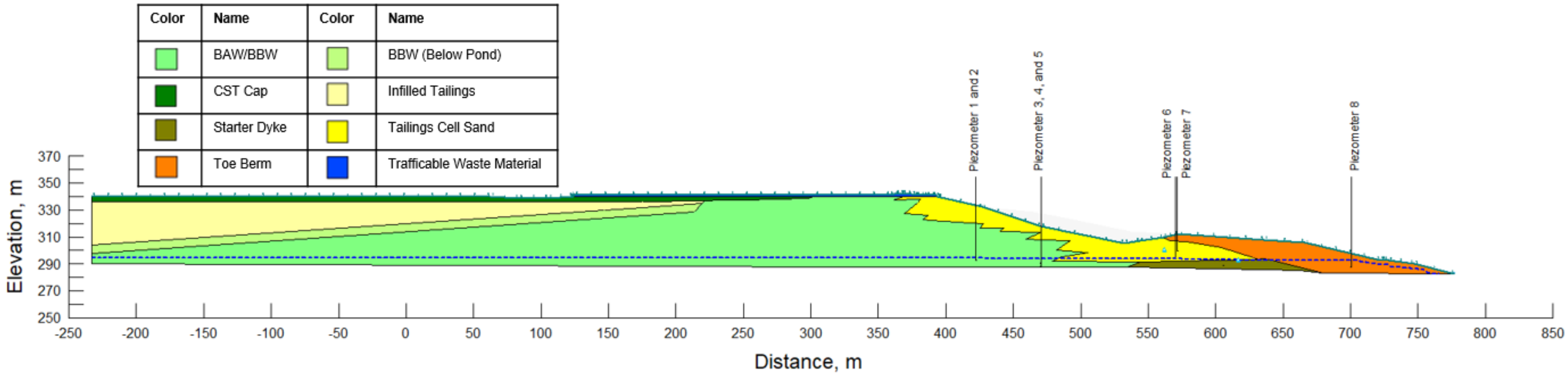


Figure C-34: Erosion Scenario 3 final phreatic surface after 100 years

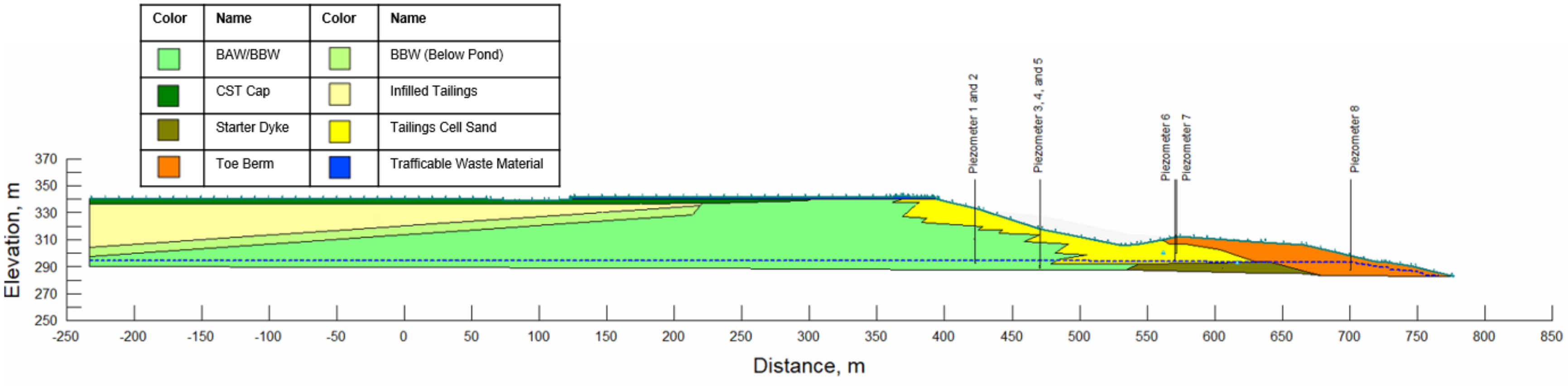


Figure C-35: Erosion Scenario 4 final phreatic surface after 100 years

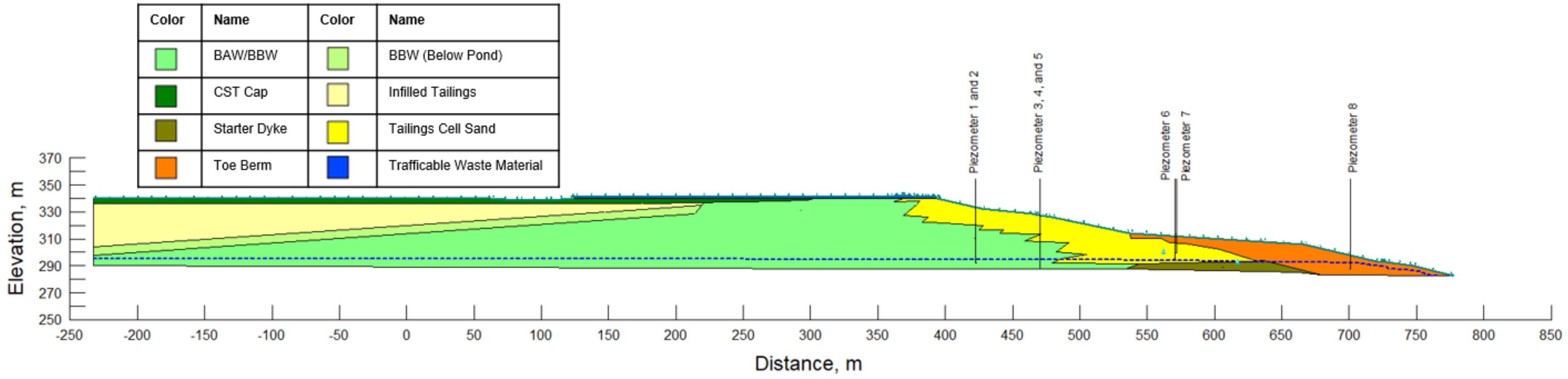


Figure C-36: Climate change Scenario 1 final phreatic surface after 100 years

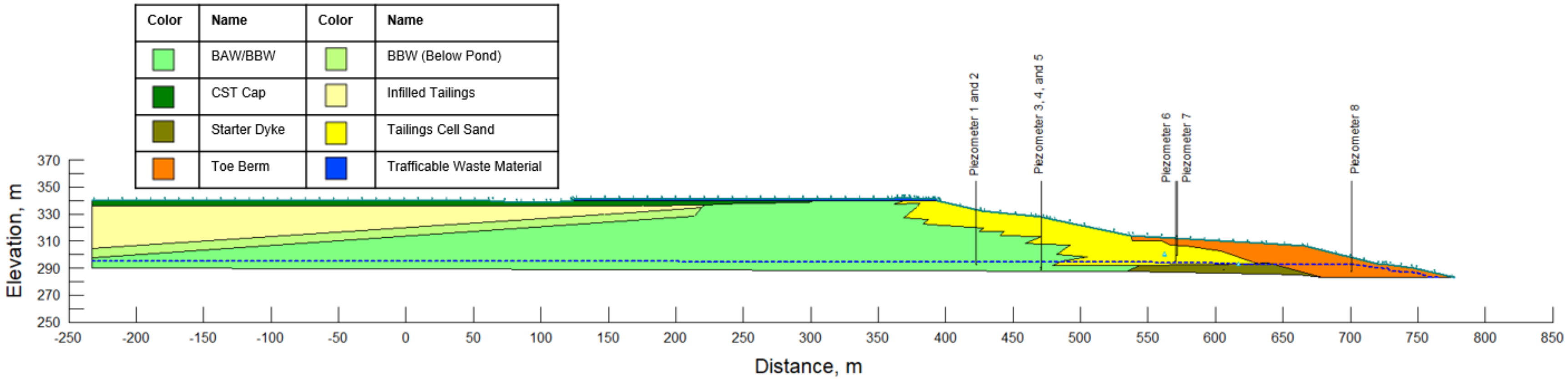


Figure C-37: Climate change Scenario 2 final phreatic surface after 100 years

C.5 References

GEO-SLOPE International Ltd. (n.d.). Land-climate interaction hydraulic modeling of a soil cover system located in northern Canada. GEO-SLOPE International Ltd., Calgary, Alberta, Canada.