Geomorphic landform design and long-term assessment of tailings storage facilities in the Athabasca oil sands

by

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Abstract

In stark contrast to historic mine abandonment, current international best practices in mine reclamation call for geomorphic designs and stability (physical and chemical) for a minimum of 1000 years. Current regulations in Alberta state that post-mining landforms shall be maintenance-free with equivalent land capability to pre-mining conditions, in line with accepted sustainability principles. However, external tailings storage facility (TSF) design in Alberta presently does not assess geomorphic changes due to erosion, nor has this potential risk been evaluated for the design life required. As the first of the oil sands TSFs prepare for closure, a quantitative estimate of erosion risk, and geomorphic assessment of present TSF closure design is necessary to evaluate long-term stability. Using a TSF in the Athabasca oil sands (AOS) within Alberta, Canada, as a study site, this research included five core components: 1) Geomorphic design for closure of the TSF using current best practices in the region, 2) identification, classification, and quantification of erosion on the active TSF using remote monitoring methods and subsequent evaluation of methods for potential use in closure monitoring, 3) proposed integration of geomorphic stability assessment in the tailings dams design process, 4) parameterization and application of the CAESAR-Lisflood LEM to the study site and a section of the dam slope to assess long-term geomorphology with three future climate change scenarios, and 5) assessment of five erosion mitigation design options for tailings dam slopes through stress-testing using CAESAR-Lisflood.

Both wind and water erosion were identified on the TSF dam slopes in the form of deflation, rills, and gullies. Using LiDAR and 'Purview' software with digital stereo aerial photography, the estimated annual soil loss from dams is 48.5 Mg/ha which falls into a 'very high' soil erosion hazard class. Neither of these remote methods provided all necessary information for post-closure erosion monitoring; however, in conjunction the methods were effective in identifying areas at risk, cause, and extent of erosion. Present design strategies for closure of TSFs in the AOS retain active dam slopes unaltered, which were found to be actively eroding at a high rate. Using CAESAR-Lisflood to simulate landform evolution, recent historic climate and a future climate scenario as represented through climate only and through cumulative effects (climate and vegetation change) generated large gullies that could pose a threat to dam stability. The cumulative climate change simulation resulted in greater soil loss over an extended time frame and erosion rates failed to stabilize over 100 years, while historic climate inputs lead to erosion rates reaching an equilibrium within about 20 years on the dam section modelled. When the entire TSF is simulated equilibrium erosion rates are attained within about 50 years. These results suggest that the current estimates for active dam maintenance and monitoring post-closure of less than 20 years are under-estimated. The majority of predicted erosion occurred on dams, with minimal impact to the geomorphically designed central plateau of the TSF. Integration of geomorphic design into the tailings dam downstream slope, followed by stress-testing, resulted in substantially less erosion than in other mitigation options simulated, including the geomorphic design with channel armouring. This indorses the concept that long-term stability of these landforms is best achieved by designing with nature rather than against it.

Preface

Some of the research conducted for this thesis was part of a collaboration with others.

Chapter Four of this thesis has been published as Slingerland, Beier, and Wilson: "Oil sands tailings dams: Design considerations for ease of closure", in *CIM Journal*, 10(2). DOI: 10.15834/cimj.2019.7. This paper was generated from findings of the design research I conducted as described in Chapter Three. Both N. A. Beier and G. W. Wilson acted as supervisory authors, providing review and manuscript editing.

Chapter Six of this thesis is the preprint for an article published as Slingerland, Sommerville, O'Leary, and Beier: "Identification and quantification of erosion on a sand tailings dam", in the journal *Geosystem Engineering*, DOI: 10.1080/12269328.2018.1538823. I was responsible for the data analysis and manuscript composition. A. Sommerville provided technical assistance for data analysis. D. O'Leary provided the software and hardware to conduct analysis. N. Beier was the supervising author. All three co-authors provided manuscript editing.

The original concept summarized in Section 7.4, and by Figure 7.3, was published as Slingerland, Beier, and Wilson: "Enhanced geomorphic design for reclamation of rural waste-scapes", in the journal *Detritus*, vol. 2, 170-179, DOI 10.31025/2611-4135/2018.13655. I conducted the research and manuscript preparation, while N. Beier and G. W. Wilson contributed to manuscript editing. This concept was refined with the assistance of fellow graduate student Sebastian Fernandez Ortiz to the form presented herein, and was subsequently published as part of a conference paper: Slingerland, Isidoro, Fernandez, and Beier, "Geomorphic analysis for tailings dam design in consideration of a 1000-year closure design life", presented at, and published in the proceedings of the 2nd International Congress on Planning for Closure of Mining Operations. A. Isidoro acted as technical advisor, and together with N. A. Beier, assisted in manuscript editing.

Chapter Nine contains the preprint submitted for publication as N. Slingerland, N. A. Beier, & G. W. Wilson, "Modelling tailings dam evolution post-closure: erosion assessment using three methods of future climate representation", in *Earth Surface Processes and Landforms*. I was responsible for the data collection, modelling, analysis, and manuscript writing. N. A. Beier and G. W. Wilson acted as supervisory authors and provided manuscript editing.

Acknowledgements

This work benefited from the financial and in-kind support of a number of companies, councils, and associations. I would like to gratefully acknowledge the National Science and Engineering Research Council of Canada (NSERC) and Golder Associates Limited for their support through the Industrial Postgraduate Scholarship, Golder Associates Limited for the Golder Mine Closure Scholarship, and the Canadian Dam Association for the Gary Salmon Memorial Scholarship. I would also like to acknowledge Alberta Innovates - Energy and Environment Solutions for their financial support through the NSERC Industrial Research Chair Program.

Much of this PhD was completed from the Golder Associates Edmonton office, and the ease of access this provided to an abundance of true professionals was invaluable. For this, I am indebted to Les Sawatsky who initially supported this work; Allison Isidoro, who facilitated this support and was always generous with her time, knowledge, and introductions; as well as Anne Sommerville and Dennis O'Leary for the use of their PurVIEW software and computers, lessons in how to use it, and for sharing in my enthusiasm for terrain analysis. Thank you.

Essential in-kind support was generously provided by Shell Canada Inc, former operators of Albian Sands. Thank you to Sajid Iqbal and Derek Etherington for their coordination; Dave Young for his great efforts and assistance collecting CST samples with me and touring me around the TSFs; Omar Chyon and Karsten Rudolf for IT support; Scott Wytrychowski and Scott Martens in particular for their extensive and beneficial review of this manuscript.

Professor Tom Coulthard at the University of Hull played an essential role by providing free public access to CAESAR-Lisflood as well as technical support over the years. Thank you.

Additionally, this document has evolved and been shaped over five years from direct and/or indirect input from a long list of individuals:

I am profoundly grateful to my supervisory committee: Dr. Wilson has been my unwavering advocate and his trust, expert guidance, and foresight has been much appreciated; Dr. Nick Beier has been a grounding force, entertaining my ideas with calm consideration and ensuring the engineering basis has been well-founded and justifiable. Dr. Beier has dedicated much energy to ensuring that the line of research established herein continues to evolve at the U of A, and it has been a highlight of my academic career thus far to work with him on this. Dr. Gord McKenna has provided enthusiastic mentorship and extensive reviews of my work over the years; his contribution was vital to this research, providing insights on landscape performance at other AOS mine sites and highlighting the work's broader applicability.

Thank you to my examining committee: Dr. Andy Fourie for his interesting and thoughtful questions at an hour when most would rather be asleep; Dr. Tim Joseph for supporting my integration into mining from the beginning and for providing me with his laboratory's modelling computer; Dr. Rick Chalaturnyk for skillfully chairing the thesis defense; Dr. Carl Mendoza for his philosophical line of geomorphology questioning during my candidacy exam.

Thank you to my colleagues: David Barsi, Ahlam Abdulnabi, Ralph Burden, Sebastián Fernández Ortiz, and everyone at the Torchinsky Geotechnical Center including Sally Petasky, Vivian Giang, Christine Hereygers, and Louis Kabwe, for their assistance and many helpful discussions. Special thanks to Bereket Fisseha, who has been a wonderful friend and colleague to have navigated this chapter of life with.

Thank you to my father, Cam Slingerland, for spending his vacations doing field work with me across Alberta, collecting endless sand dune samples and/or just being near by; you will always be my favourite road-trip companion. Thank you to my mother, Bernadette Slingerland, for our frequent conversations, her sound advice, empowerment, and for getting me through the really challenging times when I'm certain there were more important issues to be focussing on.

Gracias a la familia González (María, Fernando, y Cristiáncito especialmente) por darme la bienvenida y por ser mi hogar durante los últimos años. Siempre estás en mi corazón. Muchas gracias.

Finally, Dr. Karen Landman at the University of Guelph has been a trusted mentor since the early days of my Masters in Landscape Architecture. Her work exemplifies scientifically-driven, evidence-based landscape architecture and she has used this to enhance biodiversity and make positive environmental change. Dr. Landman has been an inspiration and because of this (and for her quick, dry wit) I will continue to be a burden on her inbox for years to come. Thanks in advance.

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List of Abbreviations

AER, Alberta Energy Regulator

AEP, Alberta Environment and Parks

ANSWERS, Areal Non-point Source Watershed Environment Response Simulation

AOS, Athabasca Oil Sands

BAW, Beach Above Water

BBW, Beach Below Water

C&R, Closure and Reclamation

C-L, CAESAR-Lisflood

CA, Cellular Automata

CAD, Computer Aided Design

CAESAR, Cellular Atomata Evolutionary Slope and River

CDA, Canadian Dam Association

CEMA, Cumulative Environmental Management Association

CFL, Courant-Freidrichs-Lewy

CHILD, Channel-Hillslope Integrated Landscape Development

CST, Coarse Sand Tailings

DEM, Digital Elevation Model

DFO, Department of Fisheries and Oceans

EPs, Equator Principles

EPA, Environmental Protection Agency (USA)

EPEA, Environmental Protection and Enhancement Act (Canada)

EU, European Union

FFT, Fluid Fine Tailings

FOS, Factor of Safety

GCM, Global Climate Models

GIS, Geographic Information Systems

GOLEM, Geomorphic Orogenic Landscape Evolution Model

GSD, Grain Size Distribution

HI, Hypsometric Integral

ICMM, International Council of Mining and Metallurgy

ICOLD, International Commission on Large Dams

IDF, Intensity-Duration-Frequency

IFC, International Finance Corporation

IMEC, Institute of Minerals, Energy, and Construction (Australia)

IPCC, Intergovernmental Panel on Climate Change

InSAR, Interferometric Synthetic-Aperture Radar

LEM, Landscape Evolution Model

LiDAR, Light Detection and Ranging

LMCP, Life of Mine Closure Plan

LOM, Life of mine

MAC, Mining Association of Canada

masl, meters above sea level

MCE, Maximum Credible Earthquake

MEND, Mine Environment Neutral Drainage

MFSP, Mine Financial Security Program

MFT, Mature fine tailings

MRP, Mine Reclamation Plan

MRRP, Minesite Rehabilitation Research Programme

NA, Naphthenic acid

NAG, Non-Acid Generating

NGO, Non-Governmental Organization

NPD, North Pool Deposit

NRCS, Natural Resources Conservation Service (USA)

NWPP, Navigable Waters Protection Program

ODA, Overburden Disposal Area

OSTDC, Oil Sands Tailings Dam Delicensing Committee

PAG, Potentially Acid Generating

PMF, Probably Maximum Flood

PMP, Probable Maximum Precipitation

PSHA, Probabilistic Seismic Hazard Assessment

RAMP, Regional Aquatics Monitoring Program

RCP, Representative Concentration Pathway

RUSLE, Revised Universal Soil Loss Equation

RUSLFAC, Revised Universal Soil Loss Equation for Application in Canada

SEA, South Expansion Area

SMCRA, Surface Mining Control and Reclamation Act

SRES, Special Report on Emissions Scenarios

SWODA, South West Overburden Dump

TIN, Triangular Irregular Network

TOPMODEL, TOPography-based hydrological Model

TSF, Tailings storage facility

TSRU, Tailings solvent recovery unit

TT, Thickened tailings

USLE, Universal soil loss equation

WEPP, Water Erosion Prediction Project

"Mining is essential to living as we know it. Mining is not an environmentally friendly activity. Extensive efforts have been made world-wide to minimize environmental damage from mining activities, but the job is not done. The biggest environmental challenge in mining is the management of mine tailings." (Vogt, 2013)

1.0 Introduction

This work begins by investigating and questioning current practices of closure design for tailings storage facilities internationally and more locally in the Athabasca oil sands (AOS), shown in Figure 1.1. Common practice today includes applying slope characteristics found naturally on undisturbed land in the AOS to tailings landforms predominantly constructed of uniform coarse sand tailings (CST). Geomorphic principles suggest that this approach will not provide the same degree of erosion resistance over long time frames as is found on natural, glacial-origin terrain.

Characteristics of mature hillslopes constructed of coarse sand tailings have not yet been defined for use in the design of new landforms. Current practice includes design of tailings dams for the relatively brief Operation Phase of the mine, followed by geomorphic design of the central plateau bound on all sides by dams that are covered with reclamation material at closure and vegetated. This tailings dam design process is expanded upon in this work through application of the landscape architectural design approach and development of three conceptual designs from which a preliminary design was chosen for a tailings storage facility (TSF) in the AOS.

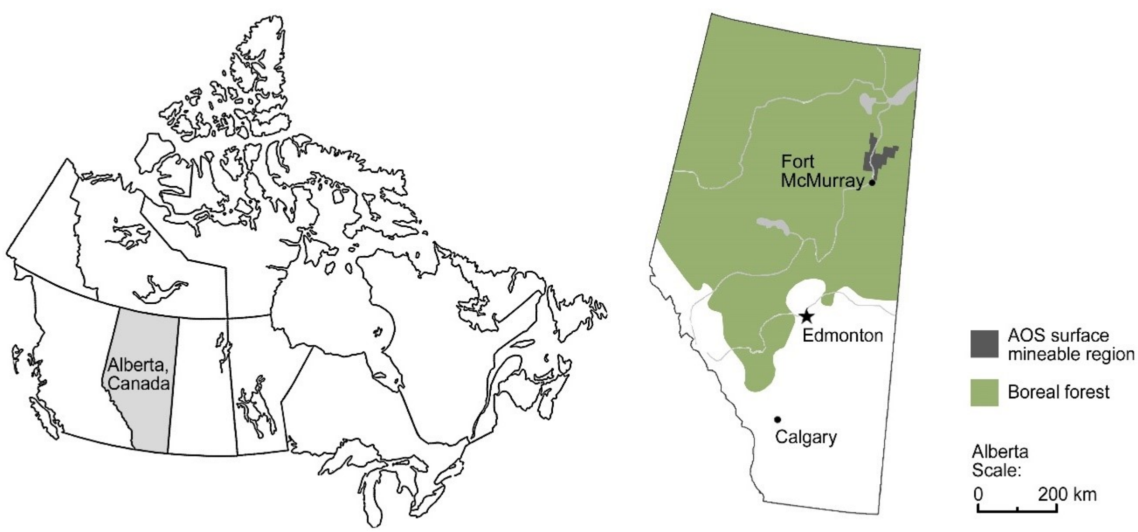


Figure 1.1 Location of the mineable Athabasca oil sands north of Fort McMurray in Alberta, Canada. Several mines and tailings dams straddle the Athabasca River.

Operators' long-term goal is to delicense the TSFs as dams following reclamation, such that they no longer meet the regulator's definition of a dam, and subsequently to attain reclamation certificates. While the erodibility of coarse sand tailings has been previously identified as a challenge (Rowell, 1977), it has never been quantified or characterized to fully understand the causation and extent of the threat. Without maintenance, erosion contributes to the long-term geomorphology of a landform. Left unchecked, erosion can remove soil cover, reduce forest productivity, and expose mine waste. Deposition of eroded material can suffocate vegetation on land and aquatic species in water, degrade water quality, and potentially require dredging for removal. Erosion and resulting degradation can therefore inhibit dam delicensing, delay a landform's reclamation certification, and increase both maintenance and bonding costs. Design to reduce erosion is therefore advantageous.

The reclamation goal in Alberta is to create a locally common boreal forest ecosystem that is maintenance-free and performs just as the natural terrain would (at which point a reclamation certificate would be issued). This presently means the landforms holding mining waste must be physically and chemically stable in perpetuity. As such, this work seeks to evaluate the extent of erosion presently occurring on tailings ponds; at the same time providing insight as to the geomorphic performance and environmental loading in a "walk away" scenario, with no reclamation whatsoever (note: this is a worst case scenario, not presently considered an option by regulators, but of interest if only to reinforce the importance of reclamation).

The current state of practice with respect to erosion prevention is installation of a thin (0.1 – 1.0 m) layer of mixed mineral soil and organics with sufficient water holding capacity to sustain boreal forest vegetation. Gullies formed in the years following this prescriptive reclamation strategy are repaired, though they often re-establish when CST is intercepted. Most structures rely on diffused sheet flow and, to a greater degree on vegetation, for erosion prevention. While there is a design basis for this prescriptive cover design, there is considerable concern for the erosional stability of these structures in the AOS, and more broadly for sand dams globally.

Given that present design methods for tailings ponds do not consider slope stability due to erosion over long time frames, a natural process that may potentially lead to failure of caps or covers, reclamation works, and dam stability, prediction of erosional processes on AOS tailings dams is of interest. The recent Intergovernmental Panel on Climate Change 'Global warming of

1.5 °C’ report and the increasing severity of storms. forest fires, and other extreme events, also incite the interest how climate change projections do or do not impact erosion-based degradation of these structures. Landscape evolution modelling and semi-empirical soil loss analysis of tailings dam slopes over a range of temporal and spatial scales may provide information regarding how and when dam slopes are likely to change, in turn providing opportunities for: design guidance for new TSFs, design guidance for conversion of existing TSFs into closure landforms, insight into erosion-prone topography, testing of mitigation scenarios, and guidance on the timing (return period) of landform inspections and maintenance post-closure.

1.1 Research question and objectives

The current state of international design practice and regulatory requirements for reclamation and closure of tailings dams do not explicitly consider their long-term geomorphology via inevitable erosional processes, specifically of interest for sand-constructed tailings dams. Regulators are increasingly requiring a 1000-year design life for closure plans, yet closure designs are rarely evaluated for compliance with respect to geomorphology. This research seeks to identify a design basis for a long-term stable TSF, particularly with respect to downstream dam slopes. The following objectives were outlined:

1. Identify existing considerations in tailings dam design and for the design of post-mining above-ground tailings landforms.
2. Inventory, classify, and describe erosional processes acting on aboveground tailings ponds and identify resulting mechanisms causing erosional features to form, informing delicensing considerations with respect to landform stability.
3. Quantify, using semi-empirical analysis, the potential soil loss from tailings dam slopes as they are presently designed.
4. Evaluate the susceptibility of aboveground tailings landforms to erosion resulting from current and projected climates, and identify geotechnical and environmental implications, if any, using a landform evolution model.
5. Through the design and analysis process, identify design considerations for ease of closure and long-term stability for both existing and new (proposed) aboveground TSFs.

Dam delicensing is at the foundation of this work. In this context, the term "delicensing" refers to a process whereby the end result is a solid earthen landform that no longer meets the Canadian Dam Association (CDA) definition of a dam, and is therefore not considered by the regulator to be a dam. Dam delicensing is discussed throughout the following chapters and particularly in Chapter Two.

This thesis is a hybrid of a traditional format and a paper-based format. Paper-based chapters (Chapters Four, Six, and Nine) include a precursory statement including the article's citation, or the journal that is assessing it for future publication. Chapters Seven and Eight include sections from refereed conference papers, which have precursory statements where sections have been reproduced, or citations where figures alone have been reproduced.

2.0 Mine waste management and closure

This section provides an overview of historical mine waste management practices, materials, structures, including those in the oil sands region, international best practices, and revisits the end goal of mine waste management and mine closure. This chapter was predominantly compiled through a literature review with the aim of achieving the following:

1. To place the study into context with previous research, scientific and engineering knowledge (Babbie, 2004) and to summarize existing knowledge (Smith & Brandon, 2008)
2. To identify voids and conflicts within current research knowledge and application (Marshall & Rossman, 1999; Smith & Brandon, 2008)
3. To demonstrate the researcher's knowledge of background information and current practices (Marshall & Rossman, 1999)
4. To outline the formal drivers of tailings dam design and performance objectives which may be enhanced through subsequent research within this project.

A limitation to the use of literature reviews is that they are qualitative in nature and lack rigorous methodical analyses, posing a challenge in replication. Additionally, while current practices are documented they often lack the numerous details which geotechnical engineers encounter and manage daily in dam design. These details may be small, but they contribute to the end product and are therefore of importance and interest. With respect to the mining industry specifically, practices are unevenly distributed and can evolve rapidly once the decision to change has been made; Current regulations are not necessarily indicative of the state of practice or even best practices. While the regulator in Alberta is considered a world-leader, oil sands' mine reclamation technologies are scaled-up and evolve especially quickly with little publicly available documentation. The literature review was therefore supplemented with informal conversations and consultation wherever possible with geotechnical engineers and those active in design, construction, reclamation, and closure of tailings dams in the AOS.

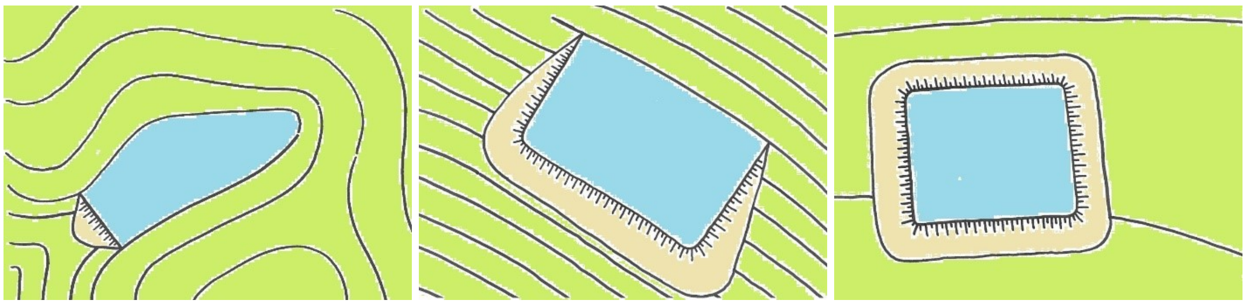
This chapter provides an overview of historical and current practices in mine waste management specifically TSFs) throughout the mining lifecycle from an international perspective as well as within oil sands mining (which is often rather insulated within the broader mining community). This life cycle review encompasses planning, construction, and closure / relinquishment goals. In general, it is found that design and construction for the active mining stage is well understood, as is the desired end landscape; it is less well understood how to accomplish this transition and how to determine when the end landscape is achieved. The remaining chapters of this thesis look at this challenge with respect to TSF erosion and geomorphology specifically.

2.1 Mine waste landscapes: materials and methods

Mining involves the extraction of non-mineralized rock (waste rock) or overburden, followed by extraction and processing of profitable ore beneath. Historical mining frameworks progressed through the stages of exploration, pre-feasibility, feasibility, design, construction, operation, and ended in abandonment. All mining operations, with the exception of quarries, produce two types of waste streams: waste rock / overburden, which is typically dry and ranges in particle size from several meters to less than 1 mm in diameter, and tailings, which result from processing and are typically fine, and can be wet or dry.

The management of mine waste streams (internationally) has evolved over time from the most economic means possible towards inclusion of environmental considerations, particularly in the developed world. Waste rock has historically been dumped without regard for internal structures or resultant leachates, and tailings were commonly deposited in rivers, oceans, or other low points (U.S. Environmental Protection Agency (E.P.A.), 1994; Strachan & Davis, 2016). While these activities are no longer widely practiced, present standards vary considerably based on the regulatory body, cultural values relating to the environment, and (broadly speaking) on the size of the mining company. As of 2013, marine or riverine disposal of tailings was used at 18 of the roughly 2,500 industrial mining operations world-wide (Vogt, 2013). Waste rock is frequently dumped down hillsides, but is also used in dam construction. Where undesirable or reactive waste rock exists systems of encapsulation have been developed (Geoteam, 2016; INAP, 2009).

Tailings are commonly placed behind a waste- (or earthfill-) constructed dam, the layout (ring dyke, cross-valley, side-hill, valley-bottom, single or tiered, pit deposition, for example shown in Figure 2.1) for which is dependent on site topography, local site factors such as seismicity, and economics (Vick, 1990). According to the CDA (2007), a dam is a barrier that is at least 2.5 m high and capable of impounding 30,000 m^3 of liquid. These tailings dams may be on-site, or at a distance away from the mine depending on the factors above as well as economics. Dams constructed in valleys or on hillsides require additional water diversion or management methods since they will collect runoff from the contributing natural watershed catchment. Since ring dykes form new high points, they have no additional surface water inputs to their ponds other than that from direct precipitation. Most of these dams are constructed from mine waste generated on-site, and tailings are deposited behind as dams are raised, such that costs of construction are dispersed over a long period of time (U.S. E.P.A., 1994). Methods of construction include upstream, downstream, and centerline methods, shown in Figure 2.2. Tailings dams and the contents they hold are cumulatively referred to as tailings storage facilities (TSFs).

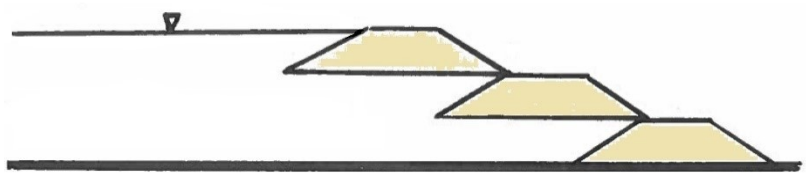


a) b) c)

Figure 2.1 Tailings dam layouts: a) valley-fill or "cross-valley", b) Side-hill, and c) ring-dyke.

Other site specific considerations in dam design and siting often include the volume of tailings to be held and their rate of production, subsurface geology, environmental requirements such as water course diversion and sensitive environments. Thorough (and often iterative) assessment of siting conditions and tailings options leads to optimal outcomes (U.S. E.P.A, 1994). This is particularly true when closure and post-closure landscapes are considered.

The waste products generated from mining (in terms of volume and area covered) often dwarf the extraction site, or open pit. The design of these structures in their brief history has focused on geotechnical stability and resistance to static and dynamic failure modes during active construction and raising. The phreatic surface and excess pore water pressures within a tailings dam and foundation influences its stability under seismic and static conditions; best practice during construction includes maintaining a beach width as wide as possible next to the dam, and maintaining a low phreatic surface below the downstream face using drainage and high-permeability zones (OMNR, 2011; Vick, 1990). Blanket drains and chimney drains along with necessary filters are frequently used to reduce pore pressures. Pore water pressures and phreatic surfaces are monitored during filling and dam construction such that shear strengths are not exceeded (U.S. E.P.A., 1994). Computer and numerical modelling of mine waste facilities has played a dominant role over the last few decades, including slope stability, seepage, and seismic assessment.



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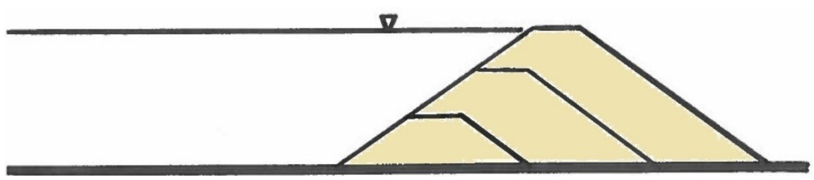

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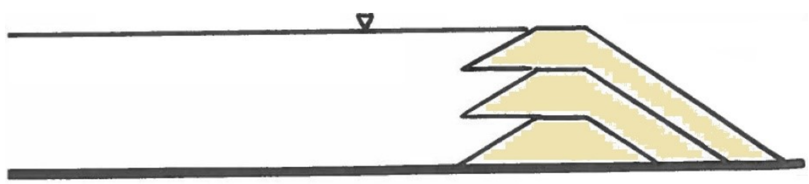

c)

Figure 2.2 Tailings dam construction types: (a) upstream, (b) downstream, and (c) centerline construction. Upstream construction is banned in many seismic regions.

Stability analysis for the initial design of a tailings dam is used to optimize construction costs and physical dam stability, by modifying internal and external geometry and material properties. The geotechnical engineer will start with a basic design and using site specific inputs will evaluate the structure across a range of possible failure modes until a balance is found between cost and factor of safety. Common Factors of Safety used in assessment are listed in Table 2.1. Common failure modes evaluated throughout construction include:

- Rotational sliding
- Foundation failure
- Overtopping
- Surface erosion
- Piping (subsurface erosion)
- Static liquefaction
- Dynamic liquefaction

Throughout operation the dam is raised and monitoring via instrumentation and direct observation takes place. Inclinometers and manual markers are used to measure dam movement, and piezometers are used to measure pore water pressure, for example. Freeboard, beach width, and seepage discharge should also be measured regularly (ICOLD, 1996). Increasingly remote techniques are being used, such as InSAR (Interferometric synthetic-aperture radar) and satellite imagery to measure horizontal and vertical movement and identify seepage zones.

Table 2.1 Example Factors of Safety for static and seismic assessment. Adapted from Ontario Ministry of Natural Resources (2011) and CDA (2014)

Loading Condition	Factor of Safety (minimum)	Slope
End of construction	>1.3	Upstream and downstream
Long-term (steady state seepage)	1.5	Upstream and downstream
IDF loading condition	1.3	Upstream and downstream
Full or partial rapid drawdown	1.3	Upstream
Pseudo-static	> 1	
Post earthquake	1.1	

2.1.1 Oil sands

Overburden in the oil sands is variable in its thickness and composed of clay, clay-shale, silt, and sand; however, mineralogy and water content is highly variable (McRoberts, 2008). Overburden is variable in its properties: some is considered “lean oil sand” as it contains less than 7% bitumen, while some contains no bitumen at all. Similarly, some overburden is called “slop” due to high water content, while some is relatively dry. Once removed, overburden is deposited in a “dump” where it is compacted in lifts until the design height is achieved. Challenges with respect to overburden reclamation have been summarized in (Slingerland & Beier, 2016).

Ore processing varies from site to site, but oil sands are typically: 1) crushed to increase surface area and improve separation of bitumen from sand, then 2) mixed with warm water and chemical processing aids to mobilize the bitumen. Bitumen is extracted as a froth, whereas the remaining slurry of process water, solids, and residual bitumen is kept separate (Alberta Government, 2015). This slurry is often treated to reduce the water content, and further separation of coarse and fine fractions occurs using a cyclone (Sobkowicz, 2013). The coarse fraction is called "coarse sand tailings", or CST, and the remaining suspended clay and silt solids in process water are called "fluid fine tailings", or FFT.

"Above grade", "out-of-pit", or "external" tailings dams are constructed in the Athabasca oil sands (AOS) to hold the first 8 - 15 years of tailings produced, often in the form of a ring dyke due to low naturally occurring topographic diversity (McRoberts, 2008; Alberta Government, 2015). Over this time sufficient space is created in-pit to construct in-pit dykes and begin backfilling in-pit. The majority of external tailings dams are initiated with construction of a starter dam composed of compacted overburden at what will become the downstream toe, then raised upstream sequentially with thin lifts of hydraulically placed CST and compacted (Figure 2.3). As the dams are sequentially raised, instrumentation, chimney, and blanket drains are built into the structure for drainage and monitoring purposes. FFT is placed behind the dams hydraulically such that a beach is formed around the upstream dam crest leading to a central pond. After two years the tailings that remain in an unconsolidated state are referred to as mature fine tailings (MFT). Reclamation challenges with the slurried tailings stream are abundant and have been summarized for both tailings and process-affected water in (Slingerland & Beier, 2016).

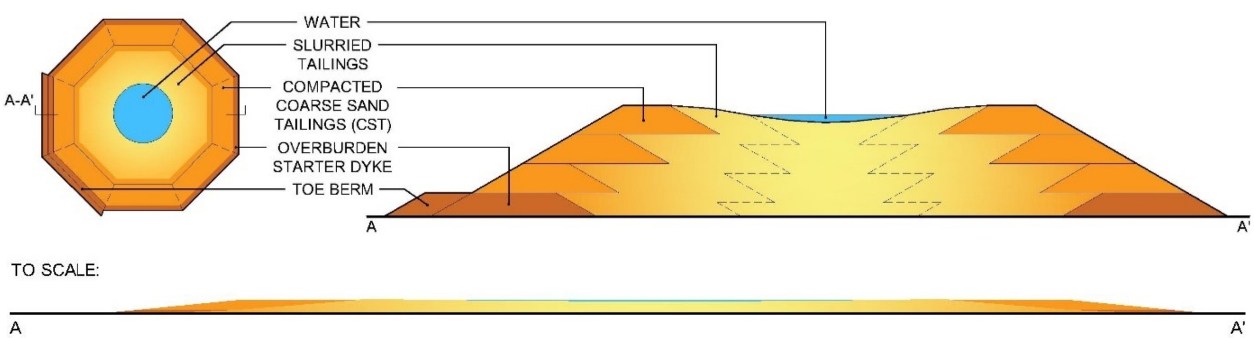

Figure 2.3 Fictional TSF in plan view (left) and section (right) at approximately 10x vertical exaggeration. Drawings not to scale. TSF cross section drawn to scale below.

2.2 Mine reclamation and closure planning until present

Mine closure planning is a relatively new concept, evolving since the 1970's to its present state. The complexity of this task has been largely underestimated in its brief history as evidenced by the many unsuccessful reclamation attempts and exhausted mine sites with major ongoing challenges (McKenna & Dawson, 1997; Peck et al., 2005; Slingerland, Baida, & Wilson, 2014). Prior to the mid-1980's, uneconomical or exhausted mines were often abandoned; boards were occasionally placed over underground access points for safety, but no further actions were typically taken (Peck et al., 2005; Roberts, Viega, & Peiter, 2000; World Bank & IFC, 2002). Abandonment has occurred due to lack of closure regulation or policy, poor enforcement where regulation or policies existed, lack of (or insufficient) financial security measures (bonding) to ensure closure works are funded, abrupt change in political unrest or metal prices that lead to sudden abandonment due to safety concerns or bankruptcy, and many causes as outlined in (Peck et al., 2005). Mine abandonment has led to the economic and social downfall of rural communities and hazardous environmental legacies at sites around the world (World Bank & IFC, 2002).

The practice of abandonment has continued to the present time, but its prevalence has decreased steadily in many regions coinciding with increased legislation, financial securities, and knowledge, particularly in Australia, the United Kingdom, parts of Europe, the United States, and Canada. Modern mining frameworks follow the operational phase with closure, post-closure, and relinquishment phases. High quality reclamation including adaptive re-use of the land is more often found at suburban quarries and clay or gravel pits without waste streams, compared to rurally located mines with complex waste materials (Slingerland & Wilson, 2015). For these rural mines, simply relinquishing the land by meeting minimal requirements may pose significant technical and legal challenges. At some point either through mine corporation bankruptcy/closure or expiration of mineral leases/rights, it is reasonable to expect that mined land will once again be returned to the Crown, thus it is in the best interest of jurisdictions with mining activities to have a legal framework in place to clearly set out reclamation and transfer of mining sites back to the Crown on mutually beneficial terms (Cowan, Mackasey, & Robertson, 2013).

Readily available information and NGO involvement have increased public awareness of mining operations, which has in turn put pressure on mining companies to abide by an increasingly rigorous international standard for closure planning. As examples of early closure planning accumulate, the benefits are also increasingly acknowledged, building momentum (Figure 2.4, 2.5). Large companies operating in geographic regions without mine closure legislation have recently undertaken closure planning and construction works in part to maintain the confidence and trust of their shareholders, and to avoid litigation in the courts of their corporate country of origin (Bastida & Sanford, 2010). Barrick's El Indio mine in northern Chile is an example where international best practices in closure were followed despite the absence of local legislation.

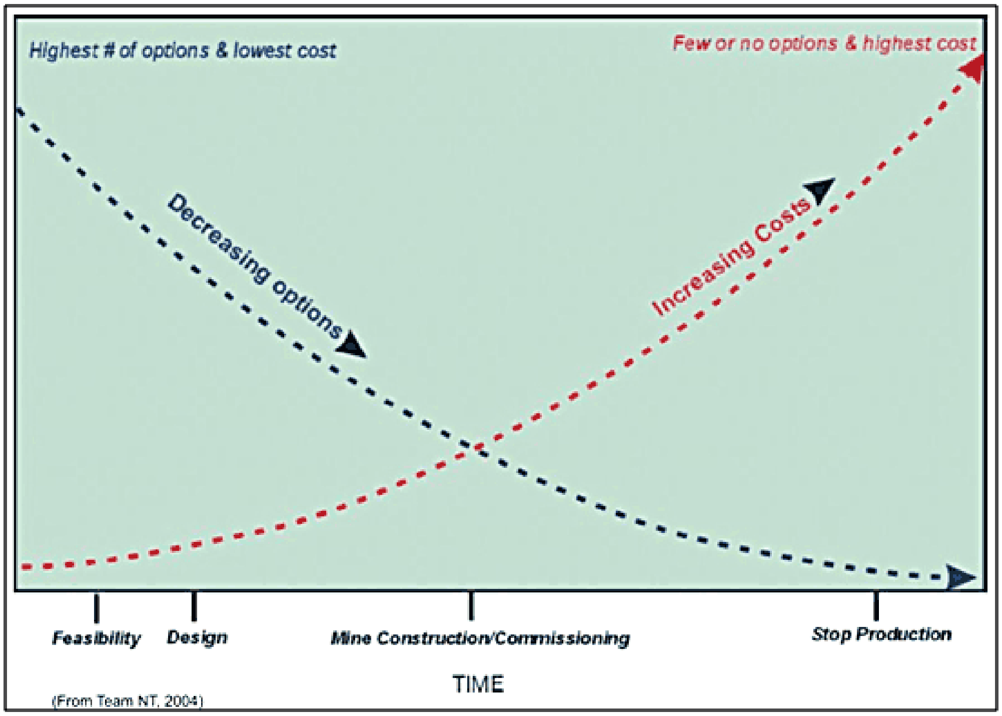

Figure 2.4 Acid rock drainage mitigation options and costs over the mine life. From the GARD Guide (INAP, 2009)

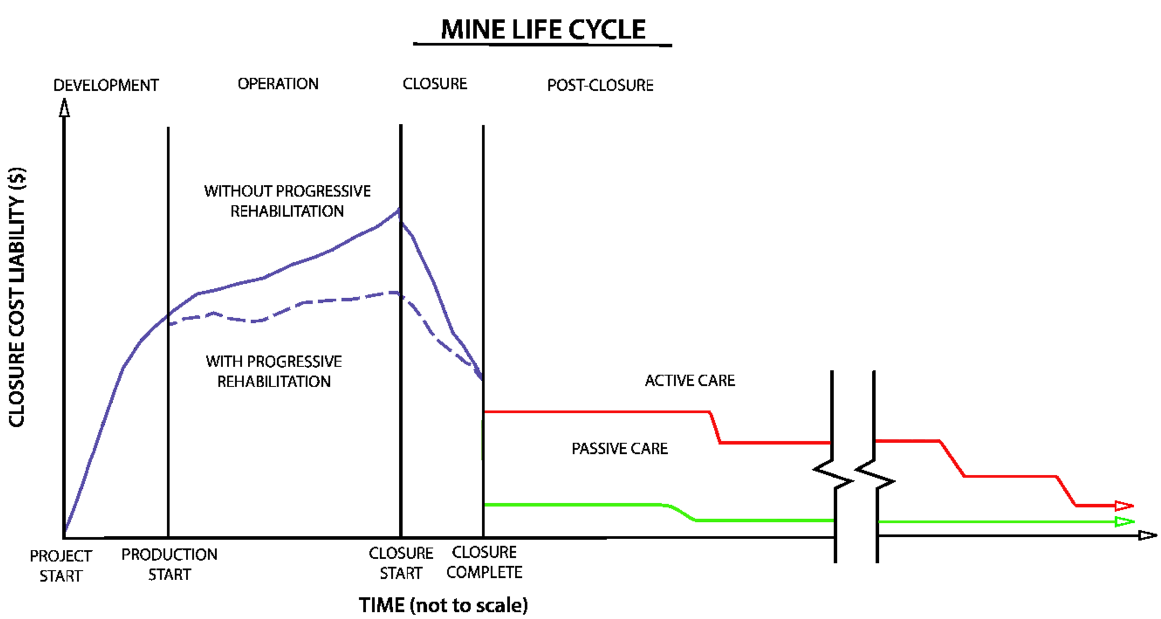

Figure 2.5 Closure cost liability with and without progressive reclamation. Bocking, 2010.

Ideally, closure plans are used iteratively to inform the mine plan, waste and water management, and vice versa, as well as to direct other aspects affecting the final landscape and its construction. 'Integrated' closure roadmaps, toolkits, guidelines, and planning aids for progressive and sustainable mine closure planning have been developed by the World Bank and IFC (2002), ICMM (2008), MAC (2019), Anglo American (2013) and others, and exist in the public domain. These planning aids are similar in that they all put emphasis on "up front" conceptual closure plan development and progressive reclamation, which includes continuous updating, review, and closure plan development until the mine is considered closed and is self-sustaining (Figure 2.6 & 2.8, for example). An additional opportunity exists within these documents to outline how progressive reclamation may be physically integrated on-site (where possible) throughout the mine life, providing examples as each site will differ. Too often, 'increasing detail within the mine closure plan' (Figure 2.6, 2.8) is interpreted as allowing for the mine plan to dictate changes in the closure plan throughout operation and leaving the "real" closure plan to be developed in the 2 – 5 years prior to end of operation.

The International Council of Mining and Metallurgy (ICMM) first introduced their '10 Principles' in 2003 that member companies are required to abide by (ICMM, 2018). Through these principles, member companies are required to assess all direct and indirect cumulative environmental impacts of mining from exploration to closure, to rehabilitate disturbed land such that it contributes to biodiversity conservation via integrated (and appropriate) land use planning, and to design and plan to meet the closure requirements of operations (ICMM, 2018). These principles were updated in 2015 and a formal position statement was made on prevention of catastrophic tailings storage facility failures in the wake of the Mount Polley and Samarco tailings dam failures (ICMM, 2016). The closure principles are integrated into the ICMM Integrated Mine Closure Framework (Figure 2.6): a best-case scenario where progressive closure works are integrated into the mine life cycle from early mining stages. This idealistic case leads to rapid and concurrent reductions in risk as the mine life progresses (Figure 2.7). Closure plans often indirectly outline how the ICMM principles are being achieved or worked towards.

The Brazilian Mining Association, IBRAM, has outlined several best practices similar to other agencies, with the addition of finer points such as progressive reclamation of degraded areas, detailed cost estimation, contingency plans, and "de-characterizing" tailings dams as dams

(IBRAM, 2015). Of particular interest is their encouragement of the geomorphic design approach as a component of geotechnical practices to achieve physical stability as well as "supporting restoration of flora and fauna communities" (IBRAM, 2015).

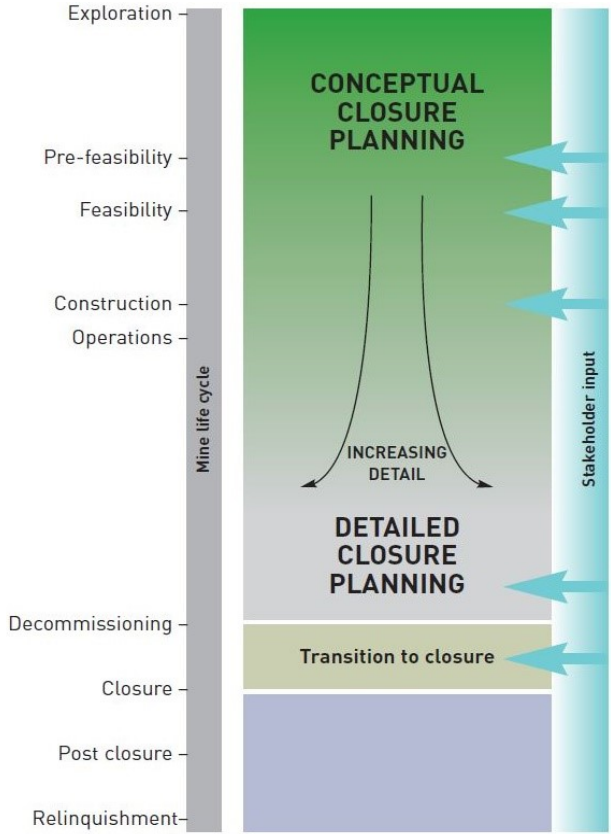

Figure 2.6 ICMM integrated mine closure framework (ICMM, 2008).

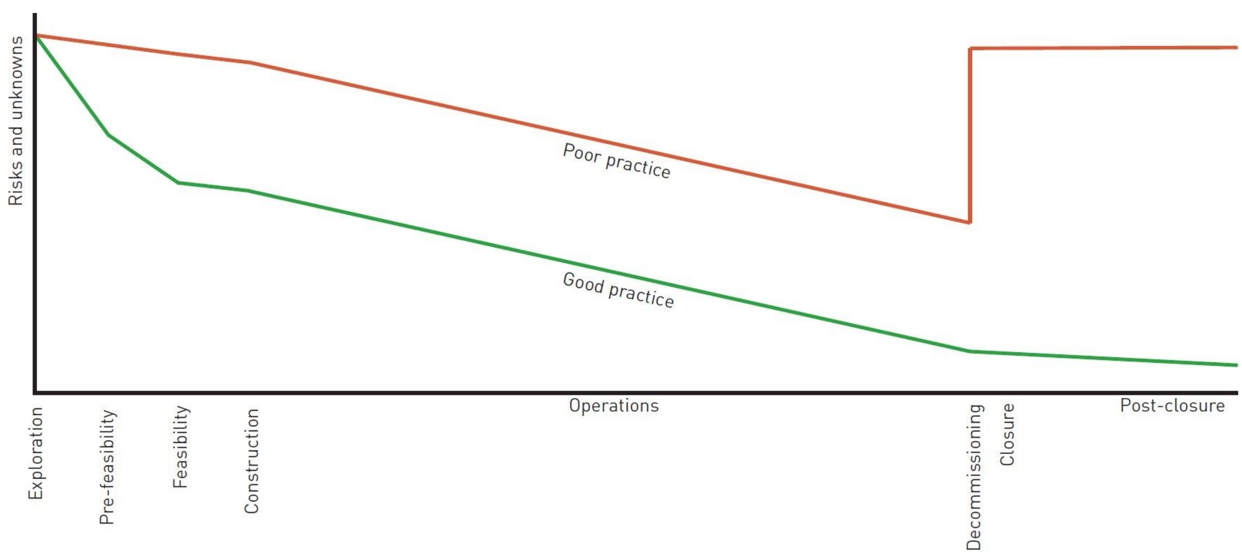

Figure 2.7 Risk corresponding to good (integrated approach) and poor practice throughout the mine life cycle (ICMM, 2008)

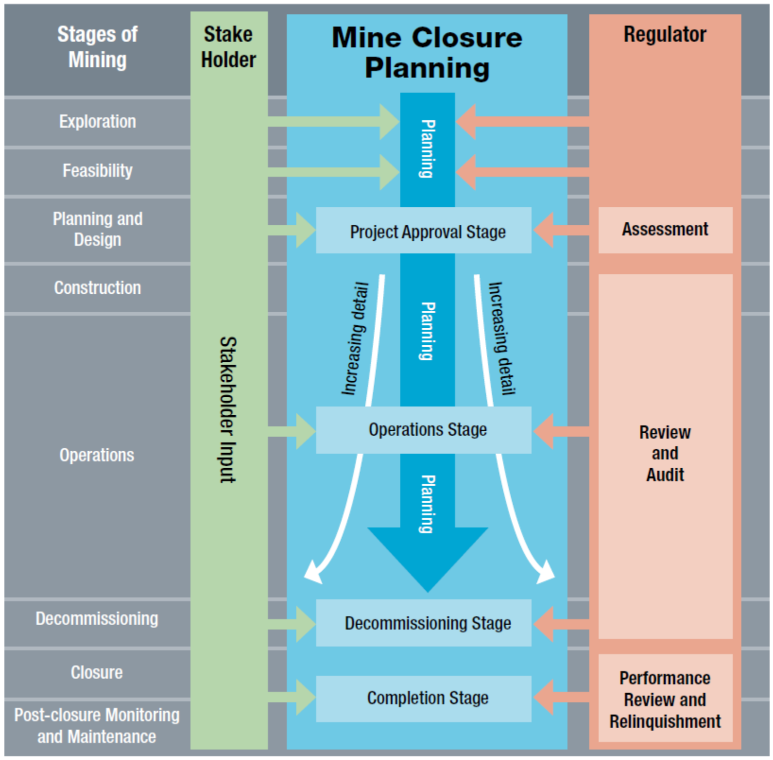

Figure 2.8 Integrated closure and regulatory approach in Western Australia (Government of Western Australia, 2015)

Closure planning has predominantly been guided by applicable regulations and international standards, mostly with the goal of reducing human and environmental health risks post-closure, especially in aquatic environments. Whereas a few decades ago the term "closure plan" was unknown, now potential miners require a closure plan to attain a mining permit in many jurisdictions. In the last few years governments have become more stringent in their mine closure regulation and financial security measures: through the new National Mining Agency Brazil requires that miners file a mine closure plan, reclaim the degraded area using a technical solution proposed by a competent authority (a professional), and has made enforcement of closure easier for officials. Chile has also introduced new mining legislation that works to prevent abandonment through financial securities and requires physical and chemical stability be achieved using a risk-based approach (Weeks, 2015). As an extreme example, El Salvador recently passed a law that prohibits metal mining in order to protect the environment.

Planning for the Waihi (or "Martha") Gold Mine in New Zealand is one example of fully integrated closure planning that balances economic, socio-cultural, and environmental objectives. Mining first began here in the 1890's continuing until 1952, and then the mine re-opened in

1987. The mine includes both an open pit as well as an underground operation. Mine owners engaged a diverse team of professionals to undertake closure planning from a technical, scientific, and socio-economic perspective prior to re-opening the mine in the early 1980's. The team included archaeologists, geologists, hydrogeologists, engineers, geochemists, rehabilitation consultants, and landscape architects who worked together to develop a viable methodology. They created two closure plans that continue to be updated annually: one in the event of closure due to exhaustion of resources (as per schedule), and one in the event of unforeseen closure due to commodity value decline. Waste rock embankments (Figure 2.9) were constructed to hold tailings ponds, which were jointly and progressively reclaimed to wetlands and pasture; cattle have been grazing on the waste rock dumps as they were reclaimed since 1991. The project is a text book example of sustainable "design for closure", a term quoined by John Gadsby in the early 1970's.

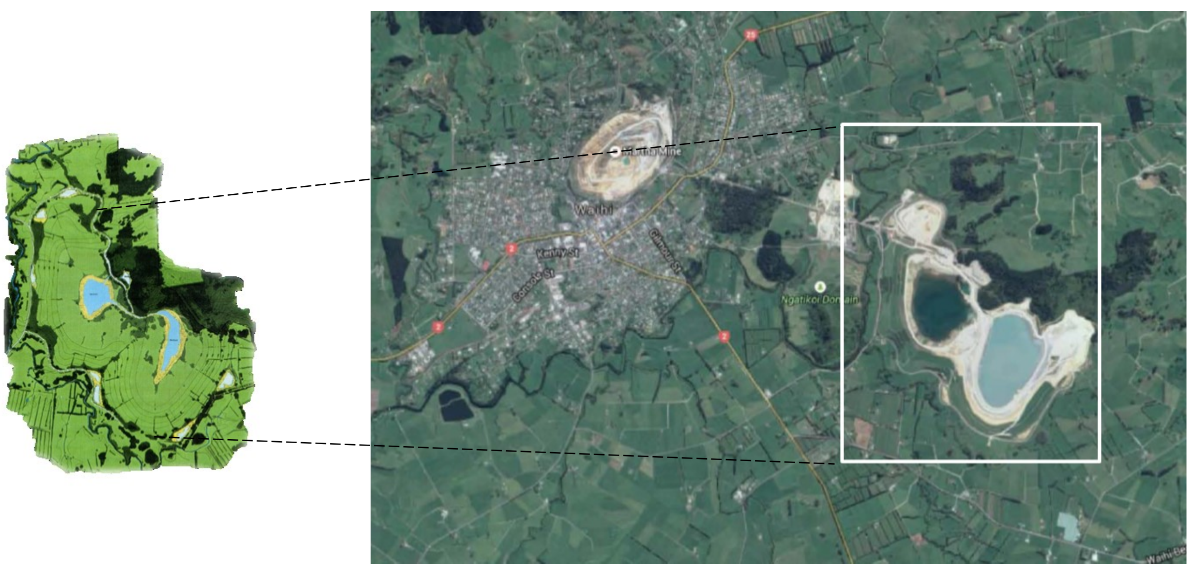

Figure 2.9 Concept plan for Waihi Gold Mine's waste rock embankments and tailings ponds (left), compared to aerial image of the site from 2015. (Concept plan from http://www.waihigold.co.nz/environment/rehabilitation, aerial image from google earth.)

2.2.1 Mine closure plans

Most developed nations regulate mine closure and planning at some level of government, but many nations with mining continue to address closure on a case-by-case basis within mining agreements (Clark & Clark, 2005). Closure plans have evolved into massive undertakings; they can be several hundred pages in length and include written documentation and graphic plans illustrating the proposed methods to achieve desired closure targets. Contents typically include:

1. An overarching closure goal and supporting objectives;
2. A summary of pre-mining conditions such as baseline water quality, geology, wildlife and vegetation surveys;
3. Mine facilities layout, mining and operational timelines, and descriptions of monitoring taking place during mine operation;
4. Required actions, management, and reporting in the case of temporary closure (care and maintenance);
5. Target performance or quality thresholds for post-mining landforms, surface water, cover systems, and vegetation;
6. Proposed final landforms, topographic and drainage designs, soil covers, revegetation, surface hydrology, water treatment, and infrastructure decommissioning;
7. Stakeholder engagement methods;
8. Identification of closure issues and their management, monitoring, and/or maintenance;
9. Financial provision estimate for closure;
10. Data and information management protocols; and
11. References to additional supporting reports, studies, or documents.

A critical component of an effective closure plans is identification of closure or completion criteria. These ideally follow the SMART method (specific, measurable, achievable, relevant, time-bound) such that clarity exists in reclamation achievement. "Closure and Reclamation Plans" (C&R plans) are revisited when major changes are made to the mine plan, or on a cyclical basis every few years depending on the local regulations. For example, in Western Australia mine closure plans are updated annually and submitted to the regulator with updated environmental assessments (Government of Western Australia, 2015).

Closure plans are written and compiled in-house by the mining company or by an external consultant and are submitted according to a prescribed schedule as well as when significant changes to the mine plan take place (McKenna, An, Scordo, & McGreevy, 2013). These plans range broadly in detail and scope from site to site, depending primarily on the regulator they are being submitted to. They rarely reflect the full extent of skill, knowledge, or experience of the team involved in their compilation; instead they more clearly reflect the minimum requirements of the regulator. Mine operators are bound to what they propose in their closure plans, and much remains unknown regarding the realities of reclamation outcomes. Methods and performance targets outlined in closure and reclamation plans are imprecise in nature as a result.

Geotechnical and geochemical stability are recognized as being a minimum requirement and pre-requisites to any other closure goals; however, even these stability requirements have been a challenge to achieve. Design for closure has been further complicated by assumptions/constraints in widely used mine planning and design software and the use of net present value/ discounting for cost estimation of closure-related works. This forecasts economic benefits to delaying closure expenditures based on a narrow scope of evaluation. Additionally, confusion over what is acceptable by regulators (where closure regulations exist) have complicated and delayed the planning process. Given these many challenges in writing a well-investigated and thoroughly integrated mine closure plan, it should be noted that this alone does not guarantee successful reclamation or relinquishment (Roberts et al., 2000). Ongoing collaboration and communication with construction operations, and diligent monitoring and maintenance are also key factors in effectively carrying out a plan (Fair, Pollard, & McKenna, 2014).

2.2.2 Oil Sands mine closure planning

In Alberta, oil sands mines are presently regulated by the Alberta Energy Regulator (AER) and Alberta Environment and Parks (AEP). Alberta regulations include bonding through the Mine Financial Security Program (MFSP) which encourages investment by deferring bonding in excess of the base amount ($30,000,000 or $60,000,000 for mines with an upgrader and with approvals dated 2011 or later) until the last fifteen years of operation (Alberta Environment, 2011). When a mine has 15 years left in its mine life the approval holder is required to assess reclamation costs/liabilities (including closure monitoring) and for the next ten years 10% of that cost less the base amount is posted per year (Alberta Environment, 2011; Perry & Saloff, 2011). Theoretically this ensures that any mine with five years of operation remaining has posted the full cost of reclamation and closure works. Return of these financial securities will occur through reclamation certification, or be held by the government to complete reclamation activities where the approval holder does not carry out the work (Alberta Environment, 2011).

Prior to 2019, C&R Plans were submitted every three years, and Life of Mine Plans were submitted every five, following initial submission. As of December 2018, Mine Reclamation

Plans (MRPs) are submitted every three years to the regulator, and Life of Mine Closure Plans (LMCPs) are submitted every ten years. Tailings management plans are also scheduled every five years, unless otherwise directed. These plans are normally quite large documents that require many months to prepare. As such, they are often based on at least some information that is out-dated by their submission date; Regardless, the knowledge transfer and the process continues to be beneficial to both the regulator and the operator. With each submission, lessons are learned across the industry and it is likely these submissions and their requirements will evolve. Closure planning in the AOS is hindered by lack of knowledge regarding specific reclamation certification and delicensing requirements, and a lack of knowledge regarding material behaviour characteristics over long time frames, as mentioned by Shell Canada Energy (2012):

"*Innovation in natural design is anticipated over the period of mine life and parallel research efforts are expected to yield applicable findings. The closure plan is therefore dynamic and open to adaptation to emerging best practices.*" (Shell Canada Energy, 2012) Pg. 87

Conducting extensive planning and design work early-on with the expectation that assumptions or proposed technologies will be obsolete by the closure date is deemed unproductive. While substantial innovation is taking place, the major challenges faced by industry today are the same ones faced by industry in the 1970's, most notably consolidation of fine tailings, contaminated process water, and erodibility of coarse sand tailings.

2.2.3 Gaps in closure planning

Knowledge gaps as well as gaps in the perceived transition from mining to closure landscape construction were noted throughout the review and evaluation of closure and reclamation plans, as well as through informal conversations with industry professionals. The following section documents perceived gaps in the closure and reclamation plans reviewed with implications more generally for existing closure regulation to be improved.

In general, construction methods for the final landscape are omitted from plans. Current capping specifications of many oil sands operators call for a minimum of 1 m inert coarse tailings ('inert' means tailings sand which meets the chemical criteria for suitable cover material) followed by a minimum 50 cm lift of reclamation material over tailings and overburden landforms. The challenge herein is construction overtop of unconsolidated (and therefore untrafficable) fines. At Suncor's Pond One, fine tailings were dredged from one end of the pond for transfer in-pit while CST was simultaneously pumped in at the opposite side (Anderson & Wells, 2010). CST is trafficable more quickly allowing for subsequent landform grading, capping with reclamation material, and vegetation installation. Lighter coke materials have been used at Suncor's Pond Five to cap fine tailings in place. This method used geotextiles and winter construction to place the low-density coke over top of the frozen FFT with some success (Wells, Caldwell, and Fournier, 2011). The light nature of coke poses new problems: it is highly erodible and does not provide a stable medium for large woody plants to be grown, should the root zone extend beyond the layer of reclamation material. For example, wind can easily topple a large canopy deciduous tree or shallow-rooted evergreen tree, exposing underlying tailings. Low-lying small shrubs and grasses may be safer alternatives here. Additionally, coke is considered a resource with the potential for re-mining at a later date, which would disturb any reclamation that had previously taken place. This method is a more challenging option on mine sites that do not produce coke, requiring transport of material from those that do. This method is also unlikely to be suitable for above-grade TSF's as contents remain flowable for an extended timeframe making delicensing improbable under the current theoretical framework (OSTDC, 2014).

The costs associated with stabilization and reclamation at Suncor Pond One and Pond Five were quite high; Extensive research is being conducted by mine operators to solve this fine tailings/TSF conversion gap. In the meantime, little information has been included in C & R Plans to date with respect to methods of achieving a trafficable surface as research is ongoing.

An essential component of a post-mining landscape is a functional drainage network. Drainage plans are included to varying degrees in closure plans; however, the lack of detail on some plans suggests that in these cases the purpose of their inclusion is as a discussion point rather than for planning purposes. The majority of drainage plans illustrate high level topographic designs that are frequently not functional as shown. For example, excessively steep or shallow slopes are prevalent, drainage channels that follow rectilinear pathways with right angle turns are used, large regions exist with no contours whatsoever, and outlets from tailings pond crests are undersized. Some 2015/2016 C&R updates demonstrated a marked increase in detail in this respect.

Drainage is illustrated (for the most part) as a continuous network across the lease at the end of construction. All closure plans indicate that they undertake progressive reclamation, which means that construction of these drainage networks will be completed in a discontinuous manner, just as a quilt is constructed square by square. Unfortunately, each square of the drainage network is built to collect precipitation from a set area, then direct and convey it to the next piece of the network: when the next piece of the network is not yet completed, temporary diversion ditches are necessary until a point in time when the entire drainage corridor is constructed. These interim drainage strategies and construction methods are not illustrated, nor is a method of patching these drainage networks together proposed. Inclusion of operational drainage plans which outline an interim strategy throughout construction of the closure landscape would be beneficial.

Many closure plans state that they will change in response to their mine plans and tailings plan. This is not in line with sustainable development principles as it delays detailed closure planning until later stages of mining when few changes are anticipated. Plans do not address timelines for closure or reclamation in detail, nor do they address planning for extreme/catastrophic events and associated emergency response. When maintenance and monitoring are discussed, they are regarding present-day reclamation monitoring works only, some of which is framed as "ongoing" or having taken place for many years and likely into the future; these tasks are assumed herein to continue post-closure and are listed in Table 2.2 under Post-Closure Monitoring. Table 2.2 provides a summary of AOS mine C&R plan submissions with respect to geotechnical design criteria, topographic/drainage design for closure, erosion control, and post-closure monitoring and maintenance. In many cases, landform design for closure is not site specific, instead textbook descriptions of reclamation tasks or a geomorphic approach are provided. From a regulatory perspective, this ambiguity makes plan evaluation difficult if not impossible. In several cases, the generalized nature of closure design presented is evident in duplicated criteria: entire charts and paragraphs are identical across several different submissions, despite differing location, materials, landforms, and geotechnical context. The Government of Western Australia acknowledged this as a problem early in the evolution of their closure regulation; As a result the Department of Mines and Petroleum will no longer accept generic or non-site-specific closure plans (Government of Western Australia, 2015).

An additional concern in AOS closure plans in that very few quantifiable criteria are provided for all structures, most glaringly with respect to geotechnical stability and landscape performance. None of the submissions provided detailed criteria for all three focal areas (TSFs, overburden disposal areas (ODAs), and site wide (general)) with respect to stability, landform design, erosion, or monitoring. Where quantifiable guidelines or targets are provided, they are done so without explanation of the numbers chosen, and inconsistently across the landform types. For example, landscape performance may be indicated by vegetation coverage, soil or water quality, soil loss from landforms or sediment loading of drainage channels. Geotechnical stability may be more difficult to quantify post-closure than it is during operation where factors of safety are targeted: Szymanski and Davies (2004) suggest that engineering judgement rather than specific metrics be used in dam evaluation. While this approach is technically sound, it requires a high degree of trust in dam engineers on the part of the regulator and by the public, which has (arguably) been eroding with each new high-profile dam failure (of which there have been at least three in the last five years). It follows that an additional method of evaluation involving quantification is necessary for post-closure stability.

While the 2011/12 R&C / LOM plans were lacking in a number of areas, they were a good first attempt and continue to improve with each iteration. Given the substantial reclamation and closure research conducted by operators, the plans in their present state are not sufficiently reflective of this knowledge and perhaps fail to achieve all of the desired objectives.

The extent and complexity of land disturbed by oil sands mining has put it on the global stage. Closure plans are public documents and provide an opportunity to demonstrate the progressive steps being taken to advance possibly the largest land and ecosystem reconstruction project ever attempted. Greater demonstration of integration across adjacent leases, explanation and incorporation of how varying and sometimes opposing objectives are optimized, and more rigour with respect to geotechnical closure criteria would be a beneficial next step in closure planning. Many of the TSF's will be coming to the end of their active filling periods in the next few years, and reclamation work in several cases has already begun; long-term geotechnical and monitoring criteria in particular should be well founded and documented in order to gain the confidence of the public and of regulators in working towards reclamation certification.

Table 2.2 Summary of landform design criteria from AOS Reclamation and Closure Plan/Life of Mine submissions in 2011/2012. Mine names have been removed. Plans for mines G and H were combined into one document.

Mine:	A	B	C	D	E	F	G	H
Geotechnical Stability	**Site wide:** • Any landmass containing ponded water or liquefiable material to be equipped with a 10 m min. freeboard and an overall hydraulic gradient less than 20H:1V **TSFs:** • Landforms to nolonger meet 2007 CDA dam definition (30,000 m^3 containment and 2.5 m ht) • No dams greater than 2 m depth	**Site wide:** • Structures subject to rapid deterioration due to extreme flood events to be excluded from closure landscape **TSFs:** • Landforms to nolonger meet 2007 CDA dam definition (30,000m^3 containment and 2.5 m ht)	**TSFs:** • Considerations after closure include settlement and dewatering of fine tailings • Failure mechanisms: piping, liquefaction, material mobility, earthquakes, overtopping, rising water table, slope instability, retrogressive erosion, slumping, and toe erosion. **ODAs:** • Min. design FOS of 1.2 (short term) and 1.3 (long-term)	**TSFs:** • Post-closure considerations: settlement and dewatering • Failure mechanisms: piping, liquefaction, material mobility, earthquakes, overtopping, water table rise, slope instability, retrogressive erosion, slumping, and toe erosion. • Maintenance-free seepage controls **ODAs:** • Min. design FOS of 1.2 for (short term) and 1.3 (long-term)	**Site wide:** • Terraces should be eliminated from the closure landscape or limited to grade of at least 3%, sloped outward to avoid water ponding. **TSFs** • No dams greater than 2 m depth • Dam EOR approves reclamation planting plans for that dam • No regrading of tailings or overburben dykes permitted	**TSFs:** • No dams more than 2 m depth • EOR approves the reclamation planting plans for that dam • No regrading of tailings or overburben dykes permitted • Closure configuration of the landform needs to take into account the long-term phreatic surface and seepage regime and should consider plugging internal drains and the sedimentation of ditches.	**Site wide:** • Beaver activity in channels was considered using a minimum valley depth of 4 m **TSFs:** • Risk of failure is highest during operation, decreasing after closure • Dams to be decommissioned and excluded from the closure landscape as per Canadian Dam Association and Alberta Dam Safety Branch standards. • Outlets of declassified dams will be designed with enough freeboard for geotechnical stability, including beaver dam activity, settlement, and residual capacity • Outlet side slopes range from 8H:1V to 15H:1V	
Topographic Design	**Site wide:** • Average overland slope to be 0.2%, maximum of 30%. • No side hill channels parallel to contours. • Undulating landscape of small pockets and mounds **ODAs:** • Side slopes: 4H:1V to 10H:1V • Crowned, or contoured with secondary drainage channels **TSFs:** • Cap shaped into ridges, swales • Average overland slope of 0.4%	**Site wide:** • Any landmass containing ponded water or liquefiable material should be equipped with a 10 m minimum freeboard and a small overall hydraulic gradient not greater than 20H:1V • Overall slope to be 0.2% to a maximum of 30% • No side hill channels parallel to contours. **ODAs:** • Side slopes: 4H:1V to 10H:1V	**Site wide:** • Plateau landscape with 0.1 - 0.01% slopes interspersed with 10% slopes to lower plains. • Floodplains to convey 100-year flood. • Drainage density: 1 km/km2 • Dams/structures requiring long-term maintenance are excluded from closure design. **TSFs:** • dyke slopes: 4H:1V to 10H:1V. **ODAs:** • Max. slope: 4H:1V • Geomorphic design to be used	**Site wide:** • Floodplains to convey 100-yr flood **ODAs:** • Max. slope: 4H:1V **TSFs:** • Dype slopes: 4H:1V to 10H:1V • Plateau landscape proposed with 0.1 - 0.01% slopes interspersed with 10% slopes (8.5:1 on sand dykes) • Channels sloped at 0.3%	**Site wide:** • To accommodate beaver activity, designed closure channels and valleys should be at least 4 m deep • Undulating landscape with small pockets and mounds for topographic diversity	**Site wide:** • Fluvial geomorphic approach used to encourage self-healing. • Rigid construction avoided. • Any landmass containing ponded water or liquefiable material should be equipped with a 10 m minimum freeboard and a small overall hydraulic gradient not greater than 20H:1V. • The max. height of beaver dams found in the AOS is about 2.5 m. Channels to be built considering beaver dams	**Site wide:** • Floodplains for main drainage channels were sized to convey bankfull discharges (average 2-year return period flows). The adjacent floodplains were sized to convey higher return period events up to the PMF **TSFs:** • Conceptual sand hummocks vary from 200 to 300 m wide with 5H:1V side slopes. Heights range from 1 to 5 m depending on the volume of sand available for construction of each landform. • Conceptual coke hummocks vary from 400 to 600 m wide with 5H:1V side slopes. Coke hummocks are wider due to their higher permeability compared to those constructed of tailings sand. • An overall slope gradient of 0.5% designed for the main drainage channel of tailings deposits to ensure positive drainage.	
Erosion Control	**Site wide channel erosion:** • Negligible erosion during the 10-year flood event; Little erosion during the 100-year flood event; and moderate erosion during the Probable Maximum Flood (PMF) event. • Channels to be lined with minimum 0.3 m depth of adequately sized material to reduce erosion. • Recommended minimum channel depth is 0.5 m and bottom width is minimum 1.0 m.	**Site wide channel erosion:** • Channels to withstand change over geologic timeframes and sediment yeild from reclaimed surfaces should be comparable to that of similar natural systems. • Negligible erosion during the 10-year flood event; Little erosion during the 100-year flood event; and Moderate erosion during the PMF event. • Simons & Senturk (1977) used to calculate channel D50 • Minimum channel depth of 0.5m and bottom width of 1 m. • Upper limits: 2-yr flood peak discharge <10 m^3/s and channel bed slope < 0.75%.	**Site wide channel erosion:** • Schumm (1977) and Bray (1972) used to guide channel design on sandy, mild slopes and overburden-based, steep slopes, respectively. • Erosion protection for 100-year storm • Main channel slopes over sandy soils to be 0.08 - 1% • Min. channel width of 1 m **Site wide:** • Adequate erosion measures to stabilize reclaimed soils	**Site wide channel erosion:** • "designed to minimize erosion rates and sediment loading... 10% slope from plateaus to low areas, which will result in high velocity and shear stress." [(1)] • Schumm (1977) and Bray (1972) used to guide channel design on sandy, mild slopes and overburden-based, steep slopes, respectively. • Erosion protection for 100-year storm.	**Site wide:** • Dynamic drainage systems capable of accomodating evolutionary changes[(1)] **Site wide channel erosion:** • Designed to withstand a significant flooding event[(1)] • A material with a high boulder and/or cobble content may be added below the channel to provide an armouring layer. • Passive and geomorpphic erosion controls used where high velocity flow not expected.	**Site wide:** • Negligible erosion during the 10-year flood event; Little erosion during the 100-year flood event; and moderate erosion during the PMF event. • Maximum 30% slope, minimum 0.2% slope. • No side hill channels parallel to contours. • Alluvial channel side slopes to be max. 2H:1V, if vegetated max. 4H:1V. • Maximum allowable flow velocities for channels in sandy soils (overburden) are: 2-year flood: 0.5 (1.0) m/s 10-year flood: 1.0 (1.5) m/s 100-year flood: 1.5 (2.0) m/s PMF: 2.0 (3.0) m/s	**Site wide:** • Negligible erosion during the 2-year flood; Moderate erosion during 10-year flood event; Significant damage during a greater-than- 100-year flood event, no catastrophic downcutting • Geomorphic controls include max. overland flow path (MOLFP) and max. drainage area, both slope dependant **Site wide channel erosion:** • Channel dimensions selected using equations by Bray (1972), Schumm (1977) • Passive, geomorphic, and structural erosion control will be used, such that channels need little to no maintenance • Structural control: engineered rip-rap or other hard armouring installed • Passive control: sinuosity to avoid ccritical velocities, wide-bottom channels to increase roughness, flood attenuation via wetlands; vegetated floodplains to accommodate PMF. • Max. allowable flow velocities in sandy soils (overburden) are: 2-year flood: 0.5 (1.0) m/s 10-year flood: 1.0 (1.5) m/s 100-year flood: 1.5 (2.0) m/s PMF: 2.0 (3.0) m/s	
Post-Closure Monitoring	• Erosion control & slope stability. • Weed control. • Revegetation density / plant type. • Long term water quality/quantity control facilities. • Biodiversity, habitat establishment monitoring including species presence. • Wildlife monitoring cameras installed, site inspections	• Wetlands will be monitored for: surface water depths; water table fluctuations; water quality; erosion and stormwater runoff; composition, cover, and vigor of vegetation; composition, abundance, and diversity of wildlife; wildlife habitat quality; and weed species occurrence.	• Proposed adaptive management approach from early project planning stages through to post-mining stage. • Active water treatment facilities are not deemed necessary by current models.	• Following cessation of mining activities, instrumentation and monitoring of ETFs will be phased out over a period of years. • "Routine maintenance activities will not be required, except where future human activities lead to re-disturbance of areas." • Active post-closure water treatment facilities are not currently deemed necessary. • Vegetation & erosion monitoring will take place, no strategies currently proposed.	• Vegetation assessments, establishment and regeneration surveys will continue to take place, no strategies proposed. • Adaptive management approach based on ongoing monitoring of reclaimed areas as mining progresses.		• Soil (moisture content and bulk density) and vegetation (diversity and productivity) monitoring long term. • Landform performance monitoring via spring aerial tours to identify areas with drainage or erosion problems. • LiDAR survey database of both mine sites from 2008 for settlement tracking on tailings and OB landforms. • Long Term Plot Network (LTPN) annual monitoring with CEMA. • Wildlife monitoring and surveys, including winter tracking. • RAMP partnership ongoing.	

(1) These two statements are in contrast, the latter requires substantial armouring to prevent erosion.

2.3 The end goal

The first step in closure planning is to identify closure goals, and secondarily, to determine criteria and indicators for evaluation of the goals. Mine closure goals should be site specific and generated with input from all identified stakeholders or their representatives (Van Zyl, 2009). Goals can be prescriptive, whereby a specific and often quantifiable target must be achieved (the U.S. Surface Mining Control and Reclamation Act (SMCRA) (1977), for example, sets out highly prescriptive criteria (Udall, 1977)), or performance-based, which uses land behavior to gauge achievement (McKenna & Dawson, 1997). The Mining Association of Canada recommends a performance-based approach whereby overall practical and quantifiable goals are measured using detailed performance indicators (MAC, 2017). The ultimate goal is typically related to elimination of liability through relinquishment of land leases.

In Australia, once reclamation completion criteria are met, the mining company can relinquish the site to a “responsible authority”, usually the State Department of Mineral Resources; however, lands requiring ongoing maintenance typically will not be considered (Australian and New Zealand Minerals and Energy Council (ANZMEC) & Minerals Council of Australia (MCA), 2000). The U.S. SMCRA, applicable only to coal mines in the U.S., is written such that once detailed construction, maintenance, and reclamation specifications are met, land can be returned to the government (Roberts et al., 2000). In contrast, non-coal mines are regulated at the state level (Federal regulation can be used where state regulations do not exist) with variable degrees of regulation, thus end goals may be equally variable.

2.3.1 Relinquishment in Canada

Mines are permitted under territorial and provincial regulations in Canada, and are only subject to federal requirements where waterways under jurisdiction of the Department of Fisheries and Oceans (DFO) and/or Transport Canada’s Navigable Waters Protection Program (NWPP) are impacted (Government of Saskatchewan, Ministry of Environment, 2008). In Alberta, the Environmental Protection and Enhancement Act (EPEA) requires that approval holders reclaim their leases with soil and landforms that support self-sustaining, locally common boreal forest (CEMA 2011). Correspondingly, in 2011 and 2012 each of the oil sands mines outlined their overall goal of reclamation in the first combined Life of Mine/ Closure and Reclamation Plan submission as a “maintenance-free” and “self-sustaining” ecosystem, with “equivalent land capability to pre-development conditions" in their reclamation goal statements. Half of the mines also listed attaining reclamation certification such that the land can be returned to the Crown (known as the 'State' elsewhere) as a reclamation goal. Such a generalized (and lofty) overall goal neglects to address the potential need for long-term maintenance such as ongoing water treatment and the extensive planning associated with facilitating that maintenance (Cowan, Mackasey, & Robertson, 2010). Physical and chemical stability are a prerequisite for achieving broader reclamation goals and are therefore implied. The overall idea is that reclaimed mining landscapes should behave and have similar risks to natural or untouched terrain.

For mining leases on public land, mine closure leading towards a transfer of the land back to the Crown (i.e. relinquishment to the State) is how the mining cycle is completed and how the operator is relieved of their liability. Few mined lands have gone through this process, with Gateway Hill being the lone example in the AOS often described as an excessively long (10 years) and arduous process. In Alberta this "reclamation certification" process has been proposed to occur after a staged process; however, it is likely that with time and experience the framework will be refined. The oil sands tailings dam delicensing committee (OSTDC), composed of experts from oil sands operators, consultants, and the regulator, outlined this process in (OSTDC, 2014). The process is summarized and compared to other mining and tailings dam life cycles in Figure 2.10. For tailings dams, active care following reclamation works leads to dam delicensing: the TSF no longer meets the definition of a dam and risks are similar to those of natural landforms. This is followed by passive care of the "solid earthen structure" to ensure landform behavior is as expected, which leads to reclamation certification and return to the Crown. This process remains theoretical due to the absence of agreed upon and well-defined criteria/ requirements to evaluate whether a dam can be delicensed or land can be deemed reclaimed. While OSTDC (2014) currently places dam delicensing prior to reclamation certification, it may be possible to attain both in the reverse order; Reclaimed toe berms, for example, are part of the TSF, but may attain reclamation certificates prior to the overall TSF being delicensed.

Dr. Norbert Morgenstern's International Oil Sands Tailings Conference (IOSTC) 2012 keynote lecture (Morgenstern, 2012), he refers to "the ideal end game" in the oil sands that (amongst other criteria) honours government policy while encouraging investment through well-defined reclamation requirements and therefore the possibility of certification and liability transfer. This is the theoretical model described previously with the addition of precise definition of reclamation requirements. Morgenstern prefers an alternative "end game" over this ideal that includes perpetual care and sufficient funding is secured for an extended period and unforeseen events (Morgenstern, 2012).

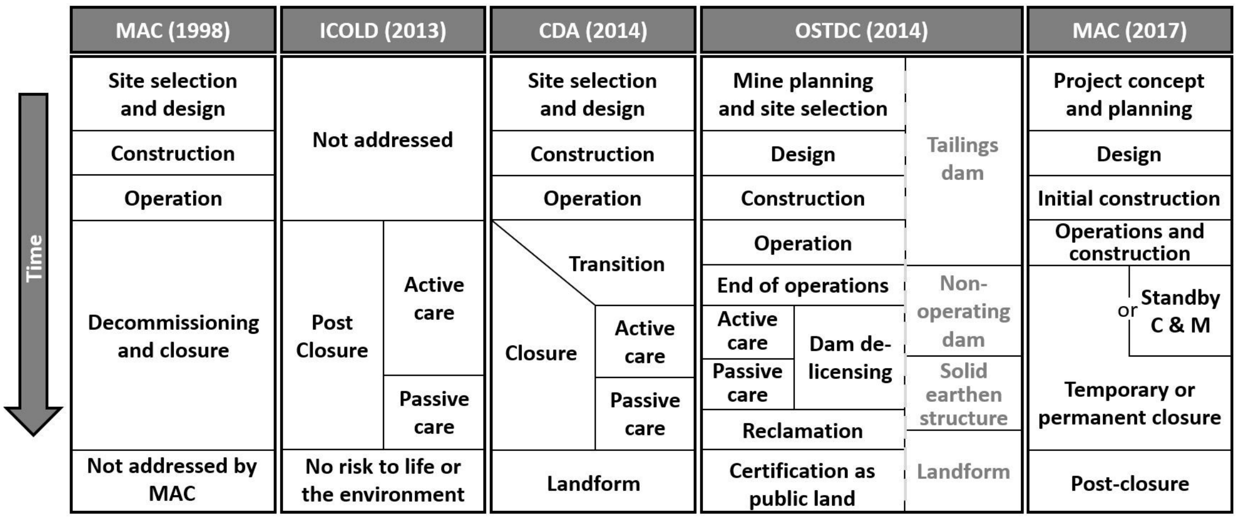

Figure 2.10 Comparison of mine and tailings pond closure frameworks over the years. From Slingerland, Beier, & Wilson (2019).

An alternate such as this was proposed by Cowan et al. (2013) following a review of Canadian mine closure case studies: following completion of major reclamation works and evaluation of long-term maintenance requirements, the responsible mining corporation should provide adequate long-term funding to the regulatory authority to fund future land management in exchange for relinquishment (Figure 2.11). In this alternative framework, mining corporations may (through evaluation of long-term maintenance and costs) deem land relinquishment undesirable. Notably, Morgenstern (2012) leaves the long-term responsible party undefined while Cowan (2013) assigns this role to the government.

In 2007 the province of Saskatchewan brought the 'Reclaimed Industrial Sites Act' into legislation, which provides conditions where the government will accept responsibility for reclaimed land that requires long-term monitoring and maintenance resulting from industrial activities (The reclaimed industrial sites act, chapter R-4.21 of the statutes of Saskatchewan, 2006). Relinquishment in Saskatchewan requires meeting all agreed upon closure criteria, payment of registration fees, and payment of agreed upon fees to: 1) an Institutional Control

Monitoring and Maintenance Fund, and 2) an Unforeseen Events Fund used to cover costs following extreme events. This is rare as to the author's knowledge no other province or Territory in Canada presently accepts land that requires ongoing water treatment, maintenance, or monitoring. At present and until a clear path is delineated by the regulator, the AOS "end game" remains idealistic: reclamation to boreal forest, certification, and return of land to the Crown, as described by the EPEA.

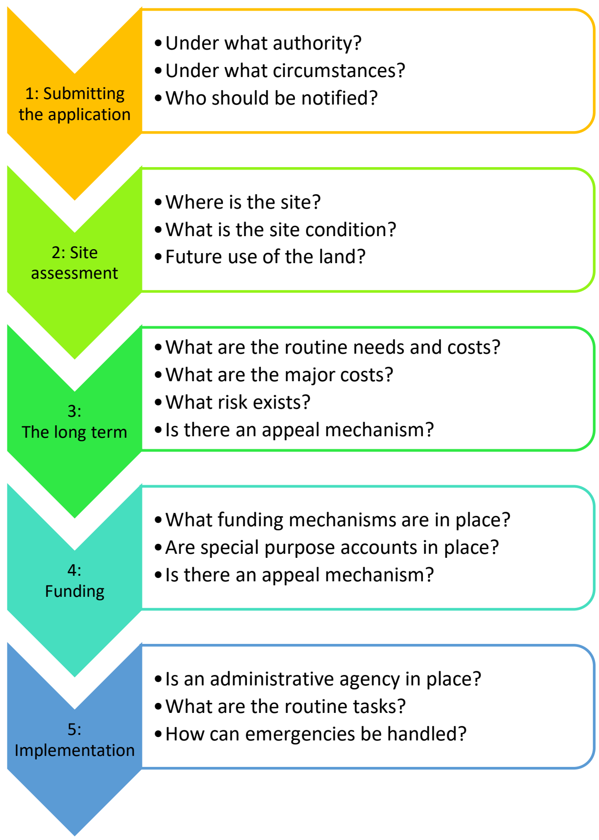

Figure 2.11 Alternate framework for mined land relinquishment proposed by Cowan et al (2013) for NAOMI.

2.4 International state of practice in closure design

Through programs such as MEND, MAC (both based in Canada), IMEC, MRRP, the Australian Environmental Protection Agency (all of Australia), and other international organizations, best available practices in mine closure are identified and made public for use (Roberts et al., 2000). These BAPs tend to be specific to management of surface water or acid generating materials, for example. According to MAC (2017) TSFs should be designed with the assumption that they are permanent structures in the landscape and ensuring that short term benefits do not outweigh long-term, post-closure risks. Design criteria used during the relatively short period of operation are insufficient over the much longer (possibly infinite) closure timeframe (Szymanski & Davies, 2004). Tailings storage facilities are arguably the most sensitive and challenging structures to design for a mining operation, with the greatest inherent risk due to failure consequence, therefore the focus within this section is on TSFs. The failure modes that dominate during active construction shift in their relative importance after closure, and those that caused little concern play a more prominent role over the long term. Cumulative effects of changes over time should optimally be evaluated as opposed to a traditional silo-type failure mode assessment (ICOLD, 2013).

Design for closure is optimally guided by sustainable development principles, defined by the United Nations' World Commission on Environment and Development in 1987 (also known as the "Brundtland Report") as:

> *"..development that meets the needs of the present without compromising the ability of future generations to meet their own needs".*

This definition and approach has also been accepted by the ICMM for use by their member companies. Closure design also needs to follow all applicable regulations that establish responsibilities and accountability for all parties involved, which may come from multiple levels of government. From an operators' perspective economic viability also needs to be a consideration in all design aspects. For new facilities, it is accepted that closure design and sustainability objectives will be integrated from early planning stages. For existing facilities these objectives should be integrated as early as possible and to the greatest extent economically and practically possible.

The International Committee on Large Dams (ICOLD) has identified the following additional objectives in working towards sustainable development (ICOLD, 2013):

1. Assessment of physical, social, and environmental risks is conducted to inform and guide the closure plan.
2. The potential impact on adjacent properties and regional context should be considered.
3. Stakeholder expectations are addressed and integrated in the closure plan.

4. Closure plan should be developed early and updated regularly throughout development and operation.
5. Long-term physical, chemical, ecological, and social (health, safety, employment) stabilization with respect to the tailings dam closure such that degradation is minimized.

In addition to design considerations discussed in Section 2.1, sustainability and long-term considerations are optimally included in closure design. Geomorphic design was first introduced on a large scale (in a basic sense) by the Surface Mining Control and Reclamation Act (1977) in the United States, where a requirement was introduced for mined land to be returned to the approximate original contour (AOC) during reclamation. Geomorphic modelling for long-term degradation has been done on few sites internationally, notably the Ranger Mine, the Scinto 6 Mine, and Tin Camp Creek all in NT, Australia (Coulthard, Hancock, & Lowry, 2012; Evans, 2000; Hancock et al., 2000; Hancock, Lowry, Coulthard, & Moliere, 2010; Hancock, Lowry, & Coulthard, 2015; Hancock, Lowry, & Coulthard, 2016; Willgoose, G. & Riley, 1998; Willgoose, Garry & Riley, 1998).

Increasingly the long-term stability of tailings impoundments is a concern due to an ever-growing body of documented effects of acid rock drainage, groundwater contamination, wind-blown dispersal of contaminated sediment, etc. and corresponding reclamation costs; in some cases greater than that of the original design, construction, and operation combined (U.S. E.P.A., 1994). Long-term concerns with respect to tailings storage facilities are dominated by water-related issues, while physical stability is often assumed to increase over time as pore water pressures dissipate. The physical properties of tailings dams are largely assumed to remain constant over time post-closure, despite ecological systems and fluvial processes being known to adversely affect geotechnical stability over long timeframes (DeJong, Tibbett, & Fourie, 2015; ICOLD, 2013). Similarly, it is expected that dams located in seismically active regions will be exposed to more than one seismic event in their post-closure life. This is an area where knowledge transfer between research institutions and practicing professionals can be improved, and where long-term monitoring can be used to build our knowledge base. Areas of post-closure in addition to those listed in Section 2.1 include:

- Physical and chemical weathering of dam/landform materials and components

- Effects of long-term self-weight consolidation of materials, changes in hydraulic gradients and phreatic surfaces
- Long term erosion under "sunny day" conditions and other conditions (following wildfires, heavy precipitation events, animal or human land use, etc.)
- Climate-change induced thermal effects, including vegetation change, mud/soil/cover desiccation cracks, and permafrost thaw
- Climate change induced hydraulic effects, including altered PMP and evaporation
- Long-term / multi-seismic effects
- Degradation and reliability of synthetic components
- Cumulative effects of those listed above

2.4.1 Design basis and regulatory requirements

Design basis documents for mine waste structures have become increasingly common place; however, long-term functionality is rarely considered despite the permanent nature of most TSFs and waste rock or overburden dumps. Design for physical stability over the long term should consider cumulative effects over the design life, including degradation of material properties (loss of strength due to vegetation root growth or dissolution of minerals, for example), stress/strain effects including consolidation of tailings (this can lead to reduced permeability and seepage problems), surficial erosion, temperature effects (such as thawing of permafrost), long-term seismic effects (multiple earthquakes assessment), piping (hydraulic gradients), and evaluation of the TSF with unnatural features in a non-functioning state (drains, geotextiles, and culverts can block and degrade, impacting piezometric levels and material migration, for example) (ICOLD, 2013). These closure criteria seek to ensure the TSF functionality is not reliant on components that will fail in time and that they behave as a natural landform would.

The management of surface water is integral to preventing surface erosion and achieving physical stability. In many areas of the world, hydrologic patterns are being altered due to climate change, and these effects need to be considered in planning for closure. A TSF converted to a landform will be equipped with structures such as outlets and spillways that are sized to the design life of the facility and corresponding climate, for example. Similarly, probable maximum precipitation event depths and intensity-duration-frequency (IDF) curves are required to satisfactorily guard against surface erosion. International practice in closure design is continually evolving and varies between (often overlapping) jurisdictions. Determination of a “design life”, or design performance period, for the closure landscape is an important first step in closure design, such that performance targets might be identified. These include an adequate PMP estimate considering climate change to properly size outlets, spillways, and erosion mitigation systems.

In the USA most states require the use of an indefinite design life, which necessitates the use of the present day PMP as the prescriptive design storm and the maximum credible earthquake (MCE) as seismic design criteria. Sweden uses a 1000 - 2000 year design life, in line with older European Union guidelines. More recent guidelines from the EU recommend a design life extending until the next ice age. Australia requires a design life in excess of 1000 years for their overall performance, and a specific design life of 200 years for cover systems on their uranium mines. Most regions in Canada use PMP and probabilistic seismic hazard assessments (PSHA’s) as guiding design events, since most of Canada is free from active fault zones. Where the design life is at least 1000 years and failure might result in environmental damages or loss of life, it is recommended design criteria include the PMF and MCE as opposed to lower criteria that may be viable over the 1000 year performance period (Federal Emergency Management Agency (FEMA), 1998; ICOLD, 1987; Szymanski & Davies, 2004; U.S. Army Corps of Engineers, 1995). Notable areas with less stringent guidelines include the state of Arizona, where a 100-year storm is the official guideline, but this has been known to shift between 25 years and the PMP based on failure consequence. ICOLD also recommends a recurrence interval between 50-years and the PMP depending on failure consequence (Strachan & Davis, 2016). Internationally, the trajectory is towards a closure landscape design life of 1000-years, which necessitates the use of the PMP and MCE (or PSHA, depending on proximity to fault zones) in design assessment. Climate change projections suggest that PMP values may need to be re-evaluated intermittently moving into the future. The Government of Western Australia addresses climate change awareness in mine closure planning directly by encouraging adaptation in closure plans to changing rainfall, evaporation, fire frequency, soil moisture, and land use (Australian Government, 2016).

Design criteria or targets generally include structural stability of the (former) pond and dam slopes, protection of off-site areas from disturbance, and more general criteria such as no risk to human health or the environment. Evaluation of relative success is contingent upon thorough and agreed upon baseline (pre-mining) environmental conditions. A chart of international criteria is included in Table 2.3.

Table 2.3 International regulatory criteria for mine closure

Criteria used to achieve closure objectives	**Argentina**	**Australia (WA)**	**Bolivia**	**Brazil**	**Canada (Alberta)**	**Chile**	**Germany**	**Peru**	**South Africa**	**Spain**	**Sweden**	**United Kingdom**	**U.S.A. (coal)**
Reduction of infiltration where appropriate via plants or capping		x					x			x			x
Physical stability of pond & dam slopes		x	x		x	x	x			x	x	x	x
Chemical stability, non-polluting		x	x		x	x		x	x				x
Removal of drains							x				x		
Only maintenance-free structures / self-sustaining		x					x			x			
Protection from surface erosion		x	x				x			x	x		x
Drainage of resulting land is inward from outslopes except at specific points													x
Avoid drainage systems that accumulate water										x			
Backfill, compact, and grade land													x
Reshaping / re-contouring land		x					x			x			x
Drainage systems to lower water table (drains)										x			
Wide surface drainage canals							x			x			
Dust control		x						x		x			x
Water collection & treatment		x								x			x
No risk to human health or environment		x	x			x		x				x	x
Ecological sustainability		x	x		x			x	x				
Use of established technical norms and/or best practices		x	x										
Restoration to equal or greater land capability to that prior to mining					x			x	x				x
Restoration of mined area	x	x		x		x							

Many countries, especially those in the developing world, have little or no regulations with respect to mine closure. In these instances, international best practices and principles required by funding institutions may provide all the guidance possible (Bastida & Sanford, 2010). Closure regulations often borrow or use environmental policies already in place elsewhere - the most developed of these are found in Canada, the U.S.A., South Africa, Germany, and Australia (Roberts et al., 2000). In 2010, Bolivia passed “El Ley de Derechos de la Madre Tierra”, or the “Mother Earth” Law, that gives legal personhood to the natural environment, ensures harmony supportive of earth’s natural cycles, and collective well-being such that the interests and rights of Mother Earth prevail over all other acquired rights (Morales Ayma, 2010). In this instance it is not yet known how the new law, expanded in 2012, will affect new or closing mines. The Peruvian government has a law regulating the progressive closure of mines according to industry best practices, as well as a written a manual on closure and reclamation, which is voluntary for mining companies to follow (Pease Garcia, 2003; Peru, Ministerio de Energia y Minas, 2006).

In addition to government regulations, mining companies may be bound to environmental and social management principals assigned by the financial institution backing the mining project (Garcia, 2008). For example, 94 financial institutions located internationally have agreed to follow the Equator Principles (EPs) when evaluating and financing large project; these principles include environmental and social guidelines in member countries (Equator Principles Association, 2013). Similarly, the World Bank and the International Finance Corporation (IFC) uses environmental and social measures to determine the relative impacts of a project, and a mining department that publishes papers on sustainability initiatives in mining that they indorse (Garcia, 2008; World Bank & IFC, 2002).

2.5 Conclusions

The management of mine waste has progressed over time from complete disregard for environmental impact, to a desire to control, to a respect for natural forces and designing in conjunction with them. While this last evolutionary step describes best practice, it is not yet common practice. Governments are increasingly holding mining companies accountable for their liabilities, and with this progression mining companies are increasingly leading the closure discussion and technology development. Regulatory agencies require a balance of encouraging investment while ensuring they are not left with a liability as a result. This balance ranges internationally from regions that do not allow mining, to those with minimal requirements for closure. In terms of design life to which the closure landscape shall be built to, the global trajectory is in excess of 1000 years, but outliers exist: some tailings deposits must be demonstrated through modelling to hold all contamination for a minimum of 10,000 years.

With this requirement, geomorphic design and subsequent landscape evolution modelling has been employed to predict the landform and cover effectiveness. Australia is particularly advanced in this area, in part due to state-owned uranium mines and the associated high risk to humans and the environment. With respect to relinquishment, very few tailings storage facilities have been delicensed or successfully reclaimed to the degree promised. Long term behaviour and failure mechanisms are not yet fully understood, particularly so in the case of sand dams, and this forms a major risk for regulators and owners that is not dealt with well in design: it is often overlooked or left to closure. In Alberta, relinquishment of maintenance-free land to the Crown remains the end goal for mining companies; however, whether this is realistic as presently proposed remains uncertain.

3.0 Topographic design for closure of tailings storage facilities

3.1 Introduction

This chapter outlines the technical and design basis of various feasibility scenarios for the infilling and geomorphic design of the central tailings plateaus for an above-grade tailings storage facility (TSF) and adjacent south expansion area (SEA) within an oil sands mine. This work was completed in 2015 at the mine owner's offices in Calgary, Alberta for their later assessment, refinement, and implementation. The final design illustrated herein has undergone extensive stability and seepage modelling, and consequently minor revisions have taken place since this time. Construction of the final landform is expected to be completed sometime after the year 2025.

The fundamental assumption made was that the TSF and SEA would need to be converted from tailings dams into one stable landform, by infilling with coarse sand tailings (CST), and that the landform will eventually be decommissioned. A geomorphic design was required for the landform primarily to (1) direct the flow of water such that drainage related challenges do not occur in the future, (2) in order to maximize additional waste volume capacity, and (3) to create a more natural-looking surface that is geomorphically stable for the foreseeable future. Note a design life has not been dictated by the Alberta regulators, but the post-mining landscape is expected to be permanent.

3.2 Site overview

The TSF/SEA is located approximately 65 km north of Fort McMurray, Alberta (see Figure 4.1). The TSF is bounded on the west by Provincial highway 63 and the Athabasca River (flowing north), and on the east by Muskeg River (flowing south) which enters the Athabasca River south of the mine site. The open pit is north of the TSF. Prior to mining, this area between the two rivers was characterized by forested low undulating topography and low-sloped streams (Shell Canada Ltd., 2012).

The mine site is located in the hemiboreal climate region of northern Alberta, which is the area between temporal and subarctic regions (OSTDC, 2014). The region receives an average of 418 mm of precipitation, 316 mm of which is from rainfall (averages from 1981 to 2010)

(Government of Canada, 2015); however, on a yearly basis evapotranspiration exceeds precipitation and this is exaggerated from April to September (OSTDC, 2014).

"Oil sands" exist in the McMurray formation, which is predominantly a fine-grained marine and estuarine-origin layer of clays and silty-sands (McPherson & Kathol, 1977; Hein, Cotterill, & Berhane, 2000). The Clearwater formation overlies the McMurray formation; this early Cretaceous unit includes marine shales that contributed to trapping the oil sand in place. An erosional unconformity separates the Clearwater formation from the Pleistocene-aged surficial sediments which are of glacial-origin: predominantly sands, interspersed with gravel and till (Figure 3.1) (McPherson & Kathol, 1977; Hein et al., 2000).

Oil sands are mined in an open pit. Overburden is removed as waste, and the sand-bitumen material is transported to processing facilities. Large amounts of warm and hot water are mixed with the oil sand, creating a slurry from which bitumen is mobilized and extracted for future refining. The resulting waste product is called tailings, and contains solids, process water, and small proportions (< 7%) of unrecovered bitumen.

The TSF has been operational since September 2002: deposited tailings include coarse sand tailings (CST), thickened tailings (TT), tailings solvent recovery unit (TSRU), and whole tailings when cyclones and thickeners are off-line. Fluid fine tailings (FFT) and mature fine tailings (MFT) are a component of these materials. Due to the long settling time for many of these tailings, closure plans and tailings management plans must state their chosen steps to achieve a long-term stable tailings pond surface. At this mine an approach similar to Suncor's Pond One is being used whereby CST is hydraulically deposited from one side of the pond, displacing the majority of FFT which can then be dredged out from the opposite side of the pond and placed in pit. Deposition of CST is scheduled to cease by 2020 when construction of surficial features is expected to commence (Shell Canada, 2015). The final downstream crest of the TSF at closure will be at an elevation of 340 m, while that of the SEA will be 306 m. The neighbouring overburden dump located north-west of the TSF will be a local high point at 370 m.

Figure 3.1 Surficial geology of AOS region. Light blue= Glaciofluvial outwash sand & gravel; Medium blue = outwash sand; Dark blue = meltwater channel sediment; Yellow = Aeolian sand dunes (recent); Orange= Gully, creek valley (recent); Red= stream alluvium, fluvial deposit (recent); Green = ground moraine; Pink = ice contact glaciofluvial; Dirty teal= mixed glaciolacustrine deposits. All are from the Pleistocene epoch (2.6 M years before present to 11,700 ybp) unless otherwise noted.

3.3 Project background

At the time of publication (and design completion), landform design for closure of a sand-infilled above ground tailings pond had only been completed once prior (Suncor's Pond One - now called 'Wapisiw Lookout'). Lessons learned from the surficial drainage and topographic design process at Pond One are not publicly available, therefore this was a project undertaken without prior working experience of tailings dam closure design. (Note: several papers were published in 2010/11 regarding the capping of fine tailings at Pond One; however, this is a precursory and somewhat unrelated process). While certain desirable landform characteristics were determined at the beginning of the design work, design "goals" seemed too definitive for such an exploratory process. Instead, the design process was conducted while keeping in mind several "big ideas", listed throughout this section.

It is important to keep in mind why the TSF is being converted into a landform:

1. To achieve (after a period of time) a maintenance-free state where the former tailings pond behaves as the surrounding natural landscape does.
2. To eliminate liability due to the geotechnical risks associated with tailings dams and their pond contents.
3. To return the land to the Crown through dam delicensing.
4. To create the appearance of a natural landform.

The end-of-construction landform must be able to accommodate PMP storm events and must meet all dam delicensing criteria set out by the province of Alberta. Low sediment loads in surface runoff and minimal surface erosion are required. Localized and global stability must be achieved. Failure mechanisms including liquefaction, piping, material mobility, earthquakes, overtopping, rise of phreatic surface, slope instability, and slumping should be investigated during design evaluation (CEMA, 2010). These are requirements that must be evaluated through numerical modelling and other methods following prefeasibility design, that will then dictate specific changes be made. The purpose of this exercise is to generate a prefeasibility design as a starting point that meets as many criteria as possible.

The Cumulative Environmental Management Association (CEMA) has developed a landscape design checklist for the oil sands region based on a life-of-mine, holistic approach. Since closure planning for the TSF/SEA was initiated after the bulk of construction was complete this checklist (CEMA, 2006) and associated guideline (2010) are only partially applicable. The portions that are applicable have been outlined in Appendix B and have been identified as having been included as a part of this project or not. The vast majority of decisions made prior to TSF construction dictate future performance and issues related to closure (i.e. outlet location(s), downstream dam slopes, etc).

The addition of a geomorphically designed surface topography to a pond core expected to deform over time (from differential settlement of un-dredged tailings), will ideally allow for the landform to adapt slowly and without intervention to manage geotechnical and geomorphic stability over the long term. At the same time, it is desirable to create a landform with the physical and biological complexity expected to be found naturally within the northern Alberta boreal forest region. By constructing a landform with topographic variability, the hydrologic regime and microclimates provided will allow for a mosaic of native plant species to thrive.

In addition to the fundamental reasons for closure listed above, Four Big Ideas guided the topographic design for closure:

1. The surface should eventually be self-sustaining and require no maintenance in excess of natural surrounding terrain.
2. The surface should mimic the topography of natural terrain, including watershed size, slope angles, shape of topographic features, flow route length and width.
3. The surface should maximize waste storage.
4. The surface should be designed in consideration of the chemistry, strength, and relative consolidation of underlying trapped tailings materials. The proposed topography should evolve with a settling core and preserve adequate surficial drainage (so as to not return to a dam) with minimal intervention as surface settling occurs.

3.4 Geomorphic design

Mining-affected land is typically subject to orders of magnitude greater erosion than undisturbed landscapes. This rate of high geomorphic change can occur for decades until a “geomorphic equilibrium” is achieved between the exposed soil or rock, climate, vegetation, etc. Geomorphic design has been recognized in recent years as being a more sustainable method of design for mine waste structures than previous methods that prioritized efficient deposition over long-term performance. The purpose of geomorphic design is outlined in Section 2.1. In general, a landform designed using characteristics of a mature fluvial geomorphic system is able to adapt to changes without significant disruption to the landform itself or surrounding environment (Toy and Chuse, 2005). Slope stability under extreme conditions is improved, hydrologic response is subdued and elongated, erosion is reduced, and a greater diversity of vegetation species exist due to variable topography and water availability (Bugosh and Epp, 2014; Russell, 2012; Snyder, 2013).

Geomorphic design elements include:

- Sub-watershed size, drainage patterns, and overland flow path length/ slope equal to those found on locally similar, stable materials.
- Flow paths are shallower at low elevation areas of the reach (longitudinally convex).
- Channel width is sized according to expected flow and in alignment with regional analogues.
- Low flow watercourse path meanders across the channel width at a radium of curvature similar to that found on locally similar materials.

The TSF/SEA designed for closure herein is located such that adjustment to the perimeter dams is not possible. The scope of the geomorphic design was therefore restricted to the area within the upstream crest on the TSF and the area between the upstream crest on the SEA. The TSF dam abutting the SEA was also included in the scope.

3.5 Design process

Landscape architects are architects of the outdoor environment. They work with specialists on environmental restoration projects, urban planning, and countless niche areas in between. Landscape architects use the “design process” to aid them in making evidence-based design decisions. This design process is initiated with a site inventory to capture and often to graphically communicate the physical, biological, and cultural attributes of a site and its surroundings. Next, a site analysis is conducted which critically examines the inventory in terms of opportunities and constraints, suitability analysis, and potential methods of integration and synthesis. Good design thrives on constraints: that which makes a design site-specific, such that a continuity of space exists between the new and old. The process that identifies constraints and analyses them is required to ensure a design solution is all-encompassing, multi-layered, and integrated across several interest groups. This is especially true in a mining environment, where failure consequences can be high and the many involved stakeholders and specialists are often insulated from one-another (as individual silos, for example). For additional guidance on this inventory and analysis process the reader is directed to LaGro (2008).

This analysis of opportunities and constraints is used in preliminary design: a number of designs are generated in consideration of site programming (required design elements) and the analysis. Based on evaluation of each design, one or more are chosen to move forward with to the final design stage.

3.6 Site inventory and analysis

Regional context from a topographic perspective is shown in Figure 3.2. The mine is located just east of the Athabasca River, which is a low point sandwiched between Muskeg Mountain to the south-east and the Birch Mountains to the north-west. The topography between the two relative high points was historically low and locally undulating, with an overall slope downward towards the Athabasca River. The topography between these two high points has been drastically altered by surface mining over the last 20 years. Pits greater than 80 m deep will be filled in at closure to meet an elevation similar to pre-mining conditions; however, the external tailings ponds will remain as features 60 m to over 100 m in height well above the surrounding landscape. These features provide excellent regional views resulting from their high elevations. The height and size (tens of square kilometers in area each) of these TSF's also make them visible from great distances. The location of the TSF in relation to the northbound lane of highway 63 makes it particularly visible from this vantage.

Locally, the roughly 6 km^2 surface of the tailings pond is held at an elevation of 340 masl by a large perimeter or ring dyke, constructed predominantly of CST. The slope and position of this ring dyke is engineered for geotechnical stability and as such is considered a permanent feature to remain as is pending surficial placement of reclamation soil and vegetation planting.

Since the present design will not include planting design or vegetative components a detailed inventory of local vegetative communities has not been completed. Surrounding areas are dominated by lowland muskeg common throughout the boreal forest. Upland features that are presently dominated by aspen are expected to transition towards grasslands over the next 100 years due to climate change (Thompson, Mendoza, & Devito, 2017).

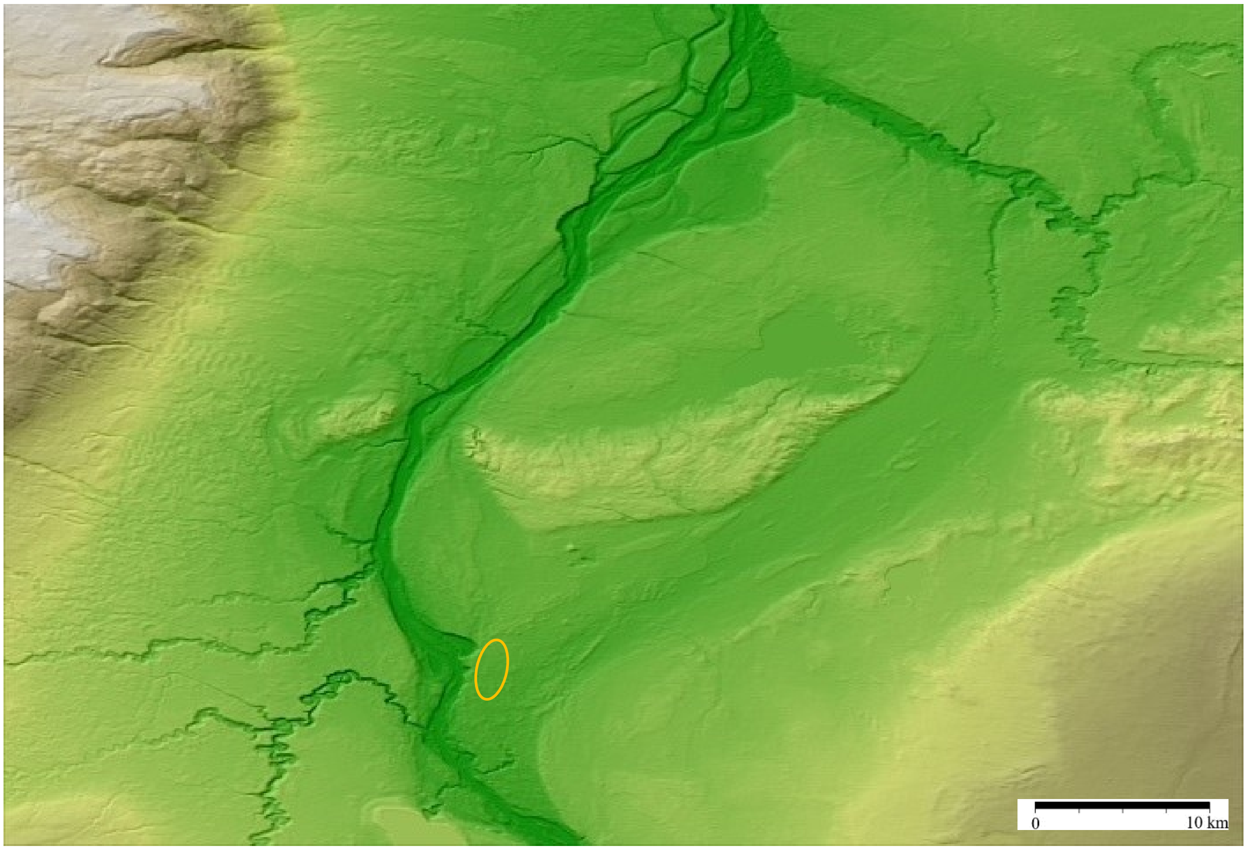

Figure 3.2 Relative regional topography surrounding TSF/SEA study site in Alberta, Canada. High elevation is white, low is dark green.

3.6.1 Geotechnical and geomorphic constraints

Due to the complex geotechnical constraints, and dominant role of geotechnical performance on the overall success of the landform post-closure, a separate Geotechnical Constraints Map has been compiled from the more broadly scoped Design Opportunities and Constraints Map. Geotechnical constraints will guide the design of the SEA and TSF due to their extreme failure consequence. These constraints are described below and shown graphically in Figure 3.3 and 3.4.

Large amounts of settlement (many meters) and consolidation are expected from the layer of MFT remaining at the bottom of the tailings pond and the FFT interlayered within the CST during infilling (for definitions see Section 2.1.1). The dredge location on the north-west end of the TSF is also expected to see extensive consolidation, settlement, and resulting alteration of the surface from the future settlement of remnant FFT. Areas expecting the greatest surface settlement over the next several decades are aligned along a path from the south east corner towards the middle and continuing towards the central north area where the dredge is located, as shown on Figures 3.5 and 3.6.

Identifying the zones within a deposit with respect to long term performance is particularly important. Depending on the type of tailings and how closely they were made to specification, each will have different consolidation rates, settlement extents, bearing capacity, and chemistry. Accordingly, a thorough analysis of each – and the deposit as a whole – is key, since each zone of tailings will have different requirements of the topography such that optimal performance from each is achieved. Some of these topographic controls include uniformly raising the water table, flushing pore water, expediting or slowing consolidation, for example. Areas of transition between tailings zones allow for similar areas of topographic transition, and where three-dimensional stability modelling may provide strong contributions.

The Tailings Solvent Recovery Unit (TSRU) beach on the north-east corner of the pond has high fines capture, with proportions of fines increasing towards the BAW/BBW interface. Overall fines content in the North Pool Deposit (NPD) has been measured at approximately 25% using a 44 micron cut off value. This deposit will experience a lesser degree of settlement than the region with remnant FFT; however, there is liquefaction potential in the BBW and loading this deposit needs to be done slowly. TSRU tailings also have demonstrated potential acid generating properties (Foght 2013; Kuznetsov et al., 2015), and as such further investigations are necessary to determine the extent of that potential and cap requirements.

As a result of geochemical concerns related to the TSRU tailings, cutting into this deposit should be avoided. Outlet locations are limited by spatial constraints imposed by the property line immediately surrounding the TSF and SEA, leaving the most viable outlet location in the center of the north dyke and directly next to the TSRU tailings. Outlet locations have the lowest elevation along the perimeter dyke as this is where surface water exits the upper plateau; however this necessity is in conflict with the need for TSRU tailings to be thickly capped and not cut into, as would be necessary near the outlet. A minimum 4 m thick CST cap has been recommended for the pond surface plateau throughout this preliminary design process. This has been illustrated in Figure 3.7.

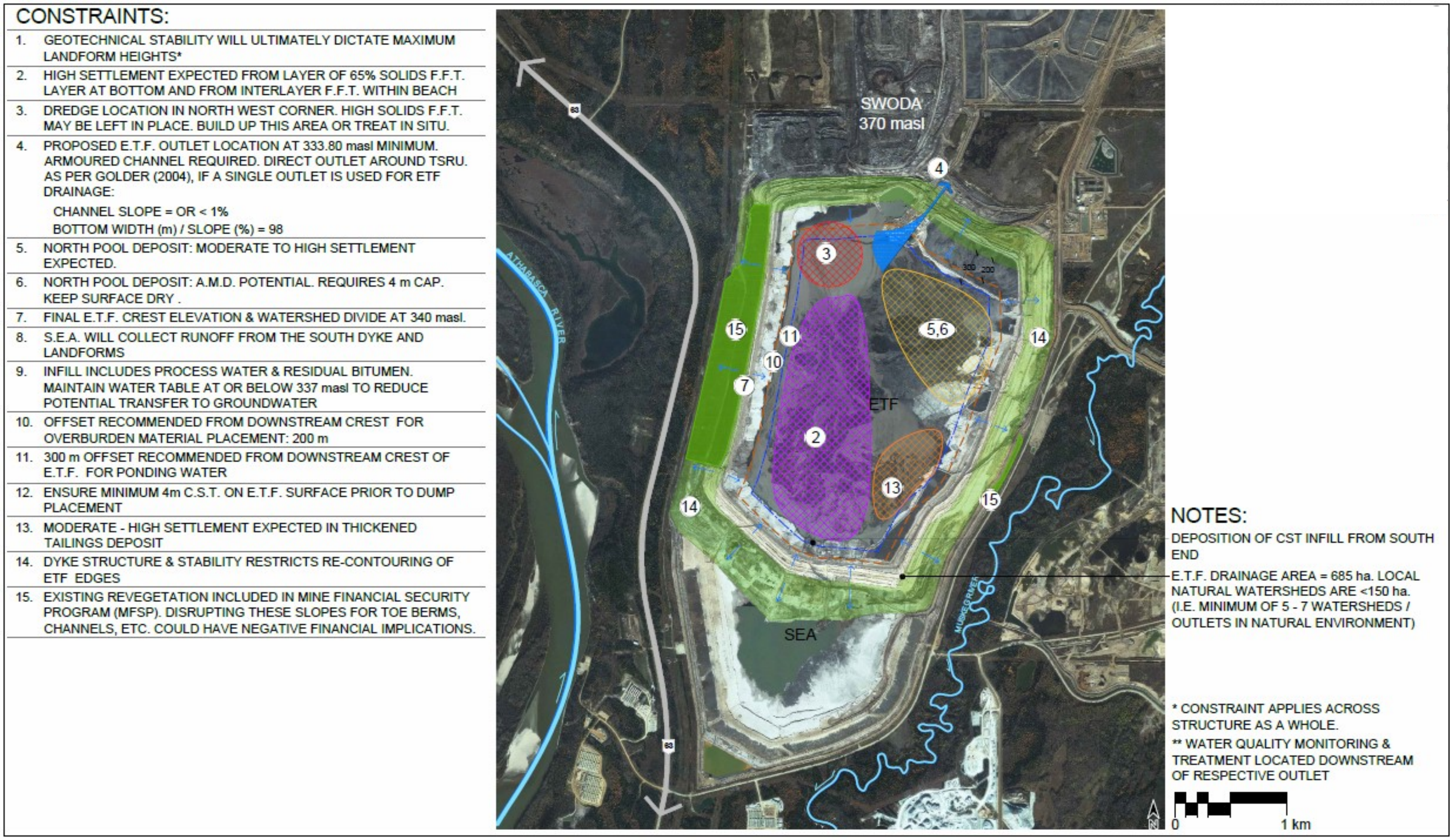

Figure 3.3 External tailings storage facility geotechnical constraints map

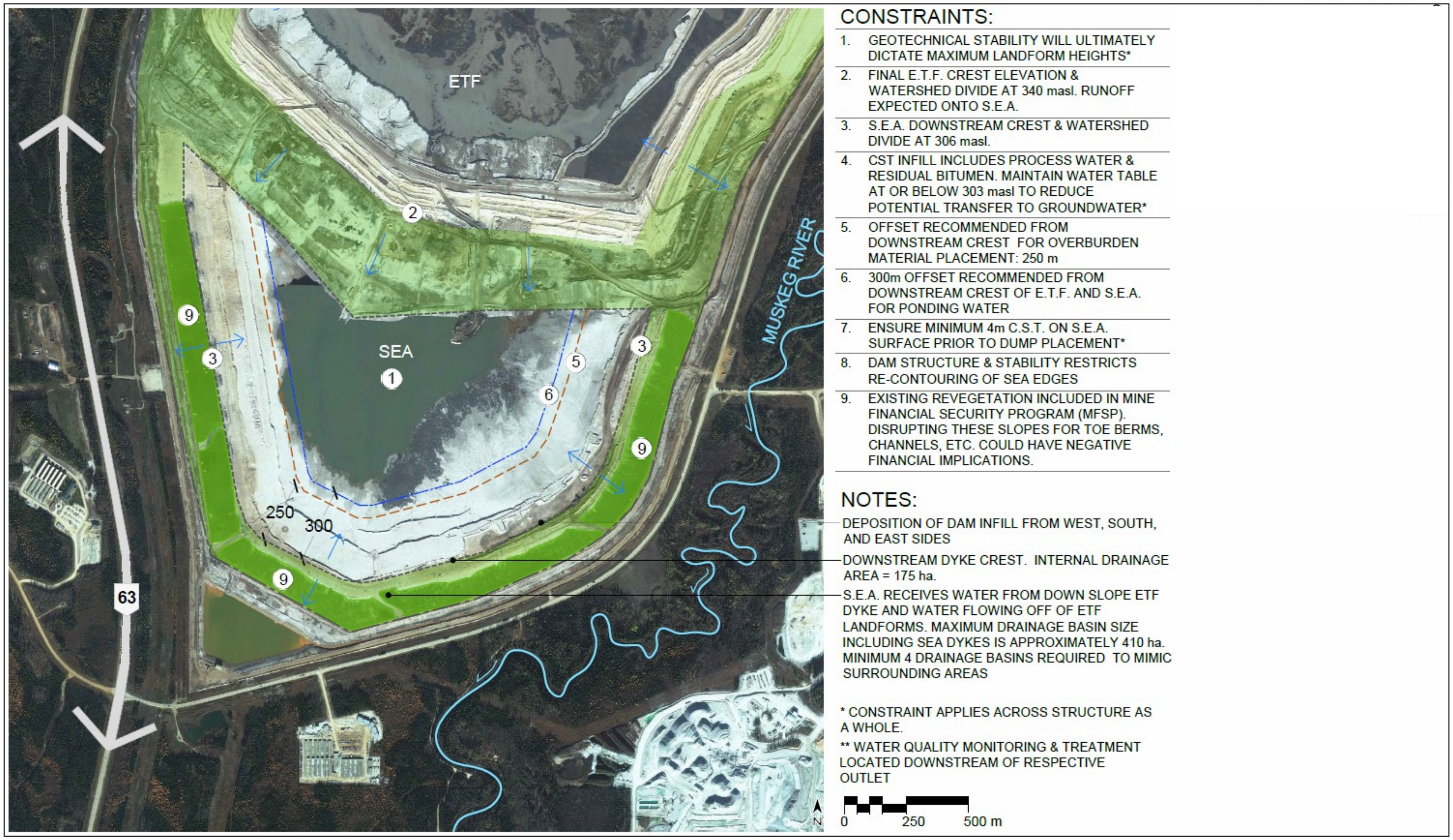

Figure 3.4 South expansion area geotechnical constraints map

Figure 3.5 Sampling locations corresponding to greatest expected MFT depth to remain following infilling. From Esposito and Nik, 2012.

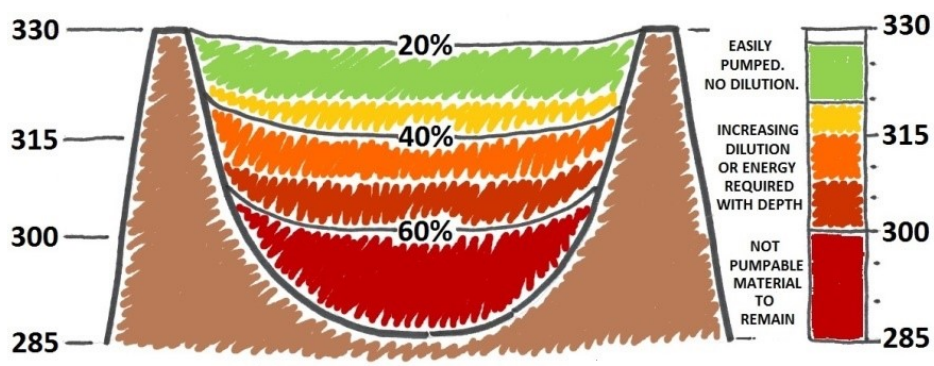

Figure 3.6 Sketch of solids content with depth in the TSF. As % solids of FFT pumped increase, the post-dilution volume increases, as do the associated time to pump and space requirements for one unit of pre-diluted material. Data from Esposito and Nik, 2012.

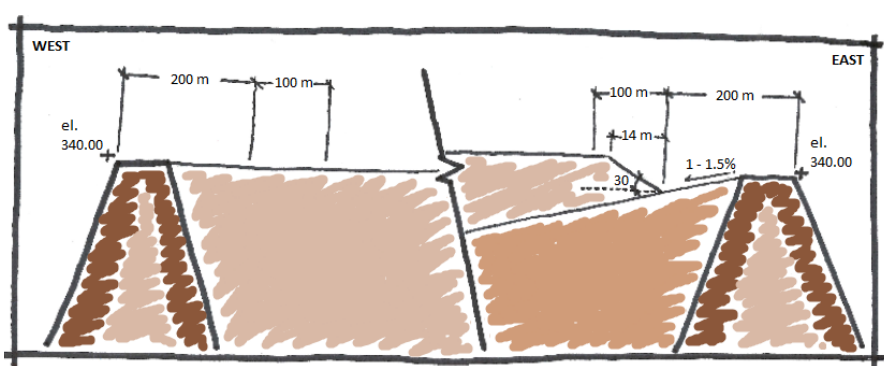

Figure 3.7 Minimum offsets from downstream crest, and capping/infill heights.

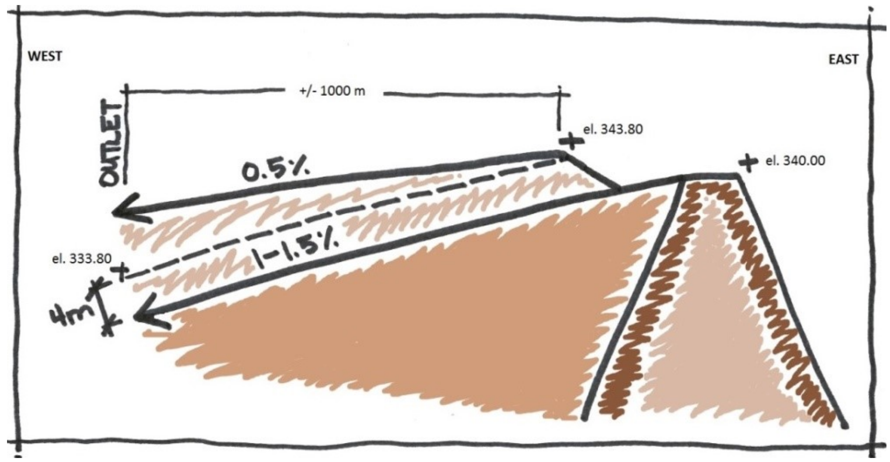

Figure 3.8 Schematic cross-section of north-east area of TSF. Outlet elevation and capping assumptions as shown. Note red wedge, loading fine materials on the west more than coarse materials on the east.

As with natural steep slopes, loading the top/crest and elevated water tables can lead to slope stability problems. For this reason, any loading of the tailings pond plateau or permitted ponding of surface water must be done well away from the dyke crest. Geotechnical engineers for the TSF have suggested a minimum offset from the downstream crest of 200 m and 300 m for earthworks material placement and surface water ponding, respectively (Figure 3.8).

The total drainage area of the TSF surface is approximately 685 ha, or 6.85 km^2, while the SEA (including runoff from the TSF south dyke) is 410 ha, or 4.1 km^2. This area is necessary to calculate the number of catchments and channel slopes necessary to maintain a vegetated channel that is not dependent upon armouring or other more engineered provisions. Additional information on calculations and criteria used for the drainage design are located in Appendix A.

It is also important to note with respect to geotechnical constraints that the ultimate height and spatial extent of any landform(s) placed on the surface of the TSF and SEA will be restricted by the localized and global stability analyses to be completed on the prefeasibility design.

3.6.2 Design opportunities & constraints

Opportunities and constraints exist beyond the geotechnical realm, and this site was particularly abundant in constraints (as are most TSFs that have been designed without early and constant consideration for closure). These design opportunities and constraints are graphically summarized in Figure 3.9 and discussed below.

Underground utilities exist along both the east and west sides of the TSF and SEA in order to transmit services to various locations around the site. Although the tailings ponds will be decommissioned, the utilities will remain necessary to service the active mine. During landform construction ditches along the bottom perimeter of the dykes will need to be widened into channels: care needs to be taken during this stage to ensure these utilities are not disturbed. Culverts are also located on both east and west sides in order convey water along the perimeter while also allowing vehicles access to the dyke and pond surface. These culverts may need to be increased in size at closure in order to convey larger precipitation events.

Vegetative buffers are legally required on either side of Muskeg River for a minimum distance of 400 m. This impacts the design and location of outlet features. It also means that any water or sediment being discharged from the east side of the structure needs to be adequately conveyed such that it does not enter this vegetated buffer or otherwise impact the environment outside of the permitted lease.

In terms of drainage, the TSF and SEA form a new high elevation feature which diverts runoff to east and west sides, then flows south. The existing south settling pond is at a low elevation where runoff and seepage water is collected from perimeter ditches. This is a natural location to house a secondary water treatment facility prior to discharging to the environment. With respect to the surface of the tailings pond, the large elevation change from crest to toe and the low slope required to impede erosion necessitates that the drainage path be quite long. The only location along the perimeter of the TSF with sufficient space is at the north end of the TSF.

Downstream slopes of the perimeter dyke have been constructed with a platform-bank style topography to allow mine vehicles access to the pond surface and dyke crest. Some of these access points will continue to be necessary during and after closure. Additionally, the TSF and SEA are bound by mine lease limits within close proximity to the dyke toe and toe berms on the east and west sides. These lease limits make it impossible to flatten downstream slopes.

Figure 3.9 Tailings storage facility and south expansion area design opportunities and constraints map

Highway 63 runs parallel to the western edge of the TSF, approximately 200 m from the lease limit. Views of the TSF and SEA are greatest along this highway north and south of the TSF. An opportunity exists for signage or "scenic vista" pull-offs to educate the public on the reclamation work done and the site's history. Dense woody vegetation should be installed where possible on the TSF within these viewsheds to emphasize the naturalization, blend the landform into surrounding terrain, and to limit deep-seeded erosion on these slopes where deposition may impact the highway. Maximizing views of good reclamation may contribute to public license in this sense, while also providing geomorphic and ecological benefits.

3.7 TSF landform options

Options analysis is an integral component of design. There are often several different methods of meeting the objectives, and an options analysis allows the designer or design team to determine which design best achieves those objectives.

In this particular case, there was an interest on the part of the mining company to look at recreating the topography of naturally occurring landforms in the area, as well as one "base case" design. The natural analogues approach to landform design is well documented (Keys, McKenna, Sawatsky, & Van Meer, 1995; Nicolau, J. M., 2003; Sawatsky & Beersing, 2014; Toy & Hadley, 1987); and can be summarized as replicating key elements of a landform that is found locally (same climate) and composed of an analogous material. At this stage, a component of the design included maximizing overburden material storage over top of the TSF, such that any additional increase in elevation proposed by the design would be constructed with overburden and a thin CST cap. No natural analogue of this surficial stratigraphy exists in the AOS. On a scale of this magnitude, no natural analogue exists for pure sand either, although dune fields do exist in the region they are incomparable. Several local landforms were outlined for preliminary consideration with respect to the landform goals listed in Section 3.3, in particular for waste storage and to provide natural appearance of topography. The opportunities and constraints associated with each are discussed below.

3.7.1 Drumlins

Drumlins naturally exist in northern Alberta as a result of glacial processes from the last glaciation. On average, they are 1000 m in length (roughly aligned in the north-south direction), 500 m wide, and 16 meters tall at their highest point on the northern side and tapering to the south. High point to high point spacing is between 260-650 m in drumlin fields and areas with a high density of drumlins tend to have smaller ones than areas with few drumlins (Annen, 2002). Table 3.1 lists the range in spatial characteristics of drumlins within and near the AOS.

Drumlins are relatively easy to construct due to their long, linear shape. They are made of well-drained glacial till, and thus do not permit ponding on their surface, but have internal drainage and drainage to their sides during heavy precipitation. This may or may not be the case in drumlins constructed of oil sands waste material; however naturally occurring drumlins are stable as a result of their high infiltration capacity, and thus material with low infiltration may not achieve similar stability or erosion resistance in this form.

The TSF is already in an elongated shape and thus drumlins fit well within the dyke boundary. The benefits are that increased topographic diversity will create diverse ecological regimes with distinct vegetation characteristics from ranging from upland at drumlin crests, to riparian areas within channels and at low points. The range in drumlin size allows for small variations in topography over areas with low substrate strength.

A drawback of this landform is that they are relatively small, so high-volume waste storage may be challenging without increasing the overall slope of the land, which would in turn increase erosion potential. This form is naturally occurring due to specific glacial conditions at their formation, therefore the durability of constructed drumlins constructed of mine waste materials is uncertain. Additionally, the visual impact of this option may be minimal, since they will be well above the view from the ground surface.

Table 3.1 Drumlin dimensions and statistics from within the Wood Buffalo Region.

Landform Characteristic	**Controlling Value**	**Dominant Characteristics**	**Secondary Characteristics**
Length (m)	1200	1000-1500	500-1000
Width (m)	700	300-500	200-300
Height (m)	20	15-20	10-15
Slope Length (m)	250	150-200	200-300
Slope Gradient (%)	12%	9-15%	5-9%

**Notes: Table adapted from CEMA (2006). The dominant characteristics have been emulated as much as possible in the drumlin design option (particularly the 9-15% slope), with some variation as a result of site requirements.*

3.7.2 Hummocky ridge and swale

This option uses a combination of broad and high elevation ridges and swales to direct water towards the landform outlet. Slopes of landforms are designed in an 'S' curve shape, which is a mature form that produces minimal erosion and subsequent sediment loading of channels while an equilibrium point is found post-construction. This design option has been exaggerated to maximize storage volume and other positive features while minimizing negative features. This landform type, on a smaller scale both spatially and with less abrupt vertical relief, is most commonly seen in the area surrounding this mine. The landforms are larger than a drumlin or esker so the work required to construct these ridges is likely to be much less than other smaller landforms. Hummock characteristics are found in Table 3.2.

Table 3.2 Hummock dimensions and statistics for a hummocky landscape with moderate relief within the Wood Buffalo Region.

Landform Characteristic	Controlling Value	Dominant Characteristics	Secondary Characteristics
Vertical Relief (m)	60	50-100	30-40
Slope Length (m)	300	200-300	150-200
Slope Gradient (%)	16	9-15	5-9
Number of catchments per 100 ha	-	5-10	-
Percent of landscape that drains off-site (%)	-	80-100	-

**Notes: Table adapted from CEMA (2006). The dominant characteristics listed here have been emulated as much as possible in the Hummocky / Ridge & Swale design option (particularly the 9 – 15% slope).*

According to CEMA (2006) these landforms typically have reversals in slope, many shallow and closed depressions, and poorly integrated surface drainage. For this design option, well integrated surface drainage has been used with no reversals in slope to encourage drainage towards our outlet. We have also followed the Golder (2004) drainage area sizes on the larger end of the scale (majority less than 150 ha) to maximize the volume of waste accommodated.

3.7.3 Eskers

Eskers are long, relatively narrow deposits of coarse sand and gravel that weave back and forth in an undulating manner across the landscape. These glacial features are formed by sediment deposition from streams above, within, or below glacial channels. The surrounding landscape is typically flat, meaning the impact of these features on drainage over the structure as a whole is limited: while these features are well-drained in themselves, they create a divide over the relatively flat landscape they traverse.

Eskers and drumlins tend to be essential elements for northern ecology in that they provide conditions for important plants like cranberries to grow; migrating animals and animals preparing for hibernation rely on plants which grown on these glacial features. Esker characteristics are found in Table 3.3.

Table 3.3 Esker dimensions and statistics from within the Wood Buffalo Region.

Landform Characteristic	Controlling Value	Dominant Characteristics	Secondary Characteristics
Length (m)	2000	1000-1500	1500-2000
Width (m)	400	250-300	300-500
Height (m)	20	15-20	10-15
Slope Length (m)	150	100-150	150-200
Slope Gradient (%)	18%	9-15%	5-9%

**Note: Table adapted from CEMA (2006)*

3.7.4 Dune field

Dune fields are formed when well-sorted and loose silt to medium sand is located in a dry, windy, poorly vegetated location. Dry silt and sand is mobilized by wind, creating characteristic topography. Both parabolic and longitudinal dunes are common in northern Alberta. These eolian features are relatively recent, having developed after the last glaciation and often forming from glacial lake sediments after the water has drained. Active, unvegetated dunes are slightly less common than inactive, vegetated dunes particularly around the Athabasca oil sands region. Dune sediments have high permeability, high strength, and low compressibility. Due to their high permeability, drainage tends to be internal with no visible surficial drainage patterns. Dune characteristics are found in Table 3.4.

Table 3.4 Parabolic and longitudinal dune dimensions and statistics from within the Wood Buffalo Region.

Landform Characteristic	Controlling Value*	Dominant Characteristics	Secondary Characteristics
Parabolic Dune:			
Length (m)	1200	800-1000	1500-2000
Width (m)	300	200-300	300-500
Height (m)	10	5-10	10-15
Slope Length (m)	150	100-150	150-200
Slope Gradient (%)	12%	9-15%	5-9%
Longitudinal Dune:			
Length (m)	2400	1500-2000	1000-1500
Width (m)	500	300-500	200-300
Height (m)	25	20-25	15-20
Slope Length (m)	250	200-250	150-200
Slope Gradient (%)	12%	9-15%	5-9%

Note: Table adapted from CEMA (2006)

3.7.5 Dome

A large dome covering the surface of the tailings pond is not a natural analogue to the surrounding environment. The estimated 200 m offset from the TSF downstream crest must still be obeyed in this design, meaning the overall shape will be that of a dome overtop of a platform. Since there is a requirement to capture and treat water from the TSF prior to releasing it to the environment, a perimeter channel is required to capture runoff from the dome before it reaches the dam side slopes and the adjacent environment. This drainage channel must be located an estimated 300 m from the downstream crest in order to reduce negative geotechnical impacts; this channel cuts into the landform, reducing the cumulative amount of material stored, as well as the size of the inner dome and associated volume of fill captured within it.

3.8 Drainage patterns

Drainage occurs when water is directed over or through surficial soils. Water conveyed over top of land is called overland flow, surface drainage, or external drainage. Water that enters the soil and is conveyed below the surface is called internal drainage or subsurface flow. In the natural environment external drainage may infiltrate becoming internal drainage, and internal drainage may seep out of the surface becoming surface drainage. Artificial drainage structures are used in man-made environments for water collection and irrigation. Design to re-create the natural environment uses artificial drainage layouts to mimic those found in nature. Both Schumm (1956) and Horton (1945) provide excellent background on drainage systems (also see Section 5.2.2).

Naturally occurring surface drainage patterns are determined by substrate material, climate, and topography. These patterns dictate how effectively water is conveyed, and thus the long-term sustainability of a landform particularly for man-made features. Since post-mining landforms are intended to be viable over an extended period of time, surface drainage design that matches the foreseeable climate projections for a region and surface material properties can improve landform sustainability. For this same reason we cannot replicate or strictly mimic local landforms and topographic characteristics when subgrade materials are dissimilar.

Drainage density is used to quantitatively describe the total length of drainage course per unit area, while drainage texture provides a more general description. High drainage density correlates to a fine texture, while low drainage density equates to a coarse texture. Drainage density is dictated by surface and subsurface geology, climate, and vegetation (Toy and Hadley 1987). Density increases as climate becomes drier, vegetative cover decreases, and slope gradients increase. In the Prairie Provinces level, well-drained deposits (similar to the TSF surface) typically have low drainage density and coarse texture (Mollard 2010).

Natural soils in the wood Buffalo region are highly variable due to the historic glacial processes and subsequent erosion. As such it is very difficult to identify variability in drainage patterns as a result of subgrade material. Where soil is less variable, the physical representation of drainage patterns is characteristic of subsurface material(s). In plan view, dendritic drainage looks like a tree: A central trunk transmits the greatest amount of water, then moving upstream smaller branches collect and direct water (with corresponding increase in stream order and decreased carrying capacity). This pattern is characteristic of relatively flat terrain over uniform soil or rock.

A simple dendritic drainage pattern has only one drainage basin and is less branched than a standard dendritic pattern. Over the same relatively flat area, a simple dendritic pattern may be indicative of coarser, more permeable soil when compared to a standard dendritic pattern.

Short-interval sheet drainage has been a goal throughout the brief history of mine reclamation in order to de-concentrate flows and reduce the energy and sediment carrying capacity of water flowing over a landform (Toy & Hadley, 1987). This is seen on dams with platform-bank topography consisting of uniform slopes. In environmental restoration, sheet drainage is undesirable due to the inevitable topographic inconsistencies at a small scale. This leads to preferential overland flow paths which eventually mature into rills and gullies in parallel and dendritic drainage patterns, depending whether the surface is flat or sloped. It is preferable to build an analogue of what the mature drainage will evolve to, where possible, limiting the amount of landform erosion and sediment transported downstream.

3.8.1 Overland flow path & dimensions

Maximum overland flow path is used to determine maximum slope for sheet flow before directed drainage methods (i.e. vegetated or armoured channels) are required. Previous research conducted by Golder Associates (2004) on surrounding natural terrain was used as a guideline for slope lengths, gradients, channel widths, etc. in the absence of long-term stable landforms constructed of AOS mine waste products. Since CST is more erodible than natural soils of the region and due to the extended design life of the structure, a conservative approach directing surface water towards channels has been used as much as possible to protect the surface from future extreme events.

The average drainage area for nearby reference sites (located at Muskeg Mountain, and Fort Hills) range from 0.2 ha to nearly 1200 ha (Golder, 2004). Most are less than 150 ha, and the smaller the size, the more likely they are to be vegetated. These size ranges have been used in the design of the TSF surface. Calculations for channel bottom width, catchment size, etc. can be found in Appendix A.

3.8.2 Channel slopes & erosion mitigation

Increased surface gradient (slope) corresponds with increased overland flow velocity, and fast-moving water is more erosive and carries a greater sediment load as a result. Channel slopes producing the least sediment load transport offsite are concave: steeper at the headwaters, becoming flattened towards the outlet (Toy and Hadley, 1987). Due to the length of the TSF, and the need to capture runoff from as large a surface as possible, channel slopes were not increased at the headwaters in this instance. The lowest slope deemed realistic to allow flow over the long channel length was used, providing the added benefit of reduced erosion potential: 0.5% (rise/run = 0.005) is considered by landscape architects to be the lowest constructible slope for which water will efficiently flow over land due to gravity. Water will flow at lower slopes than this, but construction is not likely precise enough in natural environments and with variable compaction to achieve the design as intended. This is especially true when building over materials prone to settlement.

Erosion is a concern because a small rill can quickly develop into a deep gully. Slope stability, containment of tailings, and minimized impact to the surrounding environment are basic characteristics of a closed tailings dam: excessive erosion has the potential to inhibit each of these.

Vegetation and armouring will likely be required throughout the channels and have been quantitatively determined using natural features found surrounding the mine site and documented in Golder (2004). The calculations and list of channels to be vegetated or armoured can be found in Appendix A for all three design options developed.

3.9 Landform design for feasibility study

The following sections explain how decisions were applied to the site. Assumptions made throughout the design process are discussed below. Universal design elements which are present in all three of the designs explored are discussed, particularly with respect to ephemeral pools as they are not outlined elsewhere. Finally, the three designs completed (both the median waste storage and maximized waste storage versions of each) are discussed in terms of their respective opportunities and constraints.

3.9.1 Design assumptions

Since closure plans are dependent upon mine plans in practice, the landforms and outlet locations designed herein are subject to changes in the mine plan. It is assumed that there will be no further input of tailings or other material to the TSF or SEA beyond that which is outlined in this document and those referenced herein. It is also assumed that mining in areas near the TSF will not impact the projected outlet locations and/or receiving channels / areas.

This prefeasibility design is being completed to attain a starting point for more detailed testing and evaluation. Until additional hydrologic and geomorphic modelling is completed on the recommended design option, it is to be assumed that mimicking the size and structure of natural vegetated drainage pathways will sufficiently accommodate PMP events and long-term exposure to climate in such a way that the functionality of the structure will not be compromised. It is also assumed that the foundation and perimeter dykes are capable of holding the CST infill, and that the TSF infill, perimeter dykes, and foundation structure are capable of holding waste material to a maximum elevation of 350 m, while maintaining a minimum factor of safety (FOS) of 1.3 throughout construction and immediately following. This is the minimum factor of safety currently required for the landform during construction, and the FOS is expected to increase to a minimum of 1.5 thereafter.

Since the SEA is already infilled with CST, assumptions are solely with respect to the waste material and placement. The maximum elevation of waste included in previous closure plans was 331 m on the SEA and 350 m for the TSF. These heights have been followed for the following designs in order to provide a comparison. As such, it has been assumed that the dykes surrounding the SEA will hold the waste to an elevation of 331 m while maintaining a minimum FOS of 1.3.

For the purposes of this study, it was assumed that following TSF infilling with CST, approximately 7 million cubic meters of MFT will remain trapped at the bottom due to high solids content and limitations of dredging economically. It is also assumed that some volume of MFT will remain at the dredging point and will need to be treated in place. The surficial locations immediately above this MFT are expected to have larger differential settlement than other areas of the pond.

3.9.2 Universal elements of the designs

All three feasibility options for the TSF use the north end of the tailings pond as the future outlet for surface water drainage. This was determined to be the location with the greatest downstream area available to manage the water prior to release to the environment; all other sides of the TSF are bound by protected natural features or legal lease boundaries.

Ephemeral pools (also referred to as “vernal pools” or “check dams” depending on the context) have been designed into each of the three TSF closure options along the lengths of the channels. Ephemeral pools are small, seasonal water bodies that collect small volumes of surface water after large storm events (and in spring), creating localized ecosystems. This has been done in order to reduce water flow velocity in the reclaimed channel during extreme storm events and also to maximize the drainage area captured by the channels and directed north. The ephemeral pool design shown here is purely indicative and would need final design by a hydrologist; no calculations have been completed for flood attenuation provided by this layout. Figure 3.10 illustrates how ephemeral pools or “check dams” were included to reduce the overall slope of the main channel. If hydrologic modelling indicates high flow rates, check dams would be designed and constructed with appropriately sized rock armour.

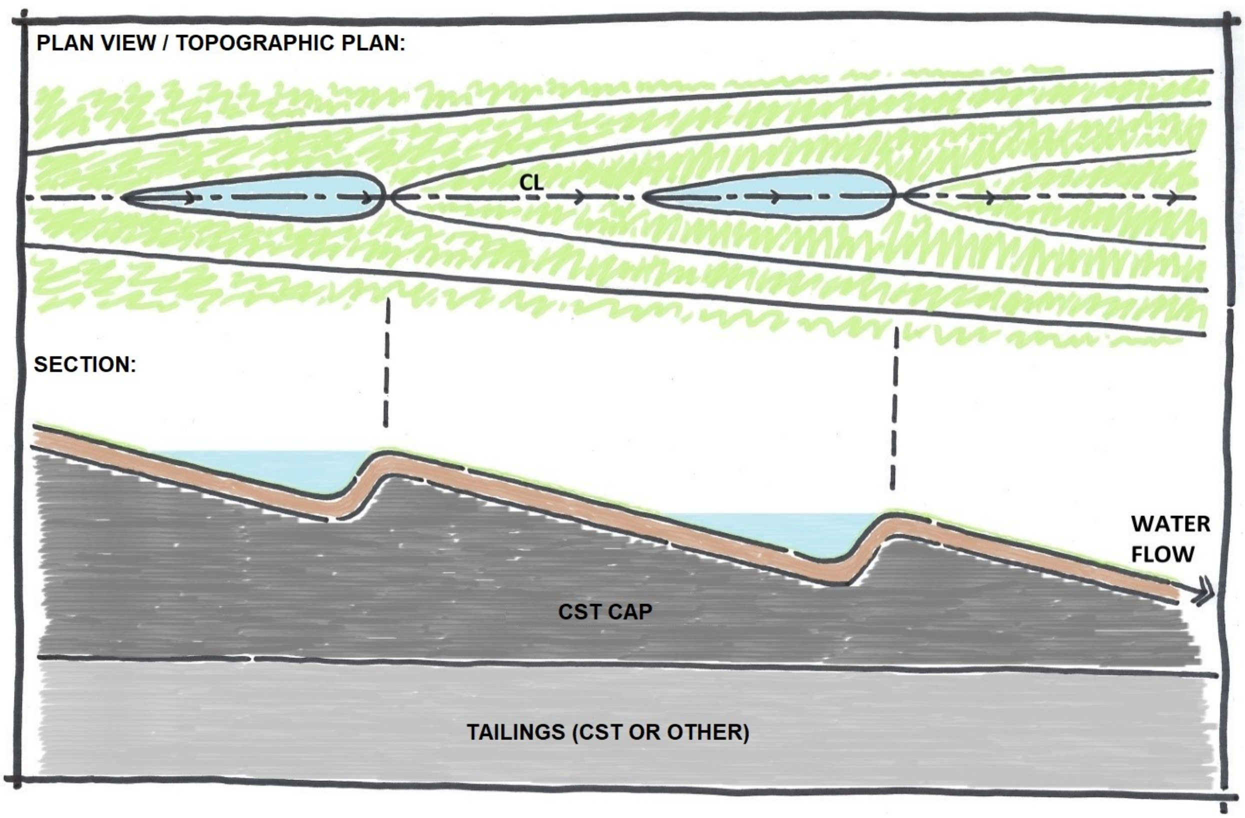

Figure 3.10 Ephemeral pools designed to slow water flow. Sketch is vertically exaggerated (in section) and has not been drawn to scale. Layer above CST is reclamation material consisting of a minimum 0.5m depth of peat mineral mix.

With respect to the overall flow over the TSF plateau, the perimeter crest of the TSF is roughly level at 340 m, resulting in steep slopes at the south end in order to direct the remaining surface water to the north outlet. Figure 3.11 illustrates how slope affects the proportion of the TSF surface which is captured and directed to the north outlet. In essence, the steeper the overall plateau slope, the less precipitation is captured and directed to the desired outlet.

All TSF and SEA designs have been completed with a contour interval of 1.0 meter. This provides sufficient detail to calculate the volume of waste accommodated while allowing some room for ease of adjustment as required. A minimum slope of 0.5% has been used for all three designs, however the channel width varies depending on their respective catchment areas.

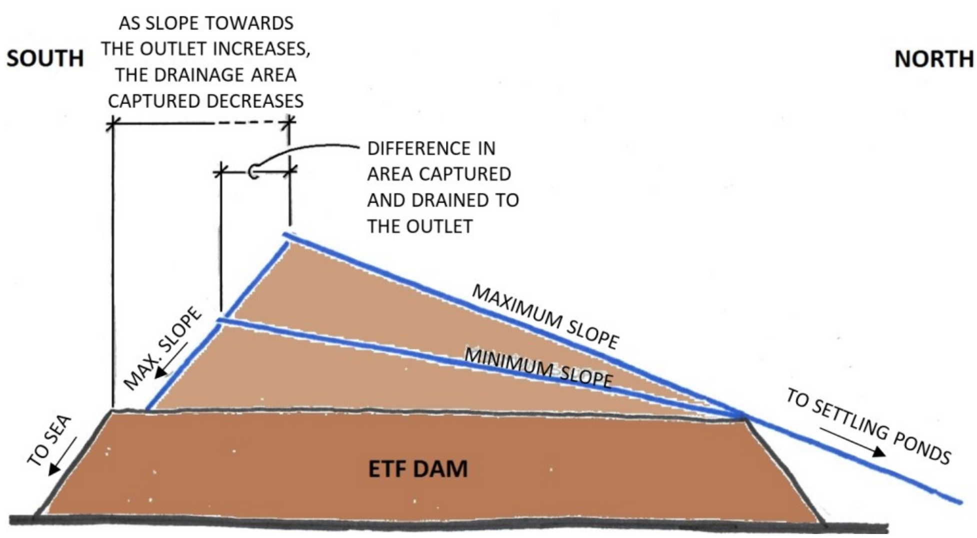

Figure 3.11 Schematic of how slope towards north outlet affects the proportion of water captured and directed to the north outlet. Not to scale.

Loading on the TT deposit and NPD has been minimized, as has the area surrounding the expected dredge location where a volume of MFT may remain. The TT and TSRU area, as previously discussed, require a minimum 4 m thick CST cap, for which placement has an eastern boundary of our 200 m offset from the downstream dyke crest. The exception to this is the area on the eastern side, between the 200 m offset and the downstream crest. This area is isolated in all designs from the catchment as a result of the 4 m cap required for TSRU and TT deposits. This cap essentially forms a ridge line at the 200 m offset on the east side, dividing the drainage to the east to flow over the dyke or to the west towards the channel and north outlet.

The maximum elevation created though additional waste storage on the TSF surface has been limited in all design options to 10 m height. This means that the maximum elevation prior to placement of reclamation soil will be 350 masl. This remains lower than the highest topographic point on site at the overburden dump (SWODA). The mounding of waste on the surface will add localized masses to the TSF; these features will need to be analyzed with respect to local and global stability.

The downstream crest of the SEA will be raised to 306 m over the next few years and will be filled to an elevation of 302 m with CST (KCB, 2015). In order to avoid negatively impacting the FOS for SEA perimeter dykes, the outlet(s) on the SEA will not cut into this 306 m level, but channels will be cross-cut to reduce slopes. The setbacks for the SEA are 250 m for landform loading and 300 m for ponding water.

3.9.3 TSF design options

Three design concepts were chosen to move forward through the next design stage: 1) a drumlin landscape, 2) undulating ridge and swale topography, and 3) a dome. The eskers and the dune landscapes were omitted due to undesirable resultant surface drainage: excessively long and straight and excessively convoluted drainage paths were the concerns, respectively. The varied topography of each of the three chosen options will produce different surface drainage patterns and different volumes of total additional waste accommodated, which is used in option evaluation.

The drumlin design was created in order to better visualize a typical glacial landscape on the TSF, and to identify ramifications of such a highly designed surface. The ridge and swale topography was seen as a median option in terms of construction effort (precision required) and volume of waste accommodated. The dome topography was designed to quantify the maximum waste holding potential of the surface as compared to the other options.

Each of these options was designed with a maximum capacity option and a medium capacity option with respect to volume of fill contained. This was achieved by using steeper slopes on the maximum capacity options (15% gradient) relative to the median capacity (10% gradient).

3.9.3.1 Option ‘A’: Drumlin landform

The drumlin option (Figure 3.12) has been designed as per the CEMA landform inventory (CEMA 2006) and the sustainable drainage limits outlined in Golder’s 2004 vegetated waterways report. The outlet has been over-designed in width to account for beaver activity, blockage, and allowing for it to be vegetated instead of armoured. The sustainable channel width in this location is 34 m based on the drainage area captured; however, it is designed here to be about 50 m wide. The drumlin field option provides a median option in terms of volumetrics (Table 3.5): a moderate amount of cut to our tailings infill and slightly less fill with waste is provided as compared to the other two options.

Benefit Summary:

- High topographic variability allows for variable moisture, vegetation, and habitat.
- Multiple channel routes provide alternatives should one become blocked.

Constraint Summary:

- Some water within 200 m offset at east and west will be left to infiltrate. The south will drain to the SEA.
- Tedious and potentially expensive to construct. Small equipment will be required.

Table 3.5 Volumetrics for Option 'A' Drumlin Field Design

Metric	**Median Option (10% slope max.)**	**Maximized Option (15% slope max.)**
Outlet elevation above 333.80 m?	Yes – outlet elevation at 333.80 meters	
Volume of waste accommodated	21,824,148 cu. m.	21,996,902 cu.m.
Tailings Volume Reduction	601,488 cu.m.	592,663 cu.m.
Total ephemeral pond volume	32,501.65 cu.m.	
Total ephemeral pond perimeter/shore	660.66 linear meters	
Drainage area within dyke crests (685 ha) captured	527 ha (includes 500 ha captured at north outlet and 27 ha captured by the SEA), or **77% of total area** between crests.	

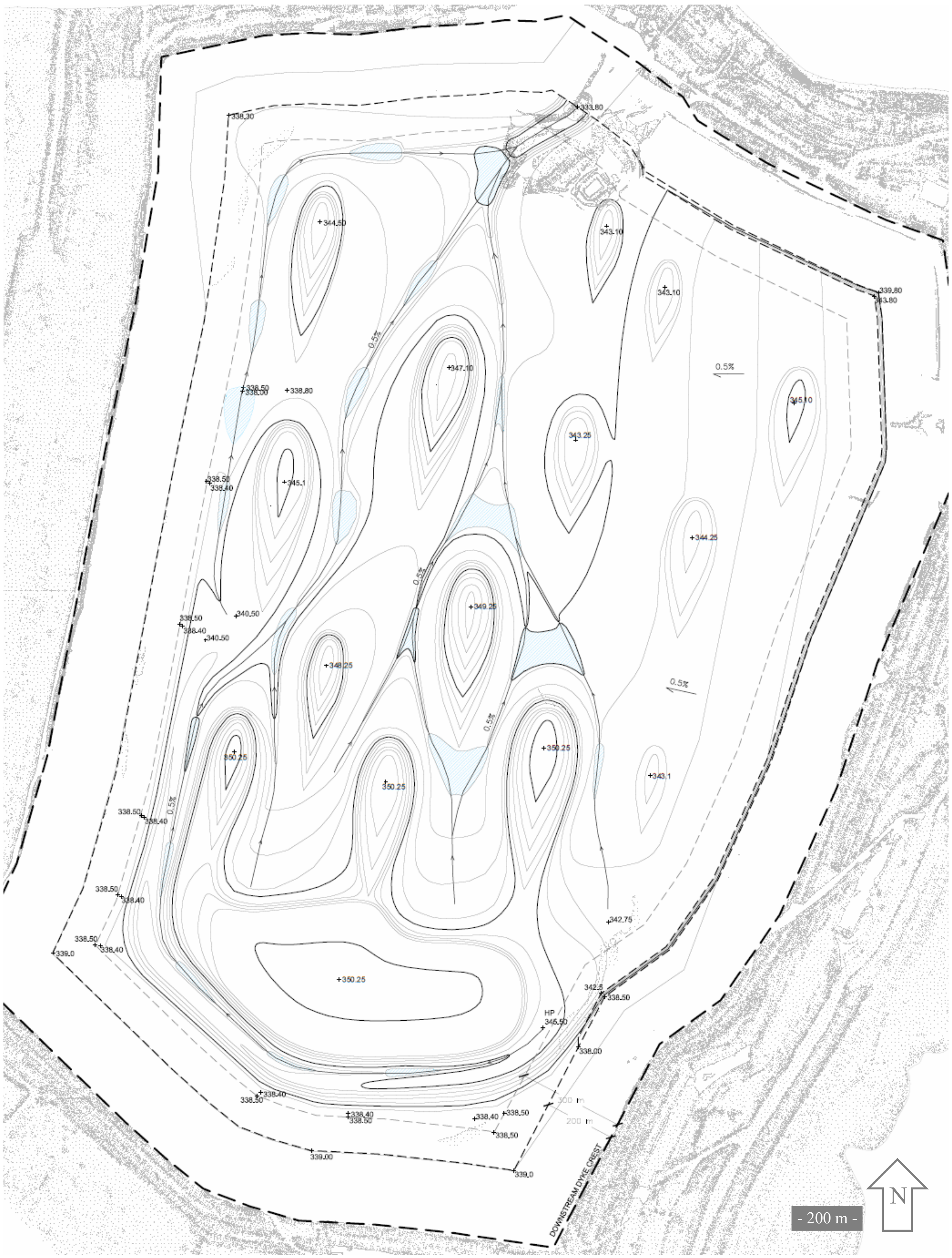

Figure 3.12 Tailings storage facility closure topographic design Option 'A': "drumlins". Volume maximization using 15% maximum slope. Drawing not to scale.

3.9.3.2 Option 'B': Hummocky ridge and swale

The hummocky ridge and swale option (Figure 3.13) has been designed as per the CEMA (2006) and meets the sustainable drainage limits outlined in Golder's 2004 vegetated waterways report. The outlet has been over-designed in width to account for beaver activity or other blockages. In theory (based on Golder 2004), the provided width should reduce flow velocity to a degree that vegetation will provide adequate erosion resistance and engineered armouring of the channel bottom will not be required. A sustainable channel width in this location is 34 m based on the drainage area captured; however, it is designed here to be about 50 m wide. The hummocky ridge & swale option provides the highest proportion of waste accommodation, and the lowest reduction in tailings infill. Volumetrics are listed in Table 3.6.

Benefit Summary:

- Moderate to high topographic variability will allow for somewhat variable vegetation, water levels, and habitat.
- Relatively easy to construct with large landform masses.
- The majority of landform grading to be completed on the more competent east side of TSF

Constraint Summary:

- Areas within the 200 m offset from downstream crest on east and west sides will be left to infiltrate or graded at 2% slope to flow over the dyke.
- Water landing on the south end of the TSF will flow to the SEA and will be captured and directed to swales there. See Appendix A for drainage basin analysis.

Table 3.6 Volumetrics for Option 'B': hummocky ridge & swale design

Metric	**Median Option (10% slope max.)**	**Maximized Option (15% slope max.)**
Outlet elevation above 333.80 meters?	Yes, elevation at 333.80 meters	
Volume of waste accommodated	28,187,983 cu.m.	28,938,990 cu.m.
Tailings Volume Reduction	232,611 cu.m.	232,630 cu.m.
Total ephemeral pond volume	19,508 cu.m.	
Total ephemeral pond perimeter/ shore	569 linear meters	
Drainage area within dyke crests (685 ha) captured	540 ha (includes 480 ha captured at north outlet and 60 ha captured by the SEA), or **79% of total area** between crests.	

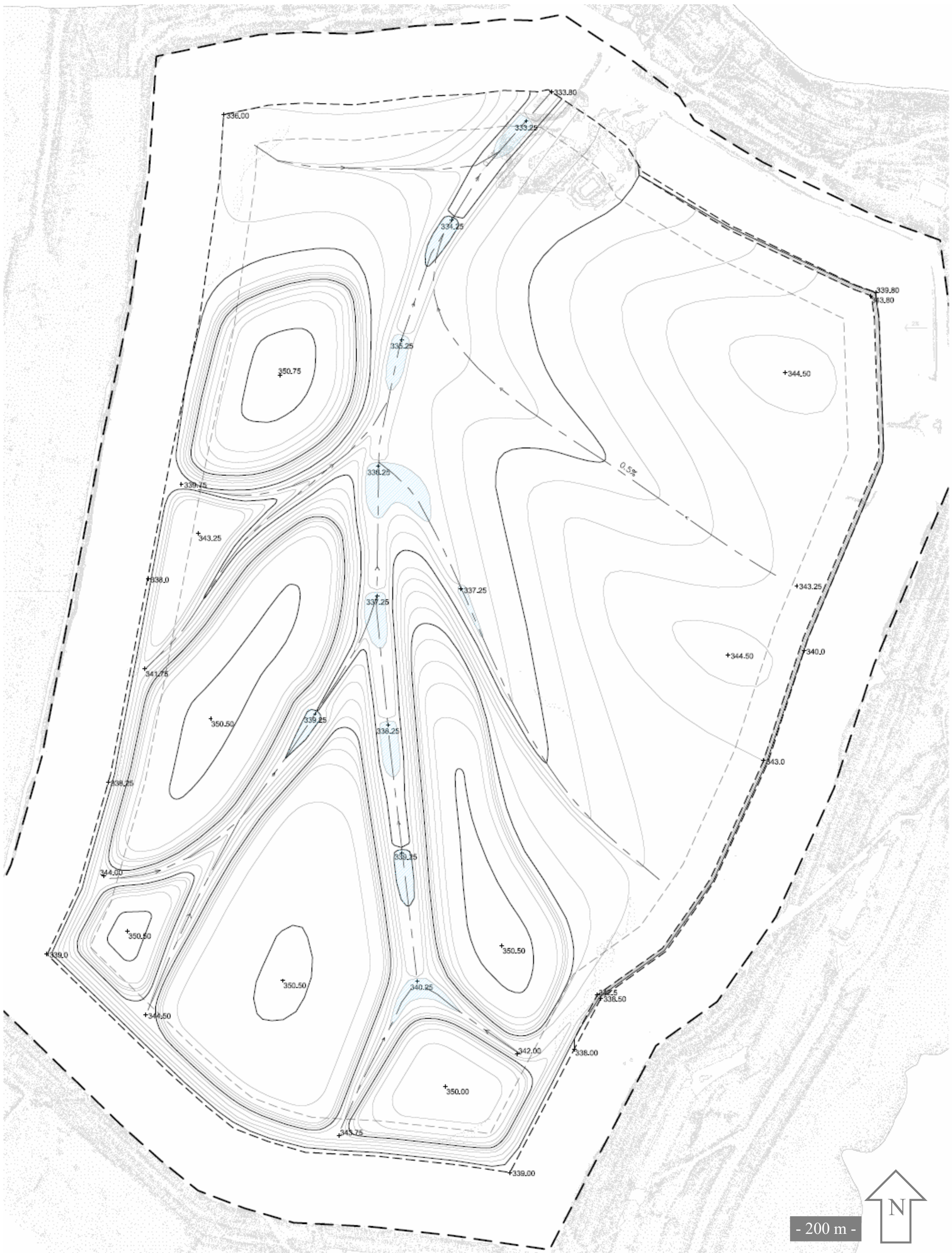

Figure 3.13 Tailings storage facility closure topographic design Option 'B': hummocky ridge and swale". Volume maximization using 15% maximum slope. D

3.9.3.3 Option 'C': Dome landform

The dome landform seen in Figure 3.14 is a simple design and would be relatively easy to construct in terms of waste placement, but quite challenging to achieve the required channel slopes at the north end. Nearly all water falling on the TSF surface within the downstream crest would be collected in a perimeter swale and directed towards the outlet. The volumetrics of this plan are listed in Table 3.7.

Benefit Summary:

- Nearly water landing on surface is collected.
- Simple design to understand in terms of knowledge transfer of design to operations team.

Constraint Summary:

- Outlet elevation and channel leading to outlet are low, cutting into CST cap and tailings deposit and making construction of slopes within tailings impossible.
- Potential AMD generation upon TSRU exposure.
- Uniform dome structure provides little topographic variability on a smaller scale for habitat or vegetation diversity.
- Structure may be prone to erosion and gully development on main structure.
- Very long channels directing water towards outlet mean a lower outlet elevation is required as compared to the other two options.

Table 3.7 Volumetrics for Option 'C': Dome design

Metric:	**Median Option (10% slope max.)**	**Maximized Option (15% slope max.)**
Outlet elevation at 333.80 meters?	No, 328 m outlet elevation.	
Volume of waste accommodated	22,445,269 cu.m.	24,230,087 cu.m.
Tailings volume reduction	5,553,722 cu.m.	5,432,287 cu.m.
Total ephemeral pond volume	15,185.50 cu.m.	
Total ephemeral pond perimeter/shore	335.50 linear meters	
Drainage area within dyke crests (685 ha) captured	630 ha, or **92% of total area** between crests. No transfer to SEA.	

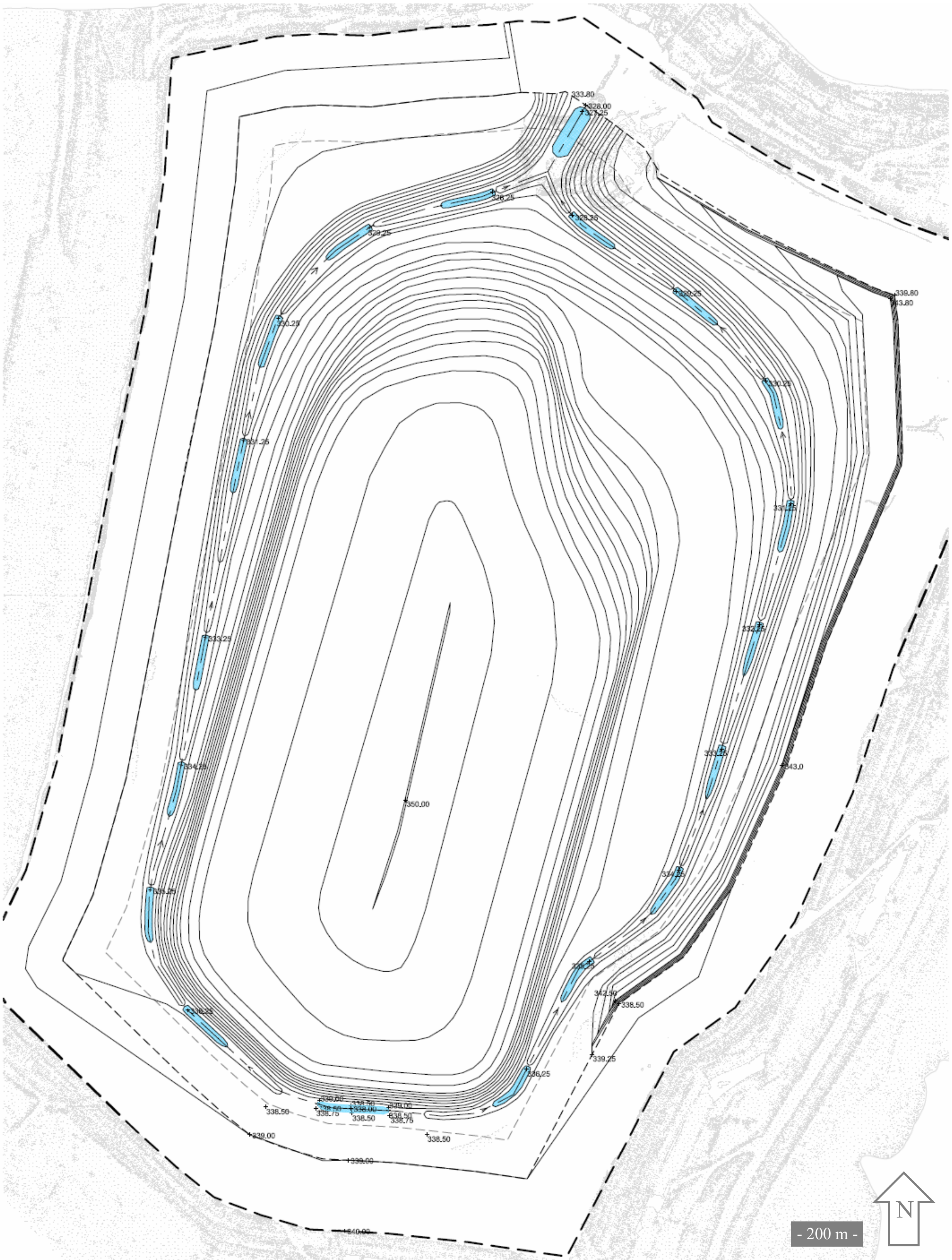

Figure 3.14 Tailings storage facility closure topographic design Option 'C': "Dome". Volume maximization using 15% maximum slope.

3.9.4 SEA design options

Three options were designed for the SEA: 1) one with 4 outlets draining towards the north (north drainage was outlined in the original mine closure drawings), 2) four outlets draining to the south, and 3) with one outlet draining to the Muskeg river as shown in the most recent closure plans (2012) at the time of this work. This drainage route could be easily adjusted to drain north or south into drainage channels for treatment prior to release off site. Four outlets were used for two of the options in order to stay in line with the roughly one drainage basin per 100 ha ratio used in the hummocky / ridge and swale option. The third option, which uses only one outlet and drainage basin, was completed because this was proposed in the 2012 ICC&R plan; working through this design allows us to evaluate its relative functionality compared to the other options.

Option One was completed to show how water collected from the surface of TSF and SEA dykes might be transported in a channel along the bottom of the dykes to the future north pit lakes area for water treatment before being released to the environment. This would be necessary in the case that water cannot be treated or captured and redirected from the south end due to spatial or other constraints.

The existing channel along the bottom of the dykes transports water to the south where it is captured in a water management pond. Option two follows the assumption that this drainage path will continue to transport water to the south, which follows the natural slope of the land and provides an opportunity for an additional permanent end pit lake or settling pond in the south.

The third option uses only one outlet on the north-eastern edge of the SEA, as was shown in Shell Energy Canada's 2012 MRM integrated Closure, Conservation & Reclamation Plan (Figure 7-1 Site Topography, on page 96) as developed by consultants CH2M Hill. This outlet drains to the Muskeg River as we have duplicated here; however, it is likely that water treatment will be necessary prior to release into the environment and as such this outlet can easily be altered to drain into the perimeter channel around the landform, regardless of the direction this channel drains to.

As shown in Table 3.8, the disadvantage of the third option is that it captures significantly less drainage area than do the other two options. Settlement of the CST infill is not expected to be substantial, but should the channel settle somewhere along its' length creating a blockage, a water body will form and this water body needs to be beyond the 300 m water-holding offset from the downstream crest. As such, the channel needs to be set back behind the 300 m offset, resulting in a large portion of the perimeter not captured.

Table 3.8 SEA landform design option assessment

Metric:	Option One	Option Two	Option Three
Outlet elevation(s) at 306 m?	Yes	Yes	Yes
Volume of waste accommodated:	17,895,370 cu.m.	17,775,828 cu.m.	17,530,458 cu.m.
Tailings volume reduction:	0 cu.m.	0 cu.m.	0 cu.m.
Drainage area captured (of the 410 ha measured using overflow from TSF Option 'B'):	278 ha, or 68%	281 ha, or 69%	137 ha, or 33%

Figure 3.15 South expansion area closure topographic design Option 'One'

Figure 3.16 South expansion area closure topographic design Option 'Two'.

Figure 3.17 South expansion area closure topographic design Option 'Three'.

3.9.5 Preferred topography

The preferred combination of designs for the TSF and SEA is the hummocky ridge and swale TSF design with SEA option two, collecting water in the south before treating and discharging off-site. This combination maximizes advantages and minimizes disadvantages considered within the scope of this project. Nearly 50 million cubic meters of additional waste storage is accommodated above the dam crests using this combination of designs. This combination is graphically shown in Figure 3.18.

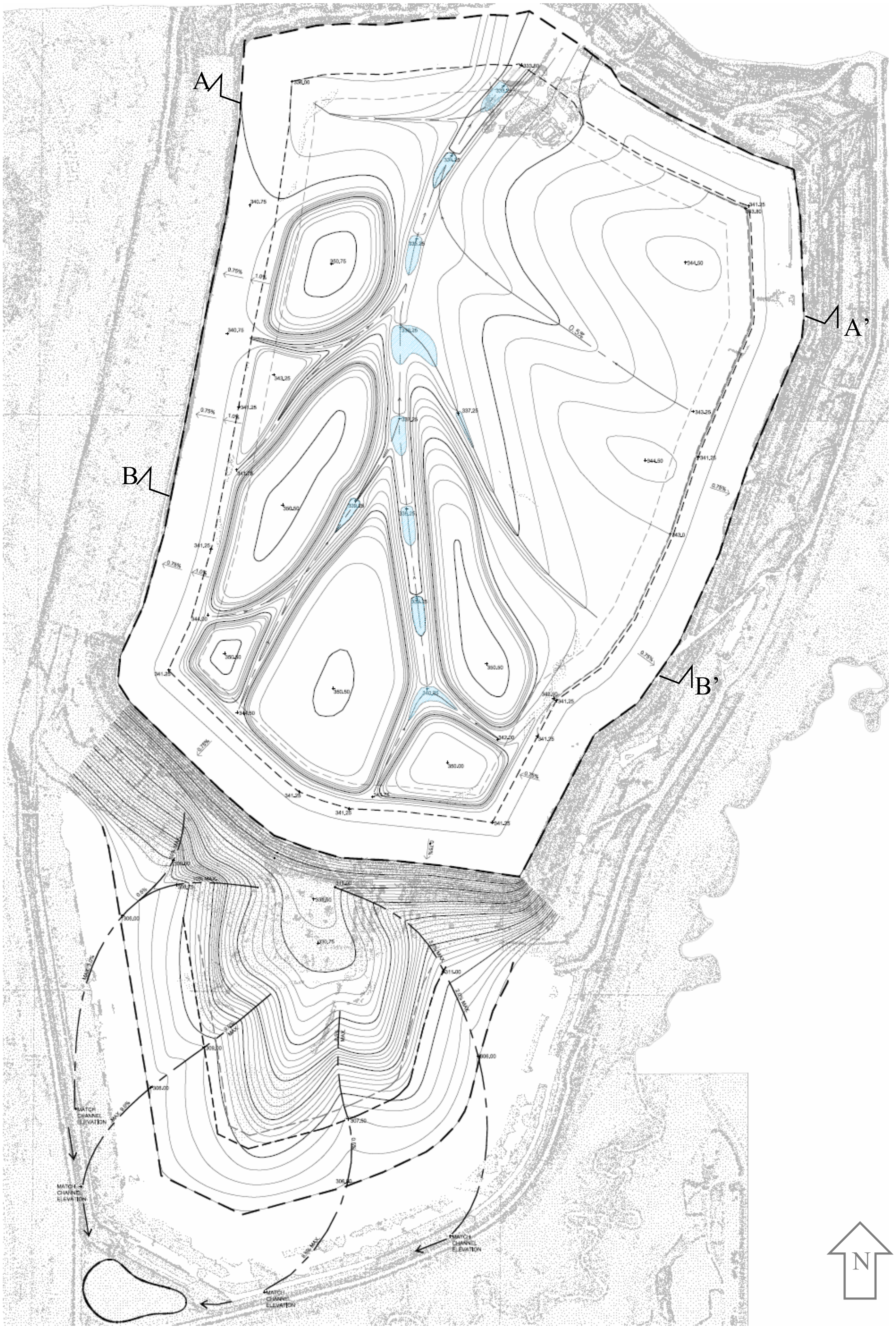

Figure 3.18 TSF and SEA preferred closure topographic and drainage design. See Figure 3.19 for indicated surficial cross sections. Drawing not to scale.

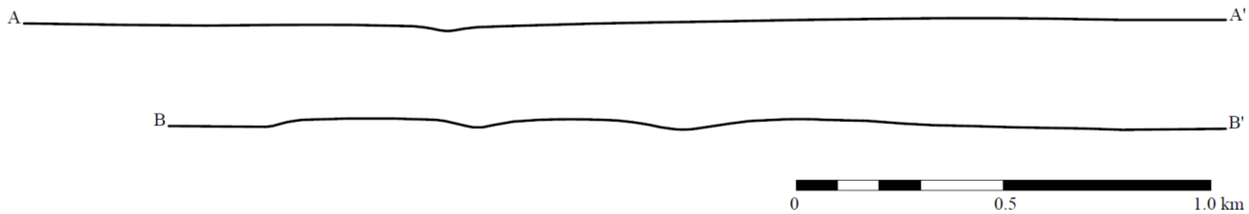

Figure 3.19 Cross sections A-A' and B-B' through geomorphically designed preferred closure topographic and drainage design (as noted in Figure 3.18). 3x vertical exaggeration.

3.10 Discussion

The geomorphic designs developed herein benefited from clarity in the opportunities and constraints associated with construction materials, site boundaries, naturally occurring and anthropogenic topography characteristics, etc. Sections 8.1 and 9.1 of the CEMA landscape design checklist (Appendix B) require that locations where additional maintenance is required be identified. The main drainage channel was designed with differential settlement in mind by locating the channel over top of areas where greatest settlement is expected (i.e. where the thickest deposits of MFT are expected to remain post-dredging); however, the dredge location at the north end of the TSF will require monitoring for an extended time frame as an area of high fines will exist here with potential for pond development over time. At the time of this work total settlement had not been estimated with certainty, but a few meters were considered possible.

Due to site constraints, the limit of work for this project extended only to the edge of the dam crest. As such, dam slopes were not re-designed or assessed as a part of the work and this is a major pitfall of the design. Natures forces recognize no boundaries, and given their composition of coarse sand tailings, it is possible that the dams will be subject to erosional changes over time.

The geomorphic design of the TSF and SEA where completed first by hand using Golder (2004) as a design basis. The natural analogue technique is best employed on natural ground since the materials are theoretically similar. Application of the natural analogue technique herein was done due to a lack of other available data and is certainly not ideal. Optimally, the natural analogue approach would find a similar material that has been subjected to thousands of years of climate to mimic; however, there are no coarse sand tailings landforms that meet these criteria, nor are there any sand landforms that are over 60 m in height. As such, a combination of vegetated channel criteria from Golder (2004) and natural landform slope characteristics from CEMA (2006) were used.

An alternative design technique is to collect design criteria from the sources used herein (as above), then enter it in a computer program such as Carlson Natural Regrade™ that uses the GeoFluv™ method to automatically generate a catchment corresponding to the inputs. Due to the many constraints associated with this tailings pond, several adjustments were necessary for functionality. For example, a concave channel flow path within the catchment is generated by GeoFluv™. While this is more in line with stable fluvial geomorphic forms, it would also have raised the topography excessively at the south end of the TSF, either reducing the area captured within the watershed, or lowering the outlet elevation beyond the minimum. Computerized methods such as this are likely to expedite closure and drainage design for overburden dumps; however, this experience has demonstrated that the constraints associated with tailings ponds require additional flexibility.

A conservative approach was taken in design by reducing channel slopes and overland flow lengths beyond that found in Golder (2004), additional testing is required prior to finalizing a geomorphic design. Geotechnical stability (local and global) models, hydrologic models integrating climate change and probable maximum precipitation events, and landscape evolution models should also be run.

3.11 Conclusions

Application of the landscape architectural design approach, including an inventory and analysis of site opportunities and constraints, has led to the development of three designs for the TSF and three for the SEA. Evaluation of those designs with respect to drainage areas, waste storage volume, and ease of construction, etc. allowed for the mine owner / operator to decide on an optimal final design combination to move forward with.

The design process requires an understanding of all contributing factors, and all factors that will be influenced by the final design. The design process is often iterative, and by its very nature as progress is made and challenges overcome, knowledge is gained. In this sense the design process is a form of research in itself. The design research conducted herein has led to the recognition of several minor adjustments in the mine planning and operation that have the potential to improve the ease, efficiency, and outcomes associated with tailings dam closure. These adjustments are documented in Chapter Four.

4.0 Design considerations for ease of closure

One of the most ubiquitous terms in mine closure literature is "design for closure". There are many definitions of this term, but the general commonality amongst these is that the site needs to be designed with the end in mind to create an ideal (and cost effective) post-mining landscape: Every decision at each stage needs to be considered in terms of its implications on the post-mining landscape design. When this is not done reclamation and closure design are made more difficult, and inadequate outcomes are more likely. The research-through-design presented in Chapter Three generated an optimal closure topography for the parent mining company to move forward with; however, it also brought to light several minor adjustments that would greatly improve the ease and outcomes of tailings pond closure if considered before and during mining. This chapter summarizes these considerations for ease of closure, particularly with respect to sand dams, and was published as an article in CIM Journal (see reference below). The preprint is provided herein.

Slingerland, N., Beier, N.A., Wilson, G.W. (2019). Oil sands tailings dams: Design considerations for ease of closure, *CIM Journal*, vol. 10(2). Pp.65-76. https://doi.org/10.15834/cimj.2019.7

4.1 Introduction

The Athabasca oil sands (AOS) underlie 140,200 km^2 of land in northeastern Alberta, Canada. Oil sands located within 100 m of the original ground surface cover 4,800 km^2 of this area and are considered to be economically mineable (Figure 4.1) (ERCB 2009). Bitumen, the thick tar-like substance contained in the AOS is extracted through open-pit mining and in-situ methods. For ore mining to take place the overburden is first removed as waste, and the sandy bituminous ore is transported to processing facilities via 400-tonne trucks and conveyor belts. Warm and hot water as well as process aides such as caustic are mixed with the oil sand, creating a slurry from which bitumen is mobilized and extracted. The resulting slurry waste product is called 'tailings' and contains mineral solids, process water, and small proportions of unrecovered bitumen (Masliyah, Zhou, Xu, Czarnecki, & Hamza, 2004; Sobkowicz & Morgenstern, 2009).

Figure 4.1 Location of the mineable area of the Athabasca oil sands within Alberta and North America. Image adapted from the Government of Alberta.

Aboveground tailings ponds are used to store fluid mine waste (tailings) until there is enough space in-pit to partition the pit with dykes and begin backfilling with tailings. This corresponds to the first 8–15 years of tailings production held aboveground. Predominantly flat terrain dictates that aboveground tailings ponds in the AOS typically consist of ring dykes filled with tailings. Together, the central pond storage and the ring dyke, or dam, are referred to as a tailings storage facility (TSF). There are more than 20 of these aboveground TSFs built and proposed in northern Alberta, which will eventually need to be decommissioned, or "closed", and re-integrated into the post-mining landscape (OSTDC, 2014). At present, conversion of tailings ponds into a solid landform is thought to be the most viable method of ensuring the safety, stability, and eventual delicensing of these structures (CDA, 2014).

Oil sands mines cover vast areas of land but are relatively shallow, and their associated tailings ponds are no different: tailings ponds range between 60 and 100 m in height at their maximum, and each spans hundreds to thousands of hectares in area. These tailings dams are typically constructed with a starter dyke of lean oil sands or overburden, followed by placement of coarse sand tailings (CST) using upstream hydraulic construction. A modified centerline construction is also sometimes used, as are toe berms, depending on substrate characteristics and space availability (McRoberts, 2008).

Other aboveground structures include overburden dumps, roads, reclamation stockpiles, and water storage areas; however, many of these are temporary. Overburden dumps and tailings dams are among the first structures to be built and are traditionally the only aboveground structures to remain in perpetuity after mining ceases. Overburden material has low erosion susceptibility, minimal consolidation following compaction, and it is generally more stable than the tailings sand that dams are often composed of: the challenges in designing overburden dumps for closure are respectively fewer than for that of aboveground TSFs (Tongway & Ludwig, 2011). Correspondingly, this work focuses on aboveground tailings dams constructed of tailings sand, also known as "sand dams", their central pond, and how each may be designed and constructed such that the transition to one closure landform may be achieved with greater ease.

Tailings dams are designed by geotechnical engineers with their operational lifespan in mind: induced pore pressures arising from dam construction and tailings deposition as well as other variables can make tailings dams both complex and sensitive structures to manage (Morgenstern, Fair, & McRoberts, 1988). While designing for stability and optimal functionality throughout the operational life is imperative, a shift in the relative importance of forces acting and corresponding failure mechanisms occurs post-closure. Forces that are of little concern through the active dam stage eventually dictate the stability and functionality of these structures once they transition from a dam into a landform. These dominant post-closure forces act on the landforms in perpetuity as opposed to a set time period, making them as important as those acting throughout operation; as such, they too require consideration when these dams are being initially designed.

The forces acting on these finished landforms are the same ones that act on naturally occurring landscapes: wind and water in conjunction with gravity, seismicity, burrowing and damming of waterways by fauna, and the rooting and uprooting of vegetation. Vegetation, particularly mixed vegetation with variable rooting depths, typically decreases the effect of erosion on landscape; however, when trees are blown over or burrowing occurs, bare soil will be exposed which increases the susceptibility and vulnerability of these structures to wind and water. The difference lies in the ability of natural versus man-made landforms to resist or adapt to applied forces: natural landforms have been shaped by and developed over time with the forces generated by nature, whereas anthropogenic landforms are comparatively pristine, having been tended to constantly, making them more vulnerable as a result. Designs for long-term stabilization and functionality must respond to these forces not only in terms of discrete (acute) events, but for long-term (chronic) exposure since a landform returned to the Crown under current policies shall be self-sustaining, requiring no ongoing maintenance in excess of that required for naturally occurring analogues in the region (AESRD, 2013; OSTDC, 2014).

The decisions outlined herein are discussed with the desire to make transitioning a tailings pond to a landform more streamlined. In some cases the considerations herein may also improve the safety of the facility by ensuring stability or environmental challenges do not arise late in the facility's active life or persist into the future. Long-term liability is commonplace in today's mining industry as a result of mining operations that did not consider the future during planning, design, and operations (Sawatsky, McKenna, Keys, & Long, 2000). Due to the large scale of oil sands mines and the global publicity directed to this region, it is in the interest of all stakeholders that closure and post-closure periods be considered early in the mine life.

The transition from tailings dam to solid landform can be a complicated and costly process, including massive earth movement and re-grading that can be additionally complicated by mine plans, tailings placement, and/or site layout that are not optimized to support closure. The ease and efficiency of this land conversion process (outlined in Figure 4.2) can be improved if the final landform design is taken into consideration during the initial and subsequent dam design phases.

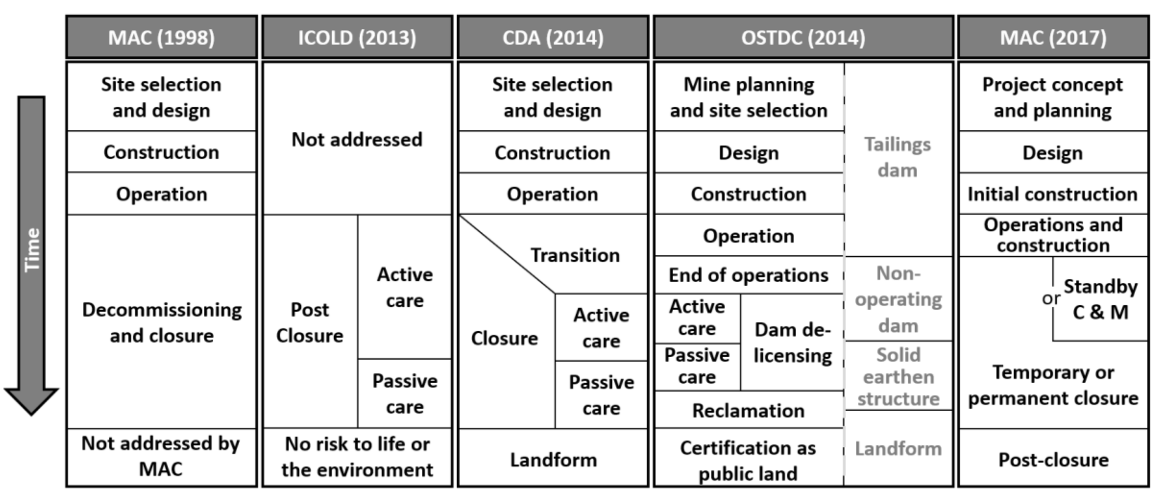

Figure 4.2 Progression of industry "life of mine" and TSF standards through time, as compared to the current approach proposed for oil sands delicensing by OSTDC (2014). Note "Standby C & M" refers to "Standby care and maintenance". Adapted from OSTDC (2014).

Not all oil sands mines have had an opportunity to undertake a rigorous design process for the reclamation of their above grade tailings ponds with the goal of eventual delicensing. Of those that have gone through this process, little has been published with respect to the challenges or lessons learned. The goal of this article is to document and share our tailings dam closure and landform design experiences with industry to date, so that others can improve their end products and their efficiency in design and construction.

4.2 Tailings impoundment characteristics

Mines in the AOS are some of the largest in area in the world, as are the tailings impoundments which hold the large quantities of liquid waste generated from mining. Due to the grand scale of these dams and the abundance of mine waste, tailings dykes and dams are constructed using the waste products of mining (McRoberts, 2008; Sobkowicz & Morgenstern, 2009; Hyndman & Sobkowicz, 2010). Starter dykes are regularly constructed with overburden or interburden, but each lift thereafter is usually CST. A fraction of the coarse sand from mine tailings are separated from the overall tailings mixture then hydraulically deposited and compacted typically using upstream construction; although, modified centerline alignment is employed for some dams. These configurations are shown in Figure 4.3. Downstream slopes range from 25H:1V to 2.5H:1V, depending on foundation conditions. Horizontal berms are used for access and instrumentation, but also have the effect of reducing overall slope steepness, as seen at Suncor's Tar Island dyke where slopes were reduced to 3H:1V overall with berms (Anderson, Wells, & Cox, 2010).

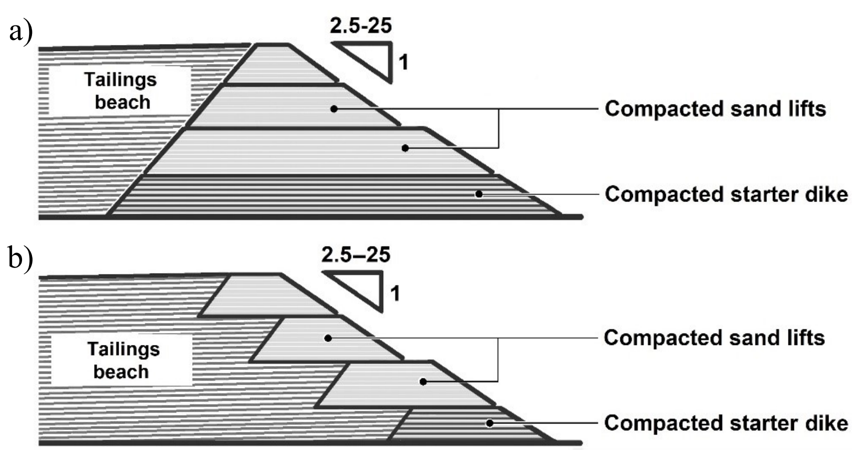

Figure 4.3 a) Common modified centerline and b) upstream tailings dam construction used in the Athabasca Oil Sands. Starter dykes are often constructed of lean oil sands, while each layer above is typically hydraulically placed, then mechanically compacted coarse sand tailings. Both sketches are vertically exaggerated and not to scale.

Due to their liquid nature, the tailings not used in dyke construction are also transported hydraulically and placed behind the dyke. Hydraulic deposition creates perimeter beaches as the pipe is moved around the structure allowing coarse fractions to settle out first, or segregate, and a central pool comprised of process-affected water and suspended fine solids.

These ring-dyke structures hold a range of fluid-like tailings materials generated from the processing of oil sands, as different methods of dewatering and strength gain have been utilized over the years (Sobkowicz & Morgenstern, 2009). Correspondingly, the properties of tailings vary both laterally and with depth depending on the location and time they were deposited (Guo & Wells, 2010). Tailings properties include hydraulic conductivities from 10^{-9} to 10^{-3} cm/s, particle distributions of less than 1 to 0.0001 mm, and void ratios of less than 1 to in excess of 10 (Sobkowicz & Morgenstern, 2009; Beier, 2015; McKenna et al. 2010). These fluid-like tailings are prone to high settlements over extended time frames (hundreds of years in some cases) and pose a challenge in converting the dams (and their contents) into solid landforms (Anderson et al., 2010). In order to optimize this process, tailings that are easily dewatered, or dry-stacked where appropriate, are more desirable. Several different approaches to tailings dewatering and consolidation are currently being used operationally with new methods undergoing trials at research facilities and mine sites in Alberta (Sobkowicz, 2012a).

In the meantime, large-scale trials have also taken place to test various methods of pond conversion into solid forms. The approach used at Suncor's Pond One, and planned for other facilities, was to relocate the pumpable fluid fine tailings (FFT) and mature fine tailings (MFT) (see Sobkowicz 2012a for various tailings types and definitions used herein) to a more suitable area, while simultaneously infilling the tailings pond with CST that readily dewater over a comparatively expedited timeframe (Anderson et al., 2010). Dredging and infilling dramatically alters the properties of the tailings containment facility due to the change in held tailings. While a lens of high-solids content (non-pumpable) MFT still remains across the bottom and sides, the central areas that would have experienced the most volume change over time are largely removed, as shown in Figure 4.4.

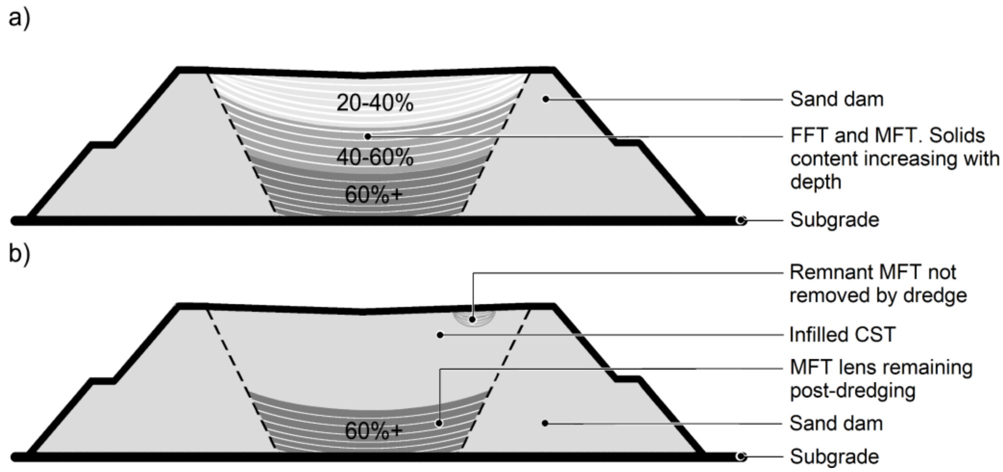

Figure 4.4 Schematic oil sands tailings dam composition a) after tailings deposition ceases and b) the same tailings dam after the pumpable portion of MFT is removed and infilled with coarse sand tailings

Due to functional limitations a small proportion of soft tailings will remain at the dredge site, meaning that this area is likely to experience surface settlement over time, or require in-situ consolidation techniques. Dredging from a location near the final outlet results in more optimally located settlement, should future maintenance be required. Additionally, initiating infilling farthest from the outlet and progressing towards the outlet efficiently pushes mobile MFT towards the dredge so it can be removed.

At Suncor's Pond 5, MFT underlain by a MFT/CST mixture, referred to as consolidated tailings, has been capped with high strength, seamed geotextile (with biaxial geogrid) then overlaid by thick layer of coke (Pollock, Liu, McRoberts, Williams, Wells, & Fournier, 2010; Wells, Caldwell, & Fournier, 2011). Coke is a product of bitumen upgrading which is slightly lower in bulk density than the tailings being capped allowing it to remain afloat (Wells et al., 2011). Wick drains were installed to help remove water from the tailings core, after which the pond will be covered with CST, a layer of reclamation material and vegetation. This has been an expensive process; monitoring and research are ongoing to evaluate the system's efficacy. Other considerations with respect to earthworks construction on aboveground tailings facilities include loading restrictions on upper beaches near dykes and maintaining sufficiently low pore pressures in the dykes such that failure is not initiated.

Frequent site features include buried or above grade utilities that are often located along the sides of tailings ponds to provide electricity for required pumps and other equipment, and culverts used to collect and convey water from perimeter ditches. Tailings impoundments may also be located near or adjacent to vegetated buffers where protected waterways or sensitive ecosystems exist, or adjacent to lease boundaries. These spatial confines pose a challenge to landform conversion where insufficient area has been reserved for closure works. This will be discussed more in the following section.

4.3 Specific challenges and design methods

When faced with the task of designing the conversion of a tailings pond into a stable landform, one is presented with the remnants of design decisions that have accumulated over the pond's active life span. These design decisions were reasonable in the context of the pond's active life, or a portion thereof, but may later impede its conversion into a landform or negatively affect performance of the final landscape.

Site selection and tailings placement arguably have the largest impacts on the final landform. The following section discusses how these factors impact the conversion of a tailings pond into a solid landform, and provides planning considerations that improve the efficiency of conversion.

4.3.1 Site selection

In the AOS, site selection of aboveground tailings impoundments is dictated by resource distribution across the mine lease. Mine planners are required to locate these structures where the lowest quantity and/or quality of bitumen exists in the substrate, such that the maximum amount of bitumen possible is mined from the lease (Government of Alberta, 2000; Sobkowicz, 2012b). Unfortunately these "low grade" areas often correspond with those having weak foundations and thick overburden.

From a geotechnical perspective, foundation conditions, geology, surficial aquifers, and availability of construction material from the mine guide the tailings dam design process. The area enclosed by the ring dyke is determined by the rate of tailings production, maximum allowable height, and total volume of tailings to be accommodated. Spatial requirements for perimeter ditches, roads, utility corridors, and related infrastructure dictate the offset used to position the impoundment from other site features (e.g., lease boundaries). Above particularly weak foundations, additional offsets may be included for future toe berms, should they become necessary.

Tailings impoundment site selection is theoretically a straightforward task. Site selection for a permanent landform on an active mine lease includes a number of additional factors, including space for geomorphically stable dyke slopes, adequate space and exposure for outlet(s) to effectively drain the landform plateau, and absence of long-term threats to the structure (for example, meandering streams which could cause dyke toe erosion). Geotechnical and hydrologic modelling, including accommodation of the design storm which could range up to probable maximum precipitation, is necessary to confirm designs throughout: this is an iterative process. Experience plays a role in design, particularly in accommodating and managing inevitable degradation due to ecological factors (DeJong, Tibbett, & Fourie, 2015).

4.3.1.1 Spatial requirements for ring dykes

Spatial considerations at closure are greater than during active operation. Steep downstream dyke slopes may be geotechnically stable during operation, but may not be resistant to erosion over longer time frames. Since lowering the crest would expose the interior, slope angles are best reduced by elongating the toe and regrading. By constructing the shallower of the two slopes (geotechnically versus geomorphically stable) the need to regrade at closure is reduced and sufficient space to achieve both geotechnical and geomorphic objectives is ensured at the outset of construction. Naturally occurring slope characteristics are listed for various soil types in Table 4.1 for reference. The most similar soil type (in Table 4.1) to CST is that of sand, measured from northern Alberta sand dunes.

Table 4.1 Naturally occurring stable landform dimensions (dominant ranges) by soil type in the AOS region. From CEMA (2006)

Slope characteristic	**Sand and gravel**	**Uncompacted glacial till**	**Compact glacial till**	**Sand**
Height (m)	10-20; 40-50	2-5; 20-25	15-20	5-10; 20-25
Slope Length (m)	100-150; 200-250	50-100; 200-250	150-200	100-150; 200-250
Slope Gradient (%)	9-15%; 15-30%	2-5%; 9-15%	9-15%	9-15%

With reduced slope angles comes increased watershed area and drainage path length, which can increase overland flow velocity and erodibility on a uniform slope. This can be counteracted by grading the slope into a mature “S” curve, or “catena” profile. Downstream slopes that are designed with an elongated ‘S’ curve profile (Figure 4.5) should be a part of the initial dyke design, as exemplified in the east toe berm at Syncrude's Mildred Lake site (List, Martens, & Meyer, 1999). Increased topographic heterogeneity also improves habitat opportunities and reduces long-term maintenance costs (Nicolau, 2003; Hancock, Lock, & Willgoose, 2003).

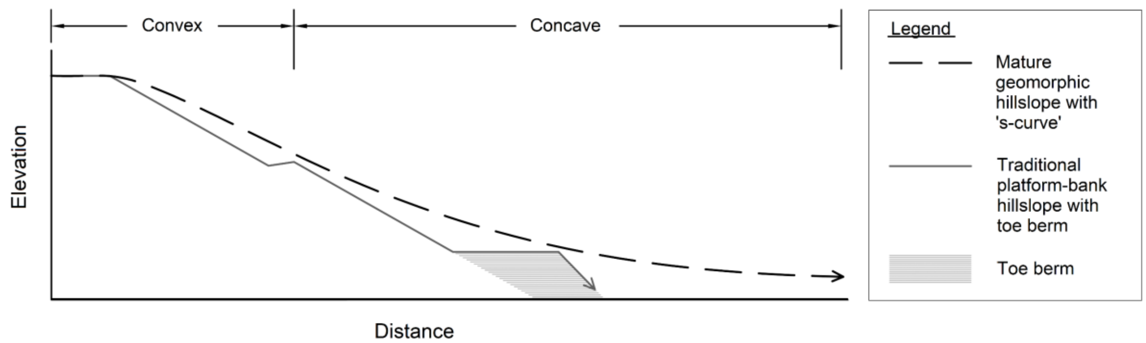

Figure 4.5 Traditional platform-bank and geomorphic S-curve post-mining slopes. In the platform-bank approach uniform slopes are broken up with oppositely sloped banks, or "benches". Uniform slopes naturally evolve into concave slopes over long time periods, suggesting this form is more sustainable post-closure than platform-bank geometry. Not to scale. Dimensions and slopes will vary.

In addition to their immaturity, uniform slopes contribute to the development of rills and gullies during precipitation events (Toy & Hadley, 1987). Uniform slopes are intended to disperse the energy that water generates through sheet flow; in reality, water accumulates in low points and focused drainage patterns develop. In doing so they erode the surface and expose underlying materials. On large landforms, such as capped or infilled tailings ponds, this can lead to significant down-cutting into covered deposits and subsequent deposition of material in drainage courses downstream.

4.3.1.2 Spatial requirements for drainage outlet(s)

In the center of the ring dyke, a plateau is created from infilling. Due to the low topographic relief of surrounding areas, these high plateaus typically form their own watersheds collecting only the precipitation that falls directly on them. As precipitation lands on the surface, the high permeability of the coarse sand used in construction will encourage infiltration to the point at which the rate of precipitation (rain or snow melt) is exactly equal to that which can be absorbed (Green & Ampt, 1911). When this infiltration potential is exceeded, runoff is generated. These large tailings landforms are designed to capture and convey water from their central plateaus to lower elevations in a controlled yet flexible manner such that various storm events are accommodated. The spatial challenge in doing so lies in the low slopes required to maintain low water energy during large storm events combined with the high height of the tailings impoundment surface relative to surrounding ground.

The structure required to convey surface water from the top plateau of the impoundment to the bottom is called an outlet. Optimally, there is more than one of these per landform, depending on the layout, site constraints, regional hydrology, mine layout, etc. Regardless of form, all outlets consume large areas. For example, the outlet for a 60 m tall tailings impoundment at a 1% slope would have a minimum length of 6,000 m. Sustainable limits for vegetated waterways with catchment /drainage areas greater than 200 ha in the oil sands region have less than a 1% channel slope; alluvial channels may have steeper slopes and therefore be tempting, albeit expensive (Golder Associates Ltd., 2004). Achieving the correct drainage density for the surficial material and climate are paramount. Similarly, outlets need to be sized according to the amount of water they are expected to convey, so width may be substantial. Incorporating lateral curves into the channel layout increases the flow path length and therefore reduces flow path slope; however, this will also increase the required outlet width.

With such large spatial requirements for these delicate structures, it makes sense that they be accounted for both in terms of size and location with reference to the impoundment as well as the broader mine site at the outset of tailings impoundment and site design (Zhang, Hassani, Zeng, Geng, & Bai, 2011). These are intricate structures that cannot be adequately designed and built for longevity once the TSF is at the end of its active life.

4.3.1.3 Locating drainage outlet(s)

The location of the outlet should be well-connected within the broader site context: Water being carried off of the impoundment may need to be held in settling pools or undergo treatment prior to being re-introduced to the natural environment. As such, the bottom of the outlet should be in close proximity to these facilities or should have sufficient space to hold these facilities in the future. As time passes, the elevation change between aboveground tailings impoundments and settling ponds is expected to allow these water bodies to persist and evolve with nature (Devito, Mendoza, & Qualizza, 2012).

Once a landform is constructed, its central drainage must be constant and unimpeded for optimal performance. Outlets should only be constructed on land which is not to be disturbed in the future, or managed in such a way that ensures ongoing drainage. Coordination with mine planners is necessary to ensure that mining, pipelines, or other activities and/or uses are not planned within the future outlet location.

Outlets should be located in consideration of surrounding site features, but also the shape of the impoundment and resultant grading implications. For example, placing an outlet on one end of an elongated impoundment can lead to significant infilling (and loading) to achieve minimum plateau slopes, such that surface water from one end is directed towards the outlet at the opposite end. In this scenario multiple outlets are optimal, though often cost prohibitive. Various simplified tailings impoundment shapes are shown in Figure 4.6 with potential drainage options. Small drainage swales are ideally used to collect precipitation landing on perimeter dykes and to avoid sheet flow generation.

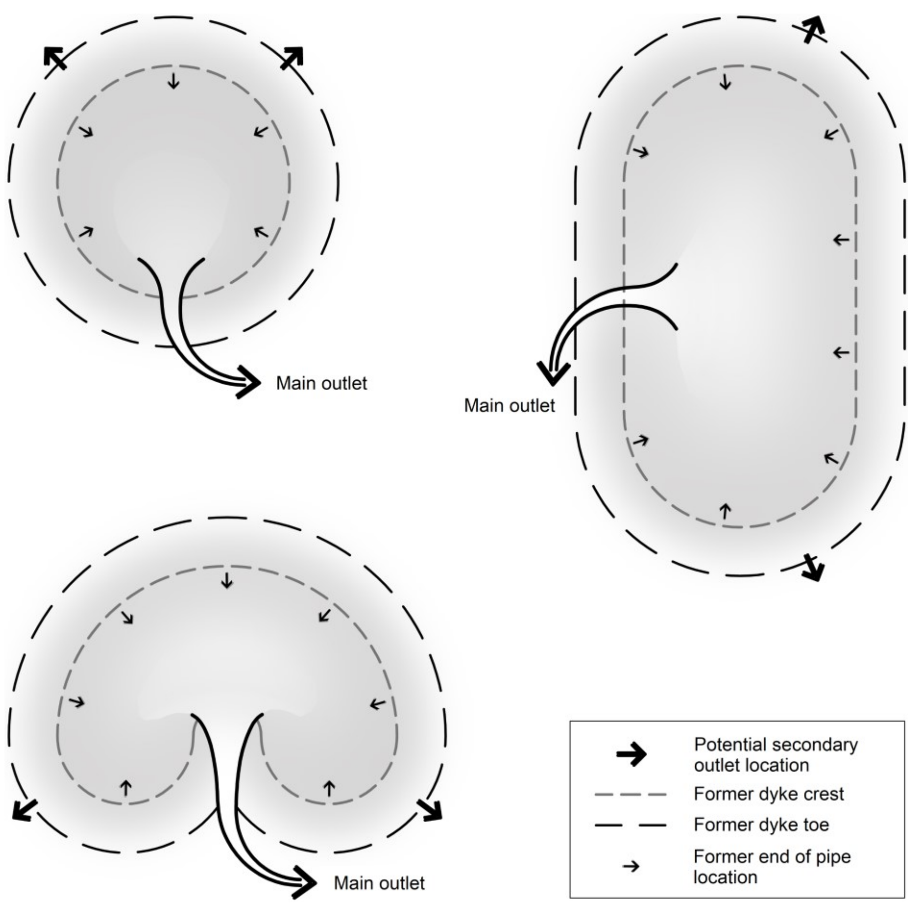

Figure 4.6 Simplified fictional arrangements of tailings landforms and respective outlet options

4.3.2 Tailings pond contents

In addition to the perimeter dyke material and design, the tailings material contained behind the tailings impoundment also has long-term ramifications to future landform performance. The interior of a tailings impoundment impacts the surface through seepage water chemistry and surface settlement, and the location of infilling pipes dictate the distribution of materials and associated properties.

Processing facilities have experimented throughout time with a range of chemical and mechanical methods of dewatering tailings and expediting the tailings' shear strength. Tailings goals have changed over time with various directives from regulators, so it is fitting that the methods of tailings production and treatment have changed accordingly. Consequently, many different types of tailings have been produced over time and have been deposited in aboveground tailings impoundments.

4.3.2.1 Fluid fine tailings placement

Different tailings types can be more or less favourable for reclamation. For example, some tailings generate beaches with high fines capture, reducing the volume of fluid fine tailings to manage; others may create long-term physical stability challenges or may be chemically reactive under certain conditions (Esposito & Nik, 2012). Mine planners and tailings engineers make several decisions when depositing various tailings behind the impoundment: one of these is whether to place tailings streams in separate locations to reduce interaction between materials (Vick, 1990). The impact of this method on the end landscape is that the surface will be a mosaic: potentially reactive, or acid generating, tailings will need thicker caps while dispersed tailings with expected high settlement over time will eventually lead to a much lower surface than adjacent deposits. The final surface generated can thus be compared to a tailings mosaic or quilt, necessitating different treatments and cover specifications.

The alternative to this first approach is to deposit all tailings, regardless of treatment method, final composition, or behavior, via the same pipe(s) and at the same location(s). This second method results in a mixing of properties and layers, for better or worse. Prediction and modelling of tailings properties post-deposition is nearly impossible when this method is used, but surficial impacts are likely to be more uniform than in the first approach. These considerations are of most importance when capping similar to Pond 5 is planned.

4.3.2.2 Tailings and pore water chemistry

While all oil sand tailings have elevated salt and naphthenic acid (NA) concentrations in their pore fluid, some are also chemically reactive under specific circumstances (MacKinnon & Boerger, 1986; Schramm, Stasiuk, & MacKinnon, 2000; Gosselin et al., 2010; Kuznetsov, Kuznetsova, Foght, & Siddique, 2015). High concentrations of salts can be corrosive, inhibit vegetation growth, and NAs can be acutely toxic to aquatic life: adequate dilution and NA degradation of this pore fluid is necessary prior to re-introduction to the surrounding environment (Allen, 2008; Gosselin et al., 2010; Kessler et al., 2010). It is expected that the pore fluid held in these tailings impoundments will take long timeframes to be fully flushed through the structure, over which time water quality monitoring and management will be necessary (Scott, MacKinnon, & Fedorak, 2005).

Potentially acid generating (PAG) tailings are chemically reactive and have the potential to cause heavy metal toxicity in the environment through acid rock drainage. Froth treatment tailings (known to be acid generating due to high pyrite and low carbonate content), comprise a minority in the AOS, yet need to be treated with care (Oil Sands Magazine, 2016). When possible, PAG tailings should be sub-aqueously deposited near the base of each tailings cell to ensure that it remains saturated, therefore inhibiting oxidation (Kuznetsov et al., 2015). As the dyke crest is approached, the tailings stream being deposited can be switched to a non-acid generating (NAG) stream.

When burial of PAG tailings beneath NAG tailings is not possible, depositing PAG tailings sub-aqueously and farthest from the outlets is preferable to inhibit oxidation and to ensure maximum cover depth overtop post-closure. To achieve positive drainage towards the outlet(s), tailings are poured down towards the outlet from opposite sides, so the farthest location from an outlet will also have the highest surface elevation and corresponding cover thickness (illustrated in Figure 4.7). The beach created via hydraulic pumping and deposition of tailings is similar to a naturally generated beach in that it slopes towards the water. Tailings beach slopes range from 0.2 to 2% and are sufficient for water to drain by overland flow.

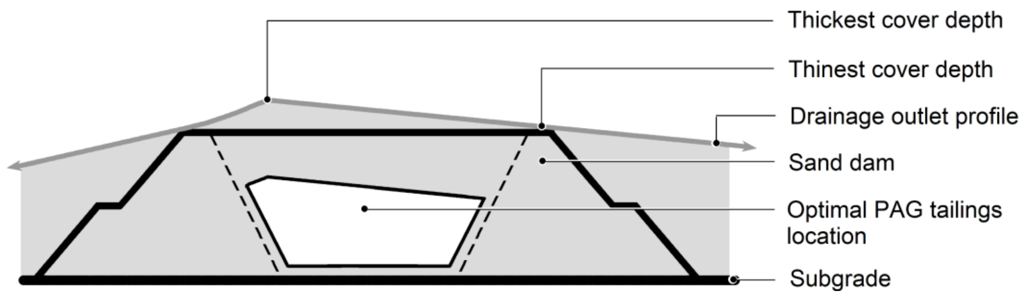

Figure 4.7 Distance from outlet and corresponding cover thickness. Cover increases in thickness with increasing distance from outlet. Potentially acid generating (PAG) tailings are placed here according to cover thickness.

4.3.2.3 End of pipe location

When tailings come out of the end of pipe, sands drop out of suspension first creating a beach, while fines and pore fluid move farther away. MFT is very soft and can take extended time frames to consolidate and for solids to settle. This consolidation process corresponds to a reduction in volume as pore water is released, which translates to settling at the surface of the landform at closure. It is most desirable to have this post-closure surface settlement away from dykes so that pools of water do not develop, introducing additional failure modes. Depositing tailings from opposite sides of the perimeter dyke (with the exception of the outlet location) forces the maximum depth of MFT to be roughly in the middle. Even after dredging, this central region will theoretically have the thickest depth of MFT. When designing the closure surface topography, the projection of this central region on the surface can then act as the central drainage pathway; this ensures that over time as this pathway settles, surface water is still being directed and conveyed along it towards the outlet. Additional tailings deposition methods and corresponding influences over the closure process and final landscape are outlined in ICOLD (2013).

In these respects, the mine and/or tailings planner designs with the settlement of material in mind: this is a major constraint in the conversion of tailings impoundments to solid landforms, requiring detailed modelling and experimentation to estimate the length of time before stabilization occurs. As long as above-grade tailings are liquefiable with potential to escape from the dykes, the landform remains a potential hazard and delicensing is unlikely (OSTDC, 2014).

4.4 Implications

Landforms are the result of regional natural history, and as such they must be flexible enough to respond to changes in their surrounding environment. The design of flexible structures begins with an evaluation of those that are naturally occurring and in equilibrium; however, this kind of forethought is a relatively new way of approaching geotechnical engineering design. Closure design of oil sands tailings ponds is made additionally difficult in that they themselves change internally over time, and there are no natural analogues to them in the region. A responsibility exists to alter the way that new tailings impoundments are approached and designed, as we continue to learn from the complex and multi-faceted conversion process of existing facilities.

The latest combined 'Life of Mine' and 'Closure and Reclamation' Plans were completed for all mining leases in 2011/12. Each and every oil sands mine operating in 2011/12 summarized their overriding reclamation goal as being to achieve self-sustaining ecosystems with a capability equivalent to pre-development conditions; three of five operators quoted this statement directly and all except one also wrote that the landscape would be "maintenance-free" (CNRL, 2011; Golder Associates Ltd., 2011; Shell Energy Canada, 2011, 2012; Suncor Energy Inc., 2011; Suncor Energy Operating Inc., 2012; Syncrude Canada Ltd., 2011). This target is particularly challenging given the nature of the materials held within aboveground tailings impoundments.

More thorough planning and consideration for the final landscape during early mine stages would provide operators with additional flexibility in latter stages, allow for a smoother transition to the closure landscape, and more optimal end results. Major communication gaps can exist between operations staff, tailings engineers, mine planners and the scientists and engineers designing the closure landscape. Those working on short-term planning are often not aware how their decisions impact closure. The implications of this divide are already evident: the path to closure is fraught with unexpected challenges, sub-optimal solutions, and closure costs in the hundreds of millions of dollars for a large tailings pond-ring dyke structure in the oil sands. Long-term maintenance of tailings landforms is beginning to be thought of by some leading experts as an inevitability.

The considerations discussed herein are those that could be easily integrated throughout early mining stages, while dramatically streamlining the conversion process from a tailings pond to a landform. They are small adjustments that lead to big benefits. Implications of the considerations discussed above include:

1. Improved long-term physical stability of dykes
2. Improved chemical, ecological, and social stability
3. Reduced negative impact of structure on surrounding environment, and vice versa
4. Reduced long-term maintenance costs associated with erosion and sedimentation
5. Consideration of loading conditions at closure with respect to capping, covers, hummocks, water tables, drainage pathways, etc.
6. Improved communication amongst varied operations, design, and management professionals
7. Improved aesthetics
8. More accurate cost estimates with greater understanding of long-term implications of actions
9. Reduced closure costs
10. A more resilient landscape designed with flexibility of internal and external form in mind

The overarching principle inherent to these implications is that given the tailings materials to remain behind the ring dykes in the AOS, there can be no physical, chemical, ecological, or social stability without long-term dyke stability (ICOLD, 2013). Due to the erodible nature of many of these sand dykes, geomorphic stability and erosion are fundamental long-term concerns.

4.5 Summary and conclusions

With the goal of eventual delicensing, preliminary geomorphic design of a landform was completed at an oil sands mine site in the AOS in preparation for its conversion from an aboveground tailings impoundment. Through this design process, methods were identified to make the conversion process of future impoundments more streamlined.

Site selection for tailings impoundments has not historically focused on the impact that final landforms will have on surrounding landscapes, and vice versa. Spatial requirements of a post-closure tailings landform are greater than those during mine active operation, and these are largely ignored during the site selection process in favour of economic drivers. A number of considerations in determining appropriate spatial requirements at closure were discussed herein, including dyke regrading, outlet construction, and mine operation. Most oil sands tailings dams are expected to hold the first 8–15 years of tailings, after which they will be converted to landforms. Meanwhile mines are operational for over 50 years in some cases. Ongoing mine operations and site activities can restrict the expansion of tailings dam footprints during conversion.

Internally, tailings placement impacts the ease with which tailings impoundments are converted to landforms. Design decisions and considerations outlined herein encourage a flexible landform design that works with nature and with long term changes, as opposed to rigidly opposing them.

The topography of the untouched landscape in the AOS is undulating but generally flat. Over tens to hundreds of years, weathering processes will attempt to flatten constructed high points—like tailings-constructed landforms—into an equilibrium with the surrounding landscape. The inclination to apply locally stable natural slopes to dykes for geomorphic stability is not possible in this situation, as no natural analogues of these sand dams exist in the region. A landform that is designed with its long-term stability requirements in mind will consume more area, but will also require less maintenance and be more easily delicensed than a traditionally constructed tailings dam.

4.5.1 Future work

As these tailings ponds approach the end of their active life, there will be more opportunity to learn how we can best prepare for their transition to solid landforms. Better and more efficient technologies continue to develop with respect to tailings production and landscape evolution modelling; both of these will aid in the planning for stable, closure landforms. In particular, climate models should be integrated into the planning of these structures early on so that changes in wind and/or precipitation rates and intensities can be accounted for in the geomorphic designs. Further evaluations of stable slopes for sand tailings used in dyke and infill construction, including maximum allowable length and grade, are necessary to gain confidence in construction methods. This work is ongoing.

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5.0 Erosion

As noted in previous chapters, CST is highly erodible by wind and water. While much effort is expended in the geomorphic design of the central pond plateau (Chapter Three), no topographic changes are proposed to the more steeply sloped perimeter dams. These perimeter dams often border natural, minimally disturbed terrain, and their degradation due to erosion is therefore of interest.

This chapter provides background information on causes and types of erosion, and an estimation of average annual erosion from the perimeter dams of the TSF and SEA (the same structure designed for closure in Chapter Three) using the revised universal soil loss equation for application in Canada (RUSLEFAC). Various forms of the universal soil loss equation (USLE) have been used for over 40 years; despite a number of shortcomings described below, this empirical approach continues to be used today due to the reliability and ease of calculation of average annual soil loss estimates.

5.1 Introduction

Many natural systems and landforms in Canada have developed into various states of equilibrium since the last ice age approximately 10,000 years ago; some remain in transition. This path towards equilibrium occurs via chemical and physical weathering of surficial geology, erosion of landforms, and deposition of eroded material downwind or downstream. In contrast, anthropogenic landforms and drainage systems have a history of large and often costly failures (Bradley & McNearny, 2000). Erosion accelerated by anthropogenic interference with the natural landscape has been identified as a financial and environmental liability with negative impacts on landscape productivity and society in general (Osterkamp & Toy, 1995).

In the same way that present day landforms have evolved over the last 10,000 years, erosional forces act on newly created landforms in order to seek equilibrium of form between geology and climate primarily. While this is a natural process, the removal, transportation, and deposition of eroded sediment into downstream waterbodies and/or otherwise fertile reclaimed or natural land can be damaging to their respective environments and the balance they seek to maintain. Surficial erosion of TSF’s can expose reactive tailings materials held within the dam (or landform) and lead to disturbance of revegetation works (Kemp, Taylor, Scott, & O'Kane, 2015).

Reduction in fish population and alteration in aquatic chemistry due to leaching of environmentally persistent and toxic heavy metals via acid rock drainage have also been noted to result from erosion in mining environments (Yellishetty, Mudd, & Shukla, 2013).

According to 2011/ 2012 combined life of mine and reclamation and Closure plans for oil sands leases, the majority of the 900 km^2 area presently disturbed by surface mining in the AOS is proposed to be capped with CST of varying thicknesses depending on the substrate (Alberta Government, 2017). Tailings dams are, with few exceptions, constructed entirely of CST (starter dykes are generally constructed of overburden) and are some of the tallest and largest structures on site.

One challenge in designing TSF's for closure and conversion to a landform is in identifying drainage-related design criteria, such as minimum and maximum slopes, drainage channel widths, and overall longitudinal slope. Present state of the art is to use values obtained from surveys of stable local terrain (for example, Golder Associates Ltd. (2004 and 2008) are routinely used among Canada's Oil Sands Innovation Alliance member companies). The problem with this approach is that surrounding natural terrain has different mineralogy, texture, is over-consolidated, and surficial sediment is often covered by a layer of stabilizing vegetation. In contrast TSF's are newly constructed, have a uniformly fine texture, and surface sediment is loose and exposed. For this reason, it is likely that the slopes and dimensions of long-term stable CST landforms are different from those for naturally stable terrain.

ICOLD (2013) lists surficial erosion as a long-term threat to the physical stability of tailings dams post-closure, and a 1994 survey of dam deterioration modes found surface erosion to be the most prevalent (ICOLD, 1994). Furthermore, erosion due to water specifically has been called "the single most severe cause of [tailings] impoundment instability" on mine sites (Robertson & Skermer, 1988). CST erodibility has been noted in the AOS since the 1970's; however little research has been conducted to better understand the challenges this may pose under varying conditions. No erosion inventories on oil sands tailings dams exist in the public domain, nor has the extent of erosion been documented.

With closure of many large AOS tailings ponds occurring in the imminent future, and in consideration of present-day TSF delicensing ideals that require maintenance-free terrain, this portion of the research sought to better understand CST erosion on a tailings dam. Specifically, the goal was to identify and inventory evidence of erosion on a CST constructed tailings dam, to determine (where possible) how the erosional features were formed, and to quantify the amount of erosion occurring. Quantification is particularly important to determine whether this is a minor issue (i.e. within adequate erosion rates as dictated by the province) or a major issue that warrants further attention.

5.2 Background

5.2.1 Types of erosion

Erosion is generated via wind and water interactions with the ground surface. The magnitude of wind erosion is not affected by topographic parameters such as slope length or gradient, but instead by surface roughness which can be easily mitigated through vegetation establishment (Schor & Gray, 2007). Consequently, this literature review focusses on the potential for erosion due to water.

Water erosion initiates when rainfall, snowmelt, or water from other sources contact the soil surface. Erosional processes have three components: detachment of soil particles, transport via wind or water, and deposition. The energy required for each of these component processes to take place will vary based on the climate and soil properties, such as grain size, cohesion, and inter-particle forces. The Hjulström diagram illustrates these thresholds, as shown in Figure 5.1 below (Hjulstrom, 1935). In particular, the diagram shows the required flow velocity of water in a channel to erode, transport, and deposit particles of various diameters.

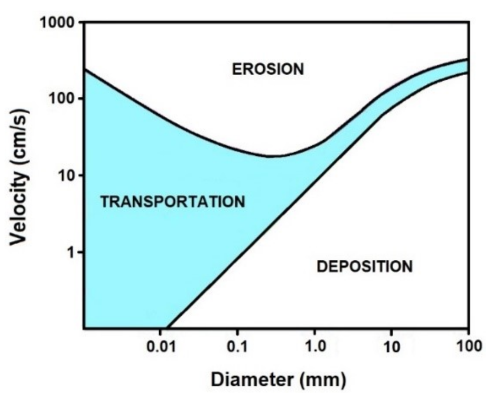

Figure 5.1 Simplified Hjustrom diagram

With respect to rain water, erosion begins when a raindrop lands on exposed soil or soil with a thin veneer of water: If the rain drop has sufficient kinetic energy, this collision results in soil particles being upwardly mobilized (Schor & Gray, 2007). In a heavy storm, soil particles on a level surface can be displaced more than 0.6 m vertically and 1.5 m horizontally simply due to the impact of rain splash (Schor & Gray, 2007). ‘Rainfall erosivity’ is the term that describes rainfall’s ability to detach soil particles. Water volume, kinetic energy of water drop impact, and intensity are typically taken into consideration when determining rainfall erosivity (Harmon & Doe, 2001).

Runoff erosivity describes the ability of overland flow to erode soil particles, and takes into consideration overland flow volume and maximum intensity (Harmon & Doe, 2001). Soil erodibility describes the characteristics of a soil that make it more or less susceptible to erosion: soil texture, structure, permeability, organic matter content, clay mineralogy, and geochemical interactions (Harmon & Doe, 2001). In the 1940’s Horton described runoff as rainfall rate in excess of infiltration rate. Additional components have since been identified that also contribute to runoff: subsurface flow through the soil and seepage of subsurface flow to the ground surface (Dunne & Black, 1970). These three components are hereon referred to as overland flow, subsurface flow, and subsurface discharge. Overland flow is the most important component of runoff as it not only provides erosive forces but also dictates transport and deposition of eroded materials. Subsurface flow is the drainage pathway for infiltrating precipitation, thus reducing the quantity and erosivity of overland flow. Where deep, high-permeability soils exist, seepage areas to the surface are rare, but may be located in areas of relatively low elevation. Where low permeability materials are overlaid by higher permeability materials, perched water tables (and discharge areas where daylighting occurs) are possible at interfaces. Discharge areas increase the quantity of overland flow, but the upward water movement also has the potential to loosen surface soils making them more erodible (Owoputi, 1994).

Soil erosion due to water has three classifications: sheet erosion, rill erosion, and gully erosion, listed in increasing depth of influence (Yellishetty et al., 2013).

On a sloped surface, horizontal movement of soil particles due to rain splash will predominate in the downslope direction, leading to a gradual redistribution of soil downslope. If more water is landing on the surface than can infiltrate, water accumulates on the surface until it can flow down the slope, constituting overland flow, or runoff. When overland flow velocities down a slope are 0.3 – 0.61 m/s, thin layers or “sheets” of soil can be removed and relocated downslope

(Schor & Gray, 2007). In this way, erosion increases with slope gradient as a result of increased soil distribution from rain splash and faster overland flow speed (Yellishetty et al., 2013). This type of overland flow does not tend to be a uniform depth or result in laminar flow, although uniformity is more likely with time (Toy & Hadley, 1987). Sheet erosion resulting from overland "sheet flow" does not necessarily have surficial signs afterwards at the area of occurrence: indications include the presence of deposited soil in the lower reaches of slopes or in ditches across bottom slopes.

Rill erosion occurs when overland flow down a slope is concentrated, generating thin but distinct channels, or "rills". When the flow transport capacity becomes greater than the sediment load and shear stress due to flow is greater than soil resistance, then detachment from soil surface occurs (Toy & Hadley, 1987). Concentration of flow generates greater flow velocity and energy in the rills than is created by sheet flow, thus the potential for soil erosion and transport is greater. Additionally, this greater force also has potential to detach and transport larger particle sizes. The strongest impact due to rills is seen in areas prone to high intensity storms and on land with loose, shallow topsoil (Schor & Gray, 2007). Many rill definitions exist, but no single one has broad consensus, so it is important to provide a definition using dimensions when categorizing features. A general definition typical of text books is that rills are parallel channels on a hillslope ranging from a few to several centimeters in width and depth that can be eliminated through use of tillage or grading equipment (Toy & Hadley, 1987). Most erosion associated with rainfall occurs due to rill erosion (Schor & Gray, 2007).

Rill erosion is particularly common in mining and road construction environments due to a number of factors. In open-pit mining overburden or non-profitable rock and/or soil must be removed prior to gaining clear access to the ore. Due to the ripping and fragmentation involved in overburden removal, void ratio and total volume is increased such that the total volume to be stored is greater than the volume removed; this is called "bulking". An increase in unconsolidated material is a common challenge in reclaiming a variety of disturbed landscapes (Toy & Black, 2000). The large areas to be reclaimed and the high cost of material movement result in minimization of topsoil depth wherever possible. This thin, loose soil layer is often difficult to establish vegetation upon; this helps to create conditions that exacerbate rill erosion. (Schor & Gray, 2007).

Gullies consist of typically ‘v’-shaped channels formed through the joining of rills and concentration of flow (Schor & Gray, 2007; Toy & Hadley, 1987). Gullies are much larger than rills so they cannot be easily repaired with tillage or rough grading equipment. Stabilization should be installed both along the bottom of the gully and at the top where it initiated to prevent further down-cutting or expansion inwards via head-cutting (Schor & Gray, 2007). Gullies on oil sands dams can be filled-in using large earth-moving equipment and regraded, but once reclamation has taken place this is more difficult due to poor access and the need to avoid established reclamation areas. Notably, gullies in CST tend not to revegetate naturally, making prevention especially important.

Factors affecting erosion and the extent of erosion can be broadly summarized as climate, soil properties, vegetative cover characteristics, and topography. These can be further broken down into: 1) rainfall event duration, intensity, and return period, 2) soil texture, permeability, particle size distribution, and organic matter content, 3) proportion of earth shielding, soil trapping, surface roughness, and permeability increase provided by vegetation canopy and roots, and 4) the shape, length, slope gradient, and aspect of a hillslope. Reclamation professionals and geotechnical engineers have the most control over topography, and as such various dam topographies are stress-tested in Chapter Ten.

5.2.2 Precipitation and infiltration

The infiltration capacity of any soil is a function of hydraulic characteristics related to the positioning and attachment of soil particles to each other, amongst others (Harmon & Doe, 2001). Infiltration has been mathematically described by Green and Ampt (1911), Horton (1940), Philip (1957, 1969), and Holtan (1961), amongst others. Each of these last three aim to simplify the processes in Richards’ equation (5.1) (Richards, 1931) representing water movement in unsaturated soil, which was actually first presented by L.F. Richardson much earlier (Richardson, 1922).

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left[K(\theta)\left(\frac{\partial h}{\partial z} + 1\right)\right] \tag{5.1}$$

Where K is hydraulic conductivity, θ is volumetric water content, h is matric head induced by capillary action, z is the elevation above datum zero, and t is time. The hydraulic conductivity of a soil may be considered to be the maximum rate of flow in a saturated soil, without interference from unsaturated pore pressures/ matric suction, or other barriers found in the unsaturated zone. Once the hydraulic conductivity is exceeded, void space within the unsaturated zone begins to fill with the excess water, and overland flow subsequently develops.

Horton brought physically based mechanistic concepts to the study of geomorphology. His chief contribution was arguably a concept whereby infiltration is solely dictated by infiltration capacity of the soil, and where any rainfall in excess of the infiltration capacity becomes overland flow. Horton (1940) described the infiltration curve as follows:

$$I = I_L + (I_o - I_L)e^{-kt} \tag{5.2}$$

Where I is the infiltration rate, I_L is the infiltration capacity at equilibrium or limiting infiltration rate, I_O is the initial infiltration capacity, k is a constant related to the rate of decrease, and t is the time of infiltration. An assumption of this theory is that at some distance from the watershed divide, overland flow gains enough velocity to remove soil particles via sheet erosion then further downslope rills develop, creating a zone of no erosion on the upper portions of a hillside. While Horton's expression is widely used for its simplicity, the challenge with this expression is that it does not take into account all influencing factors, and all of the parameters with the exception of time need to be measured experimentally (Blight, 2013; Ruth U., Kelechi K., & Ijeoma I., 2015). Subsequent geomorphologists have noted that Horton's simplistic approach is most appropriate on clay or other low permeability hillslopes, as with other conditions overland flow is rarely identifiable except in extreme storms (Kirkby & Chorley, 1967). Philip's expression is often used instead of Horton's because it requires that only two parameters be measured. Philips' equation is as follows:

$$I = I_L + \frac{1}{2}St^{-1/2} \tag{5.3}$$

Where I is infiltration rate, I_L is the limiting infiltration rate, S is sorptivity, and t is time of infiltration. Philips equation has greater simplicity of use, but similarly neglects some factors of influence.

The ability of soil to absorb water, or allow infiltration, is often generalized from Horton's equation and is stated to be synonymous to its hydraulic conductivity, which is equivalent to the limiting infiltration rate in Philips' and Horton's equations (DeJong, Tibbett, & Fourie, 2015; Government of Alberta Transportation, 2011).

In reality, infiltration rate is not only a function of saturated hydraulic conductivity and the positioning of soil particles, but also of soil moisture content, matric pressure at the wetting front, and time since precipitation began, all of which are accounted for in the Green-Ampt equation. The Green-Ampt infiltration rate equation (1911) takes these factors into consideration and is written as:

$$I(t) = K_{SAT} + K_{SAT}\frac{|\varphi_f|(\theta_s - \theta_i)}{F} \qquad \text{for } t > t_p$$

$$I(t) = P \qquad \text{for } t < t_p \qquad (5.4)$$

Where *I(t)* is infiltration rate, K_{SAT} is saturated hydraulic conductivity, ψ_f is the matric pressure at the wetting front, θ_w is the saturated water content, θ_i is the initial soil water content, t_p is the time when water begins to pond on the surface, *F* is the cumulative depth infiltrated, and *P* is the precipitation (rainfall) rate. The Green-Ampt point infiltration model, graphically represented in Figure 5.2, assumes a sharp wetting front across uniform soil.

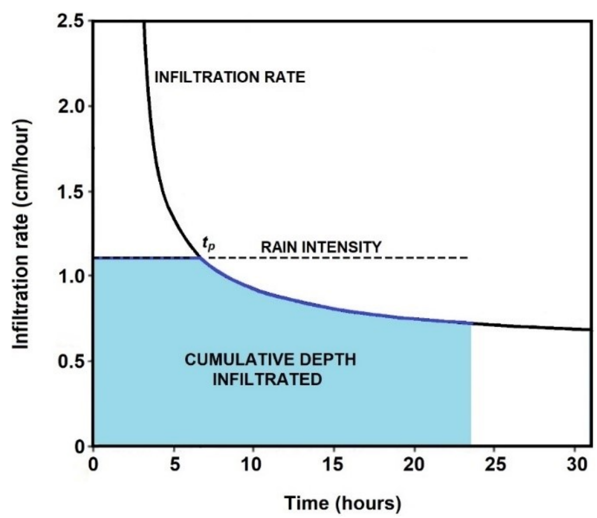

Figure 5.2 Infiltration rate changes over time, as shown using the Green-Ampt equation (5.4) above.

In each of these models infiltration decreases with time as the wetting front advances and moisture content increases. The exception to these equations occurs when soil is exposed to long periods of heat and drought, forming a crust, and low or nil moisture content near surface: in these cases runoff can initially be high before returning to normal behavior (Government of Alberta Transportation, 2011). Another exception occurs when soil is frozen and precipitation is unable to enter pore spaces due to ice lens formation. In cases where a higher permeability soil layer outcrops on the surface of a hillslope, runoff may then infiltrate if conditions allow.

These equations each aim to determine the infiltration rate of precipitation into soil, given the depth of wetting front or time passing since initial infiltration. A common drawback to these formulas is the lack of spatial influence on soil moisture content and subsurface flow. Generation of overland flow due to forced daylighting of subsurface flow at low, saturated, slope positions is a more consistent cause of erosion requiring much lower rainfall intensities for generation (Kirkby & Chorley, 1967), though this is more challenging to represent and predict empirically. This explanation also leads to more localized erosion further downslope than the Hortonian “belt of no erosion” concept, which is measured from the top of the slope or watershed. For the purposes of this study, an understanding of infiltration helps to predict how and where erosion may develop on mining landforms, given their diverse characteristics.

While all models are commonly used, the Philip Model has fewer assumptions than Horton, and the commonly used Guelph Permeameter reports its results according to parameter inputs that the Philip Model requires, contributing to its widespread usage. The Green-Ampt parameters are based on data acquired from soil texture classification or published charts, making it a popular choice as well.

5.2.3 Impact of vegetation on surficial and deep-seeded slope stability

Vegetation can have both a positive and negative impact slope stability. When vegetation foliage intercepts rainfall, the energy associated with splash on the ground surface, and associated soil displacement, is reduced (Schor & Gray, 2007). Roots of herbaceous and grass vegetation hold surface soil layers in place while creating surface roughness that will filter sediment in overland flow and reduce overland flow speed.

Woody vegetation with deep roots can provide physical reinforcement using anchoring roots if they penetrate a fractured bedrock or transition layer above bedrock (Schor & Gray, 2007). In contrast, woody vegetation planted in a thick soil mantle (does not cross a shear surface), or shallow-rooted woody vegetation, provides minimal effect on the deep-seated stability of a slope, and can be a risk where high winds create uprooting potential. Regardless of the soil profile, woody vegetation with deep roots helps to manage soil moisture content through evapotranspiration. Herbaceous and other shallow-rooted vegetation such as grasses provide a barrier to surficial soil erosion by wind and water, but no protection against deep-seeded failures (Schor & Gray, 2007; Yellishetty et al., 2013). Plant roots can both densify soil and also increase its hydraulic conductivity over time, depending on site conditions (DeJong et al., 2015). While vegetation type can moderate and control soil water content and groundwater levels (Lilienfein and Wilcke, 2004), vegetation arrangement can affect the degree of overall erosion protection provided indicating that there is an element of design required in vegetation placement for optimal results (Yellishetty et al., 2013). Regardless of the type of vegetation initially planted, it is important to note that expedited erosion can be expected where vegetation does not exist, therefore quick establishment and coverage is an important consideration in balancing species, planting layout, and economic aspects (Toy & Hadley, 1987).

An additional consideration in hillslope revegetation, particularly on post-mining landscapes is monitoring. Vegetation inherently obstructs ones view of the ground surface which can make traditional monitoring methods less effective and site inspections more difficult (Schor & Gray, 2007). Vegetation also attracts wildlife, which may or may not be desirable depending on the condition of the land, how fauna use the land (burrowing, dam building, etc.), and end land-use goals. Landscape ecology principles can be used in developing a planting and plant-grouping, or patch, layout that encourages or discourages ingress by fauna (Dramstad, Olson, & Forman, 1996). Choosing initial vegetation species based on vegetation succession is often used to demonstrate a trajectory towards the desired vegetative community.

In general, and in natural undisturbed environments, erosion increases with an increase in average annual precipitation, and decreases as vegetation density increases (Toy & Hadley, 1987). Chapter Nine addresses climate change in Alberta and the impact on erosion as annual precipitation increases and vegetation density decreases.

5.3 Coarse sand tailings (CST)

The erodibility of CST in the AOS has been documented since the 1970’s, but little has been documented with respect to erosion of mining landforms composed of CST (Rowell, 1977; 1979). CST is a fine, white, silica sand with an average roundness of 0.2 to 0.4 (typical for sands) (McLaws, 1980). Hydraulic conductivity of CST was measured at a range of scales by McKenna (McKenna, 2002), with an average value found to be 5 x 10^{-4} cm/s. Dams are constructed to heights of 40 to 100 m and with downstream slopes between 2.5:1 and 25:1 in the AOS, which are proposed to remain at closure. In an effort to evaluate active erosion occurring on an oil sands tailings dam, samples were collected to attain particle size distributions and moisture content of surficial CST at an AOS TSF (Figure 5.3, Table 5.1). Particle size distributions were used for characterization, landscape evolution modelling (Chapter Eight, Nine, and Ten), as well as comparison to other naturally occurring Alberta sands.

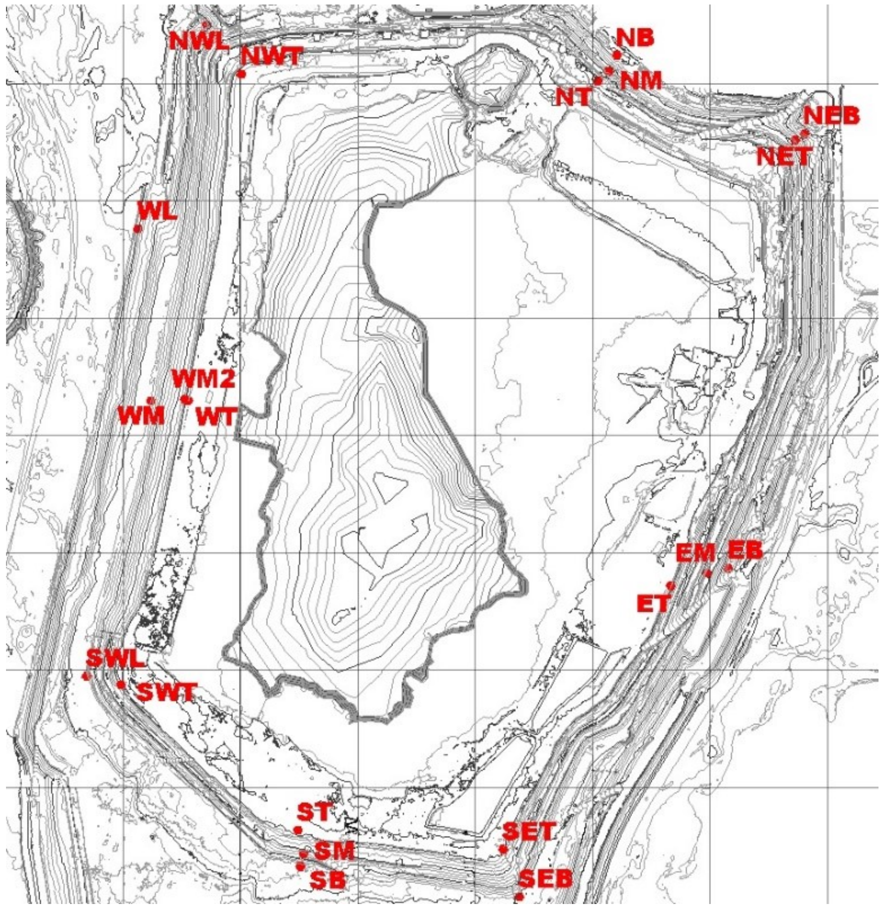

Figure 5.3 Location of CST collection locations listed by sample ID. Image created by Dave Young.

Table 5.1 Location and elevation of CST sample collection by ID. Two samples were collected at each location (0 - 150 mm depth, 150 - 250 mm depth).

Sample ID	Easting	Northing	Elevation	Sample ID	Easting	Northing	Elevation
SWL	464345	6341975	311	SEB	466187	6341034	310
WM	464618	6343148	312	SET	466118	6341236	342
WL	464562	6343881	288	ET	466832	6342360	341
NWL	464856	6344751	295	EM	466984	6342415	313
NWT	465004	6344541	342	EB	467076	6342435	294
WT	464777	6343150	342	NEB	467401	6344286	294
WM2	464762	6343155	335	NET	467361	6344260	306
SWT	464491	6341938	341	NT	466521	6344512	328
ST	465243	6341318	341	NM	466567	6344552	315
SM	465269	6341218	324	NB	466603	6344622	300
SB	465255	6341163	313				

Samples were collected from all four cardinal directions of the TSF dams at the bottom, middle, and top of slopes and from corners at the top and bottom. At each of the 22 locations, one 500 - 700 g sample was collected from the surface to a maximum depth of 150 mm, and another 500 - 700 g sample was taken from a 150 - 250 mm depth. Two samples were taken per location in order to determine if armouring of the surface had occurred. All samples were individually placed in sealable thick plastic bags, labelled with the GPS location, sample ID, and depth, and photographs were taken at each location before and after collection for documentation.

The samples were weighted, dried for 24 hours in an oven, then weighted again, and subjected to sieve analysis according to ASTM D6913-04. Particle size distributions have been summarized in Figure 5.4. On comparing samples from the 0-150 mm depth to 150-250 mm depth, negligible armouring was found to occur. Similarly, when comparing samples from the dam toe to those at the crest only slight variations were found, demonstrating little to no sorting had taken place and a relatively consistent distribution across the dam. This is likely due to the constant traffic on the dam that encourages mixing, and also due to the young age of the structure. Construction began at the TSF around 2002 and ultimate height was reached in 2014.

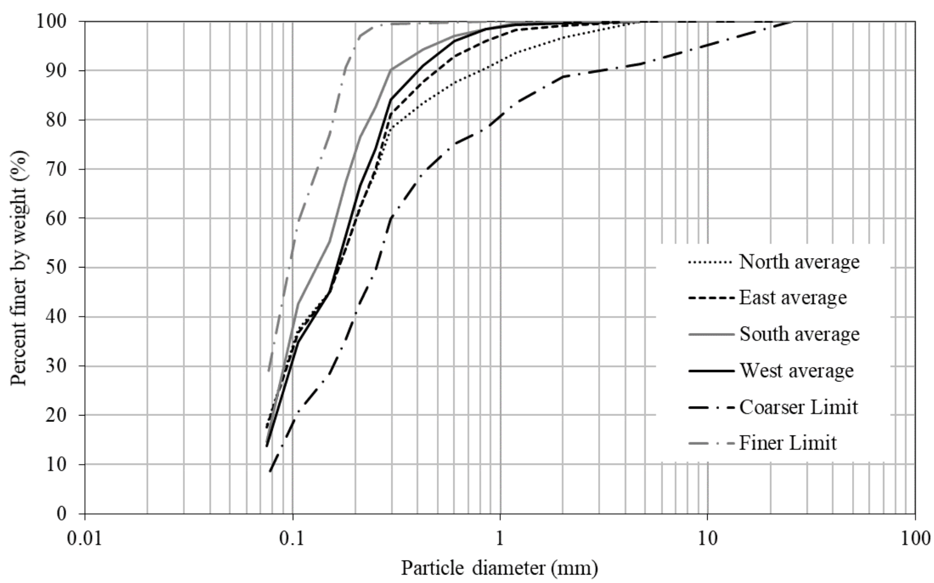

Figure 5.4 Particle size distribution for CST collected from the TSF.

Moisture content was measured for each sample, with an overall average found to be 3.5% (by weight). A few predictable trends were identified, mainly that CST from the top of the dam was more dry than the bottom, that the sample taken from the surface (0 - 150 mm) was drier than the sample taken slightly below the surface (150 - 250 mm depth), and that the south and west sides were more dry than the east and north sides (Table 5.2). Given that CST is a well-drained material, these trends are of interest with respect to future reclamation materials that are likely to have high organic matter contents and therefore retain moisture more readily. These trends should also be considered when vegetation is being selected for reclamation.

Table 5.2 Average moisture contents of CST collected from the TSF dam surface.

Location	Average moisture content (% wt.)	Depth of sample	Average moisture content (% wt.)
North side	4.9	0 - 150 mm	2.6
East side	3.9	150 - 250 mm	4.3
South side	2.5		
West side	3.5		
Top of dam	2.3		
Bottom of dam	5.2		

Soil moisture content is also important with respect to infiltration capacity and runoff generation (Toy & Hadley, 1987). Sawatsky, Dick, Ekanayake, and Cooper (1996) investigated the effect of antecedent soil moisture conditions on the erosion of a 2.5:1 sloped CST tailings dam using two 7 m by 16 m test plots each at the Suncor Mine and Syncrude's Mildred Lake mine, rainfall simulators, and sediment collection traps. Short-duration rainfall applications (ranging from 6 minutes to 4 hours) were conducted, and results showed that peak runoff rates increased by nearly 10 times and runoff coefficients increased over 30 times with high compared to low antecedent moisture conditions (Sawatsky et al., 1996). Sediment yield was relatively low for these simulations, which may be due to the short test duration.

At closure and without intensive maintenance from heavy equipment, CST material properties and the extent of reclamation completed will be the dominating factors in landform performance. Maintenance during operation has thus far included re-grading, investigation of seepage areas and construction of mitigation features, etc. These tasks have been necessary, but the fact that they were required also raises a number of questions. Are we placing too much faith in the proposed reclamation measures? Given present dam behaviour, how confident are we in their behaviour after closure?

In Rowell's 1979 report on revegetation and management of tailings sand dam slopes in the AOS, he states that "a concern might be justified as to the ability of such an area to remain intact during a poorly productive period under heavy rainfall". Indeed, a brief tour of reclaimed oil sands dams on 'Google Earth' will provide an unobstructed view of large erosional features literally visible from space. These sites are located on presently operating oil sands mines, regularly monitored and maintained. Once the mines are closed, the same monitoring and maintenance will be more logistically challenging, and more costly. The following sections estimate erosion on a dam slope for planning purposes, while Chapter Six investigates the measurement (or quantification) of active erosion, and the evaluation of two remote monitoring methods for dam erosion, each at the TSF and SEA designed in Chapter Three.

5.4 Erosion estimation using RUSLEFAC

The Universal Soil Loss Equation (USLE) predicts average annual soil loss as a result of sheet erosion and rill erosion, which are the driving erosional mechanisms under normal hillslope conditions (Schor & Gray, 2007). USLE was first developed for application on agricultural fields in the United States by a team lead by W.H. Wischmeier at the Agricultural Research Service (ARS), a division of the U.S. Department of Agriculture, in the early 1960's (Toy & Hadley, 1987; Wischmeier & Smith, 1978, 1965). The original USLE equation has not changed much, but sub-equations to determine individual parameters have altered over time with each revision. The original USLE equation, where A represents annual soil loss, is written as follows:

$$A = R \times K \times LS \times C \times P \tag{5.5}$$

The USLE is a function of many primary variables including rainfall/runoff (R), soil erodibility (K), slope length and gradient (LS), cover/management (C), and erosion control practices (P), nearly all of which are in turn comprised of secondary variables (Osterkamp & Toy, 1995; Wall, Coote, Pringle, & Shelton, 2002). (Note that the 'K' used in the USLE is not the same 'K' used in previous sections of this chapter.) The simplicity of this single equation, its extensive validation, and its widely available, wide-ranging database of factor/parameter values are a few of the benefits of USLE-based soil loss prediction (Osterkamp & Toy, 1995). However, there are also several limitations to USLE that are common to the subsequently revised versions:

This is an empirical prediction tool which uses set mathematical factors to account for covers, vegetation, and management which are likely to contain variability (Schor & Gray, 2007).

USLE predicts average annual soil loss based on a generalized storm event using the rainfall factor, R. This may not adequately represent the variability of storm events that an area may receive (Schor & Gray, 2007). The equation cannot predict soil loss from a specific storm event or a specific calendar year (Toy & Hadley, 1987) and USLE is not valid for slopes in excess of 25% (14 degrees) (Blight, 2013).

A final limitation which is imperative to our study of the erosion impact on mine waste landforms over a regional scale, is that USLE is restricted to providing predictions on the amount of soil lost from a particular area, without providing information on where this soil has been deposited (Osterkamp & Toy, 1997; Schor & Gray, 2007). Deposition of sediment is a significant component in natural environments and in those with downstream communities dependent on clean water or productive land, for example.

This semi-empirical equation was subsequently adapted to various agricultural regions in the U.S.A. (USDA Soil Conservation Service, 1972), for urban application particularly highway shoulders and embankments (RUSLE), for single storm events (Williams, 1975), and to various regions within Canada (Wall et al., 2002). Specific adaptations make the Revised Universal Soil Loss Equation (RUSLE) a more accurate predictor of annual soil loss from mining and construction sites due to rill and sheet erosion: in particular, the LS factor can contain steeper slope gradients, the K factor was adjusted to consider variability throughout the year, and K and C factors take into account rock fragments on the slope surface and variability (Yellishetty et al., 2013). Additional considerations in the mining environment should account for components outlined by (Williams, 1996; Yellishetty et al., 2013) including chemical composition of rock or soil that is in contact with water.

Other adaptations to USLE have been generated, but the most applicable to this study is the Revised Universal Soil Loss Equation for Application in Canada (RUSLEFAC), an adaptation of the RUSLE equation for use on Canadian sites. In the Canadian context, annual soil and nutrient loss due to erosion has been estimated at an equivalent of $48 – 96/hectare (accounting for inflation from the 1979 Canadian dollar) within the agricultural sector (Wall et al., 2002). Note that this figure does not include clean-up of waterbodies or adjacent landscapes due to excessive sediment and nutrient loading. One major difference in the Canadian context is the underestimation of spring runoff (R-factor) and erosion (K-factor) during the period of snowmelt at the time of ground thaw in spring; this has been rectified in RUSLEFAC through calibration.

In terms of mitigation, designers have a few options when looking specifically at the RUSLEFAC factors. The K factor may be decreased at the surface through addition of larger grain sizes and organic matter and the C factor may be decreased through quick establishment of dense vegetation and ongoing monitoring. With respect to alteration of the other factors, rainfall is out of our control, the slope length and gradient are unlikely to be altered once constructed, and the supporting practice (P) factor is undesirable on a natural landform unless new values and more natural landform shapes are integrated to RUSLEFAC. An added benefit of altering the erodibility factor (K) through increasing surface texture is that wind erosion is mitigated in addition to water erosion.

While RUSLE is a simplistic and purely empirical approach to erosion estimation, it has been widely calibrated and remains the standard in Alberta and across much of the USA. RUSLE continues to be used because the data requirements are not excessively large or complex, and it is relatively easy to use (Yellishetty et al., 2013). The RUSLEFAC equation is written as follows:

$$A = R_t \times K \times LS \times C \times P \tag{5.6}$$

Where A is predicted soil loss in [Mg ha^{-1} y^{-1}]. Note that 1 Mg (megagram) is equal to 1 tonne.

5.4.1 Rainfall and runoff (R_t) factor

R_t [MJ mm ha^{-1} h^{-1}] is a location-specific rainfall and runoff factor related to the annual kinetic energy of rainfall. It accounts for storm energy, intensity, total quantity of precipitation (regardless of state), and runoff due to precipitation and snowmelt throughout the year. R_t is estimated using isoerodent maps (Figure 5.5) for non-winter conditions, R, and for winter conditions, R_s, that are added together. Isoerodent maps have been previously generated from: 1) Calculations using measured average annual sum of all erosive rainfall events where 22 consecutive years of data are available, 2) equations based on empirical relationship between the one in two-year storm and six-hour storm, and 3) hourly precipitation records, where available.

22 years of data is a recurring requirement for initial calculation of USLE maps and values, stemming from the original data used in development by Wischmeier and Smith (1978).

There are three methods of calculation; however, isoerodent maps are widely recommended and deemed the most accurate method for the extent of their coverage within the RUSLEFAC.

5.4.2 Soil erodibility (K) factor

K [t h MJ^{-1} mm^{-1}] is a measure of soil erodibility and ability to absorb precipitation and meltwater. Soil texture, structure, permeability, organic matter content, and seasonality impact the soil erodibility factor. The RUSLEFAC model has made several adjustments from the original equation which account for Canadian conditions. In particular, a wider range of soil types including peat and clays have been included, K can now be adjusted to account for rock fragments in soil profiles, and a reduction in minimum time distributions to recognize seasonal fluctuations as brief as two-weeks. K is calculated using the nomograph provided in Figure 5.6, if the percent silt and fine sand, sand, and organic matter fractions are known for the soil of interest. These values were determined through laboratory testing and confirmed with values found in literature. Organic matter content for sand dykes and areas disturbed by mining is typically zero, which is what is assumed in this case.

The remaining information required includes a soil structure number based on aggregate size (Table 5.2) and permeability classes based on the soil profile within the top 0.6 m (Table 5.3). Infiltration capacity and rate are not included in this calculation. Since RUSLE was developed for agricultural settings, and compacted terrain in agriculture differs significantly from compacted terrain in a mining or construction setting where dykes are hydraulically placed and compacted, a modification factor (ϕK) has been proposed to be applied (Alberta Transportation, 2011). Alberta Transportation (2011) suggests that this modification should be based on engineering judgement, typically between 0.5 and 1.0, but most often about 0.8.

5.4.3 Slope length and steepness (LS) factor

LS is a slope factor which takes slope gradient and length into consideration. It also accounts for variation in gradient across a slope such as convex or concave profiles. To calculate LS factor for uniform slopes, one can use tables for slopes up to 300 meters or can use equation (5.8) below.

Determining the LS factor requires measurement of slope length and gradient, which can be done using LiDAR data. This information cannot generally be attained using topographic plans as the scale is too small to detect benches or other blockages to continuous flow on slopes. Slope limits include the top of slope on the upper end and moving down-slope the first area of broad deposition indicates the lower end, typically around 5% slope. Once again, the difference between agricultural soils and construction soils need to be addressed here in a topographic adjustment factor (ϕ_{LS}). Depending on the compaction and soil type used, this adjustment factor can range from 0.5 to 1, with 0.8 generally observed as typical construction values (Alberta Transportation, 2011).

5.4.4 Crop / vegetation management (C) factor

C is a "cover and management", or vegetation, factor which rates the relative effectiveness of soil, vegetation, and management systems in reducing soil loss. The canopy of woody vegetation, groundcover, low growing vegetation, and vegetation residues present on the soil surface are taken into consideration as they intercept rainfall from hitting the soil surface directly. In the case of agricultural fields, tillage practices such as type and frequency are also taken into account. Alberta Transportation (2011) recommends that for bare soil, C = 1 be used, for mulch-covered soil, C = 0.1 to 0.2 be used. The USLE formula for calculating the C factor is C = SLR x EI where SLR is the soil loss ratio and EI is the erosivity index, both of which are calculated without accounting for compaction. Table 5.5 lists C-values for various covers.

5.4.5 Support practice (P) factor

P is an erosion control practice factor. The effects of surface management practices which alter the erosive nature of overland flow, such as terracing, are measured. Where no supporting practice is used, as is likely on naturalized or reclaimed land, P equals 1 in the RUSLEFAC equation (Alberta Transportation, 2011; Wall et al., 2002). P-values have been determined based on the measured effectiveness of support practices on test plots relative to one another.

5.5 Calculation and results

Using measurements attained through LiDAR and sieve analysis to attain grain size distributions, RUSLEFAC factor parameters have been calculated. This process quantified predicted soil loss from existing tailings dam slopes which are not anticipated to undergo alteration prior to closure.

Tailings ponds are upland landforms thus they are not likely to act as receiving environments for soil. As such, losses are considered net losses. Process is described below.

5.5.1 R_t factor

The R_t factor was determined using isoerodent maps created for the prairies by (Wall et al., 2002).

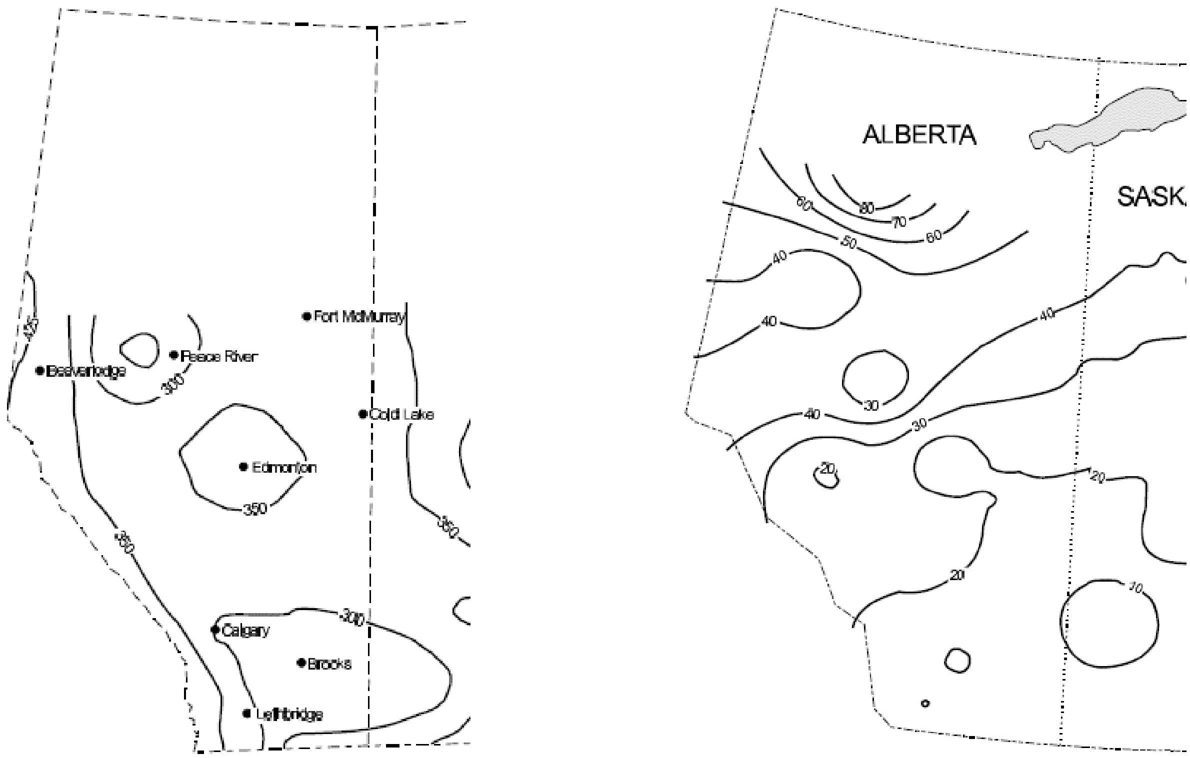

Figure 5.5 (a) Isoerodent map for Alberta showing R values (left), and (b) adjustment value, R_s, for winter conditions in Alberta (right). Note Ft. McMurray, R = 325 and R_s = 40, therefore R_T = 365. Isoerodent maps edited for clarity from Wall et al. (2002).

5.5.2 K factor

K factor was determined using the nomograph that includes particle size percentages, organic matter, soil structure, and permeability. In general, organic matter and salts reduce erodibility while high silt content increases erodibility (Yellishetty et al., 2013). Coarse sand tailings were expected to have low to nil organic matter content, moderate to high salt content due to leaching of process water over time, and low silt content. An equation or the nomograph can be used to calculate K; however, the nomograph is considered to be more precise as it includes refinement over the years. Information required to calculate includes (with values in brackets):

- Percentage of soil in the range of 0.05 - 0.1 mm (29%)
- Percentage of soil in the range of 0.1 - 2.0 mm (64%)
- Percentage of organic matter (0%)
- Soil structure according to RUSLEFAC classification (class 1, or average < 1mm)
- Permeability class according to RUSLEFAC classification (class 3, or moderate)

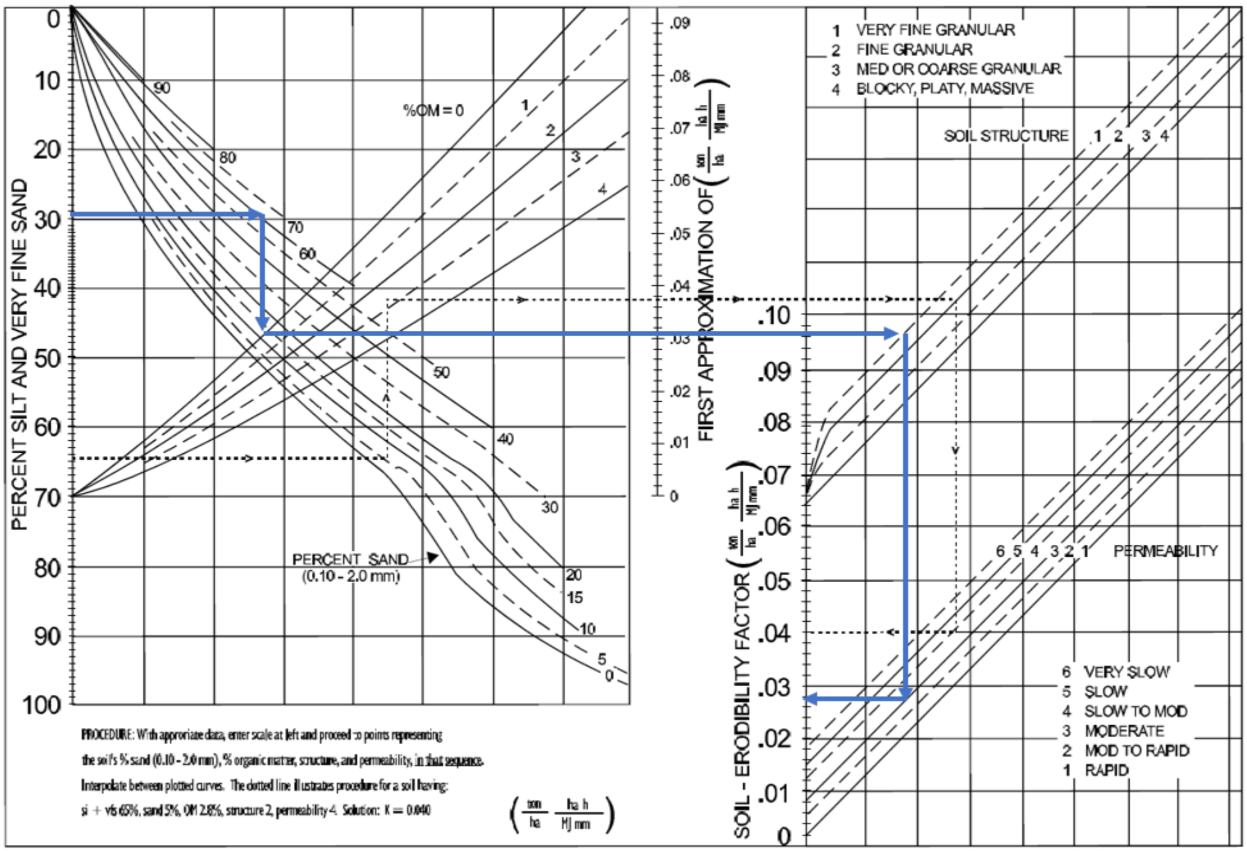

Figure 5.6 Nomograph for determination of K. In this case, for CST we find K = 0.027. From Wall et al., (2002).

The equation used to calculate K is as follows:

$$K = \frac{[2.1\times10^{-4}(12-a)M^{1.14}+3.25(b-2)+2.5(c-3)]}{100} \quad (5.7)$$

Where M = (% silt + very fine sand) x (100 - % clay), *a* is the percentage of organic matter, *b* is the soil structure classification as per Table 5.2, and *c* is the permeability class according to Table 5.3. This equation gives a K value of 0.183 (this is one order of magnitude out of range for the parameter) whereas the nomograph using the same values gives a value of 0.027 equating to a slightly susceptible soil (Table 5.4) (Alberta Transportation, 2011; Wall et al., 2002). Since the nomographs are considered more accurate, the K-factor value of 0.027 is used. It is recommended this be reduced given compacted mining conditions; however, surficial soils tend to be loose on AOS dams, so we have not applied the modifier here.

Table 5.3 Soil structure class adapted from Government of Alberta Transportation (2011), Wall et al. (2002)

Canadian Class	Aggregate Size (mm)	Structure Type
1	< 1	Very fine granular or structureless
2	1 to 2	Fine granular
3	2 to 10	Medium granular
	2 to 10	Coarse granular
4	> 10	Blocky, platy, massive, prismatic

Table 5.4 Permeability class as adapted from Government of Alberta Transportation (2011) & Wall et al. (2002).

Textural Class	Permeability Class	Hydraulic Conductivity cm/sec	Hydraulic Conductivity In/hr
Gravels, coarse sands	1 - rapid	>0.0044	> 6.3
Loamy sands and sandy loams	2 - moderately rapid	0.0014 to 0.0044	2.0 to 6.3
Fine sandy loams, loams	3 - moderate	0.00044 to 0.0014	0.63 to 2.0
Loams, silt loams, clay loams	4 - moderately slow	0.00014 to 0.00044	0.2 to 0.63
Clay loams, clays	5 - slow	0.000044 to 0.00014	0.063 to 0.2
Dense, compacted	6 - very slow	< 0.000044	< 0.063

Table 5.5 K ranges and susceptibility to erosion. From Wall et al. (2002).

Surface Soil Texture	Relative Susceptibility to Water Erosion	K ranges[1]
Very fine sand	Very highly susceptible	>0.05
Loamy very fine sand Silt loam Very fine sandy loam Silty clay loam	Hiighly susceptible	0.04 - 0.05
Clay loam Loam Silty clay Clay Sandy clay loam	Moderately susceptible	0.03 - 0.04
Heavy clay Sandy loam Loamy fine sand Fine sand Coarse sandy loam	Slightly susceptible	0.007 - 0.03
Loamy sand Sand	Very slightly susceptible	<0.007

[1] K values may vary, depending on particle size distribution, organic matter, structure and permeability of individual soils

5.5.3 LS factor

The topographic factor, LS, was calculated using the following equation for uniform slopes:

$$LS = (sl/22.13)^m S \qquad (5.8)$$

And for slopes with gradients greater or equal to 9% and greater or equal to 5 m in length, where:

$$S = 16.8 \sin\theta + 0.5 \qquad (5.9)$$

For equations 5.8 and 5.9 above, *sl* is the slope length in meters, θ is the slope angle in degrees, and m is a coefficient equal to 0.5 for slopes with an angle greater than 5%. Using these equations, and the average dimensions for the downstream face of the dams (*sl* = 400 m; θ = 8.53°), the LS factor is 12.55. This assumes a uniform slope of the same dimensions around the entire ring dyke.

5.5.4 C factor

The C value, also known as the vegetation management factor, is not applicable to an unvegetated tailings dam (C=1), as the management practices taken into consideration such as tillage practices and crop type do not exist. Approximately 1/6th of the dam slope was vegetated with short broadleaf brush with average drop fall height of 20 inches, 50% coverage, 20%

ground cover (C = 0.16) at the time of the study, therefore this was weighted to calculate the C value as follows:

$$C = \frac{1}{6}(0.16) + \frac{5}{6}(1) = 0.86 \quad (5.10)$$

This factor will be of more use once vegetation is established, and as a result, erosion estimates will be lowered considerable.

Table 5.6 C values for idle land for grasses, G, and broadleaf vegetation / weeds, W, where canopy height refers to the average fall drop height from canopy to ground as per Government of Alberta Transportation (2011), Wall et al. (2002).

Vegetative Canopy Type and Height	Percent cover	Type	Cover that contacts the soil surface Percent ground cover					
			0	20	40	60	80	95+
No appreciable canopy		G	0.45	0.20	0.10	0.04	0.01	0.00
		W	0.45	0.24	0.15	0.09	0.04	0.01
Tall weeds or short brush with average drop fall height of 20 inches	25	G	0.36	0.17	0.09	0.04	0.01	0.00
		W	0.36	0.20	0.13	0.08	0.04	0.01
	50	G	0.26	0.13	0.07	0.35	0.01	0.00
		W	0.26	0.16	0.11	0.08	0.04	0.01
	75	G	0.17	0.10	0.06	0.03	0.01	0.00
		W	0.17	0.12	0.09	0.07	0.04	0.01
Appreciable brush or bushes, with average drop fall height of 6 1/2 feet	25	G	0.40	0.18	0.09	0.04	0.01	0.00
		W	0.40	0.22	0.14	0.09	0.04	0.01
	50	G	0.34	0.16	0.08	0.04	0.01	0.00
		W	0.34	0.19	0.13	0.08	0.04	0.01
	75	G	0.28	0.14	0.08	0.04	0.01	0.00
		W	0.28	0.17	0.13	0.08	0.04	0.01
Trees, but no appreciable low brush. Average drop fall of 13 feet	25	G	0.42	0.19	0.10	0.04	0.01	0.00
		W	0.42	0.23	0.14	0.09	0.04	0.01
	50	G	0.39	0.18	0.09	0.04	0.01	0.00
		W	0.39	0.21	0.14	0.09	0.04	0.01
	75	G	0.36	0.17	0.09	0.04	0.01	0.00
		W	0.36	0.20	0.13	0.08	0.04	0.01

5.5.5 P factor

The support practice factor (P) refers to the crop management efforts that are done to adjust flow patterns, slopes, or flow direction, in order to reduce erosion. In the case of both vegetated and non-vegetated portions of the dam, no crop management is taking place presently, therefore P=1.

5.5.6 Calculation

For the inputs and characteristics considered above, the resulting average annual erosion rate calculated using equation (5.6) is about 108 Mg ha^{-1} yr^{-1}, shown in equation 5.11. This equates to a denudation rate of approximately 7 mm/year.

Table 5.7 Factor values selected for RUSLEFAC calculation

USLE Factor	Value	Range of adjustment
Rainfall and runoff, R_t (MJ mm ha^{-1} h^{-1})	365	-
Soil erodibility, K (t h MJ^{-1} mm^{-1})	0.027	0.001-0.027
Slope length and steepness, LS (dimensionless)	12.71	2.69-12.71
Crop/vegetation management, C (dimensionless)	0.86	0-1
Support practice, P (dimensionless)	1	0-1

$$A = (365)*(0.027)*(12.71)*(0.86)*(1) = 107.72 \tag{5.11}$$

Once the dam is fully reclaimed and vegetated the C-value and possibly the P-value will reduce. If substantial cover soils and organic matter is introduced at the surface, the K value is also expected to decrease. Table 5.7 categorizes this value as substantially larger than what is considered to be "very high" according to Government of Alberta Transportation (2011).

Table 5.8 Hazard classification due to erosion. Adapted from Alberta Transportation (2011) and Wall et al. (2002). Note that 1 megagram (Mg) is equal to 1 tonne.

Soil Erosion Hazard Class	Soil Erosion Potential (Mg / hectare/year)
Very low (tolerable)	< 6
Low	6 - 11
Moderate	11 - 22
High	22 - 33
Very High	> 33

It is likely, as shown in the calculation of the C factor that this number will decrease by about 80% once the entire structure is revegetated. Note this estimate does not include erosion due to gully formation.

USLE can be used to quickly and roughly evaluate options for decreasing soil loss due to sheet and rill erosion. In this instance, options include alteration of soil erodibility (K factor), slope length and steepness (LS factor), and intensification of vegetation (C factor). For example:

- Established vegetation coverage in excess of 80% can reduce the C factor to 0.01, with the result of reducing soil loss to a little over 1 Mg ha^{-1} y^{-1}. This degree of revegetation is unlikely on a CST structure and does not consider forest fire, pests and disease, or wind, all of which can all negatively impact vegetation canopy.
- If dam slopes were allowed to be extended by 200 m (for example), soil loss could be reduced to 23 Mg ha^{-1} y^{-1}. This option is unlikely, particularly on the dam studied herein, as no buffer exists around much of the structure.
- Decrease soil erodibility. The lower limit of allowable K-factors is 0.001, and if soil were to be adjusted to this value the total soil loss would decrease to 4 Mg ha^{-1} y^{-1}. In order to attain the full extent of this K-factor reduction, coarser soil and organic matter would need to be integrated; this may not be realistic for the entire length of perimeter dam but may be for isolated locations.

This quick analysis shows that soil loss due to sheet and rill erosion can be minimized though several practices, with some being more practical than others. Note the soil loss rates above (all of which equate to less than 2 mm/year) are annual estimates and therefore do not account for climate change or cumulative effects over time. Mitigation scenarios in terms of dam design are further assessed in Chapter Ten.

5.6 Summary and conclusions

Many post-mining landforms in the AOS will be capped with CST or entirely constructed of CST. Exposed CST has long been recognized as being erodible, but with the exception of Sawatsky et al. (1996), few studies have focused on the erosion potential of exposed CST and CST-constructed landforms, particularly over longer time frames than a single storm.

Using RUSLEFAC, annual soil loss due to rills and sheet erosion was estimated for a standard section of the TSF downstream dam slope. In its 2017 state of reclamation, erosion on this particular dam was estimated to be over 100 Mg ha^{-1} yr^{-1}, which meets a ‘very high’ hazard class according to Alberta Transportation (2011) (Table 5.7). This value is expected to decrease substantially once the entire dam slope is revegetated.

While this empirical approach to erosion estimation is limited, is acts as a precursory step and validates the concern for erosion potential on downstream dam slopes. Chapter Six will continue this investigation of dam erosion through characterization and direct measurement of actual erosion (predominantly due to gullies) on the TSF and SEA dams, while Chapter Eight will use a process-based computer model to predict soil loss over long time frames in three dimensions on the dams.

6.0 Identification and quantification of erosion on a sand tailings dam

The following is journal article published in 'Geosystem Engineering' that outlines two remote methods of erosion assessment, including erosion characterization and quantification:

Slingerland, N., Sommerville, A., O'Leary, D., Beier, N.A. (2018). Identification and quantification of erosion on a sand tailings dam, *Geosystem Engineering*, DOI: 10.1080/12269328.2018.1538823

6.1 Introduction

Mining is a prolific global industry; it is estimated there are more than 10,000 mine sites in Canada, including inactive and abandoned mines (Cowan, Mackasey, & Robertson, 2010; Mackasey, 2000). During operation each of these (relatively small) sites is actively maintained; however, once mining ceases maintenance is often reduced as the land continues to be subject to physical and chemical weathering processes, sometimes impacting areas off site. Best practices have evolved over the last several decades to the point where mines are now expected to be reclaimed such that they do not pose a threat to human or environmental health (ICOLD, 2013). These recent international best practices extend the length of time that work is conducted on site and introduce new costs, particularly with respect to the extended monitoring required for performance assessment.

Degradation of mining landscapes can expose encapsulated mine waste via large-scale slope slumping, sloughing, rock slides, and erosion. This exposure creates a fresh surface for interactions with the environment, and can lead to discharge of contaminated water and sediments on site reducing the effectiveness of drainage structures, or off-site with more substantial environmental, human health, and public safety ramifications (Hancock & Evans, 2006; Kingsmere Resource Services Inc, 2016). Considering the global extent of mining, the geomorphology of these anthropogenic mine landscapes is of broad importance, particularly in terms of environmental consequence, downstream impact, and implications for closure regulation internationally.

Erosion occurs via wind and water interactions with the ground surface. The magnitude of wind erosion is not affected by topographic parameters such as slope length or gradient, but is affected by surface roughness which can be mitigated through vegetation (Lancaster & Baas, 1998; Schor & Gray, 2007).

Overland flow, subsurface flow, and subsurface discharge are the three main components of run-off: a predictor of erosion due to water movement (Dunne & Black, 1970). Overland flow is the most important component of run-off as it not only provides erosive forces but also dictates transport and deposition of eroded materials. Rill erosion occurs when overland flow down a slope is concentrated, generating thin but distinct channels, or 'rills'. This concentration of flow generates greater flow velocity and energy in the rills than is created by sheet flow, thus the potential for soil erosion and transport is greater. Most erosion associated with rainfall occurs due to rill erosion (Schor & Gray, 2007). Gully erosion occurs when flow is concentrated and fast enough to remove soil to a depth and width that cannot be crossed by normal tillage equipment. This ambiguous definition comes from agriculture and has been the standard for many years. More precisely, any fluvial erosion feature 0.3 m or deeper has been considered a gully by some (Dunne & Leopold, 1978; Queensland Government, 2013), while others have considered gullies to be any fluvial erosion greater than 75 mm in depth (Fifield, 2001; Government of Alberta Transportation, 2011; P4-2).

This research focusses on tailings dams constructed to hold (encapsulate) slurried mine waste, or tailings, in the Athabasca oil sands (AOS) and the erosion processes acting on them. Tailings dams are common in mining, and throughout the oil sands region. Tailings dams typically present the greatest inherent risk on a mine site, and this continues well after closure (ICOLD, 2013). However, it has been previously noted that the geomorphology of mining landscapes is an area where few studies have focussed (Martin-Duque, Zapico, Oyarzum, Lopez-Garcia, & Cubas, 2015). The tendency of tailings sand-constructed dams to erode was documented in the 1970s (Rowell, 1979); however, little has been published on the subject since this time. Initially, soil stability investigations occurred to evaluate the impact of vegetation and fertilization on dam erosion (Rowell, 1979). Later, Sawatsky et al. (1996) used a rainfall simulator to apply multiple precipitation intensities to AOS sand tailings dams for periods less than 2 h to study erosion on plots with various degrees of reclamation. Most recently, McKenna (2002) conducted extensive laboratory and field flume testing of mostly oil sands clay shale and a few CST samples, regarding gully erosion and implications for the design of overburden-constructed landforms.

Elsewhere, erosion has been more closely examined. Gilbert and Murphy (1914) made one of the first in-depth attempts to quantify erosion and its contributing factors while working at the United States Geological Survey. Quantification of erosion is of interest on mined landscapes in order to determine sediment loading to surrounding areas and to plan and design appropriate control measures. Hancock and Evans (2006) determined gully characteristics and development thresholds in an effort to model gully position and development. Later Hancock, Lowry, Moliere, and Evans (2008) attempted to quantify rills as a precursor to gully development using a terrestrial laser scanner. Yellishetty, Mudd, and Shukla (2013) used the empirical Revised Universal Soil Loss Equation (Wischmeier & Smith, 1978) to quantify soil erosion from iron ore mines in India and potential environmental impacts. Similarly, Kim et al. (2012) used the Universal Soil Loss Equation (Wischmeier, Johnson, & Cross, 1971) in conjunction with Geographic Information Systems (GIS) maps (a digital elevation model (DEM), a soil map, and a land cover map) to estimate soil loss due to erosion on a tailings slope in Korea. Martin-Duque et al. (2015) quantified erosion on tailings dams in Spain by calculating volume change between Light Detection and Ranging (LiDAR)-generated DEMs representing the topography at two points in time 45 years apart.

Despite prior documented concern for erosion on oil sands tailings dams (Rowell, 1979), the causes, active processes, and the scale of dam erosion have not yet been fully evaluated. Erosion control is often noted by reclamation scientists as a major goal (Toy & Black, 2000); therefore, as dams approach the end of their active life, an understanding of erosion and erosion monitoring methods is required to aid reclamation planning. The objective of this research is to identify if any signs of erosion exist on an oil sands tailings dam, to classify the type of erosion and active processes involved, and to quantify the extent of erosion, and therefore the relative hazard class.

6.1.1 Tailings dam legislation and risk

Tailings dams are constructed above-grade to hold liquid mine waste produced through mineral processing. Tailings storage facilities (TSFs) refer to both the dams and the tailings held by the dams. TSFs are among the first construction sites on a mine, and one of few engineered structures that remain in perpetuity. Sand tailings dams are presently built up to 260 m in height as is the case at the Quebrada Enlozada TSF in Peru (Obermeyer & Alexieva, 2011), and can cover tens of square kilometres, as found in the AOS. Capacity varies, but the global trajectory has been towards higher capacities, and therefore taller and/or longer dams (Robertson, 2011). As capacity increases, so too does the consequence of failure, thereby escalating risk. Tailings dams can fail by a number of chemical and physical means. Physical mechanisms include slope failure, foundation failure, surface erosion, and internal erosion (seepage), resulting in property damage, environmental damage, fatalities, significant economic impact, and criminal charges (LePoudre, 2015). The 2015 Fundão dam and 2019 Feijão dam failures in Brazil, are recent examples that lead to all of these direct and indirect consequences (Morgenstern, Vick, Viotte, & Watts, 2016). The long lifespan of TSFs, their broad range of failure modes, and extreme failure consequences make them sensitive earthen features. These same criteria make their geomorphic changes of interest and significance to all stakeholders.

The design life for a reclaimed TSF is more frequently considered to be greater than 1000 years (ICOLD, 2013). The probability of extreme weather events, land-use change, changes in material properties, etc. (all of which influence geomorphology and erosion) increases over time; as such, design for dam delicensing and reclamation must consider a broad set of potential failure mechanisms.

Global trends in tailings dam reclamation have moved towards their conversion into solid landforms over time. This process is hypothesized to reduce inherent risk and allow for eventual delicensing once the former dams behave similarly to natural terrain (OSTDC, 2014). This ideal has been adopted in Alberta and is illustrated in Figure 6.1. The realities this imposes on mine owners are twofold: (1) long-term active monitoring in order to identify when undesirable behaviour is occurring so that it might be rectified in a timely manner, followed by (2) long-term passive monitoring to identify when a new landform / former tailings dam no longer poses a threat. In order to follow this proposed path towards delicensing, failure modes should be known such that the appropriate monitoring technique is used. This research seeks to determine if erosion is occurring to an extent that it may be a concern in the future, and to evaluate two forms of future monitoring.

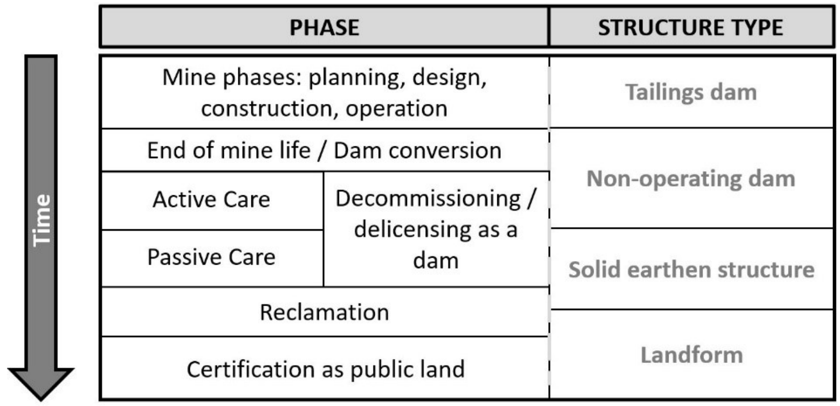

Figure 6.1 Proposed dam delicensing and reclamation process in Alberta, corresponding to international best practices. Adapted from OSTDC (2014).

6.1.2 The AOS

The absence of significant upland topographic diversity in the AOS region (Figure 1.1) necessitates the use of ring dams to store tailings. These dams can have circumferences in excess of 20 km, range from 40 to over 100 m in height, and have some of the largest storage capacities of any dams on earth. Mildred Lake Settling Basin, an TSF operated by Syncrude Canada Ltd., has an approved maximum tailings capacity over 1.1 billion m^3, inclusive of tailings used to construct the dams (Alberta Energy Regulator (AER), 2018). There are presently 14 above-grade TSFs in the AOS, with more in planning and design stages (AER, 2018).

Tailings dams in the AOS are constructed predominantly of the coarse fraction of tailings (‘coarse sand tailings’ or CST); the sand dams are raised and compacted in successive lifts, behind which fluid fine tailings are poured (Figure 6.2). CST is composed of silt and fine sand-sized solids, contributing to its relatively high permeability. The Oil Sands Conservation Act (Regulation 76/1988, 27b) (Province of Alberta, Revised Statutes of Alberta 2000) dictates that mining and site planning maximize the recovery of oil sand on the leased parcel of land. This has several implications with respect to the design of mine sites and tailings dams; however, of particular relevance is that tailings dams are often allotted little to no buffer for expansion or deposition of eroded sediment. They are often placed immediately adjacent to lease boundaries that can coincide with environmental buffers, and/or regional infrastructure such as highways.

Any dam failure would have a detrimental effect on both the AOS region and the many mine operators. As such great care is taken in their construction, monitoring, and maintenance throughout the mine life, as regulated by the Regulator and Alberta Government. Tailings dams and their contents covered a cumulative 176 km^2 of northern Alberta in 2013, and this is expected to increase as new mines begin production in the coming years (Grant, Angen, & Dyer, 2013).

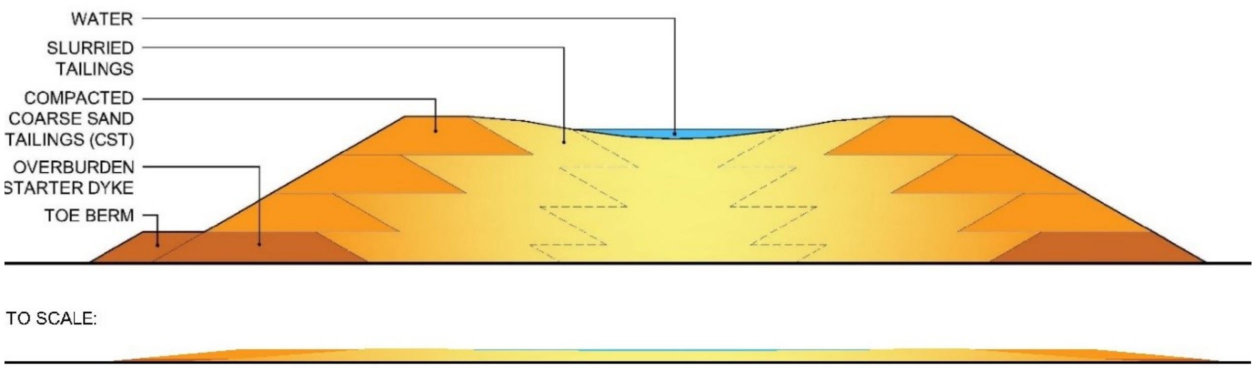

Figure 6.2 Upstream tailings dam construction in the oil sands. Shown to scale on bottom. Adapted from Slingerland, Beier, & Wilson (2018).

6.1.3 Research objectives

Given their long design life, the close proximity of lease boundaries to dam toes, and the concern regarding possible CST dam erosion, the objective of this research is to investigate the erodibility of tailings sand dams in the AOS. The following questions guided this work: (1) What can be learned from the present state of AOS sand dams with respect to erosion characteristics that will improve their design for perpetual stability? and (2) How can presently available remote methods better equip regulators and mine owners to monitor dam performance efficiently and effectively throughout reclamation with respect to erosion?

6.2 Study location

6.2.1 Climate and vegetation

The AOS is located within the Boreal Plains ecozone. Mean annual temperature is 0.7°C (daily means ranging from −18.8°C to +16.8°C throughout the year) and mean annual precipitation (455.5 mm) can range from 300 to 600 mm from year to year (Gillanders, Coops, Wulder, & Goodwin, 2008; Government of Canada, 2018). The area is sub-humid, with annual potential evapotranspiration regularly exceeding annual precipitation (Johnson & Miyanishi, 2008; Ketcheson & Price, 2016). Summer rainfall between June and August accounts for about 67% of mean annual precipitation (Keshta, Elshorbagy, & Carey, 2012), corresponding to periods of high evapotranspiration and therefore reducing surface water pooling and overland flow during these months (Johnson & Miyanishi, 2008; Ketcheson & Price, 2016). Precipitation events also tend to be convective in nature, meaning they are relatively short in duration but high in intensity. These high intensity storms are expected to cause much of the erosion presently observed on TSF dams (Table 6.1). Since 2003 the study site has not been subjected to any precipitation events greater than a 1 in 6-year return period (Figure 6.3).

Table 6.1 Fort McMurray climate normals (1981 - 2010) from Government of Canada (2018).

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Precipitation (mm)	17.7	13.2	16.7	21.4	36.5	73.3	80.7	57.1	39.7	26.2	19.9	16.4
Temperature (°C)	-17.4	-13.3	-6.2	3.3	9.9	14.6	17.1	15.4	9.5	2.3	-8.6	-15.1

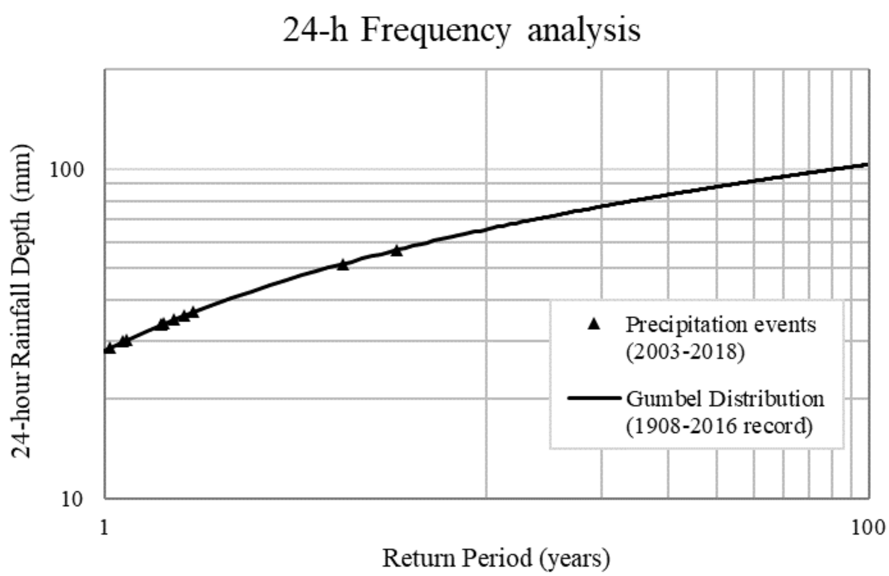

Figure 6.3 Return period of large precipitation events on study site in AOS as shown in context of historic records. Gumbel distribution was calculated from an extended climate record for Fort McMurray (1908 - 2016) documented in Song, O'Kane, Dhadli, & Matthews (2011). January 2003 - January 2018 precipitation events acquired through the Regional Aquatics Monitoring Program (RAMP) for the study site.

6.2.2 Physiography and geology

The TSF assessed herein is located approximately 65 km north of Fort McMurray in northern Alberta, Canada. Grain size distributions from surficial CST collected along the dam are shown in Figure 6.4, illustrating their range in size from erosion-susceptible silt to fine sand.

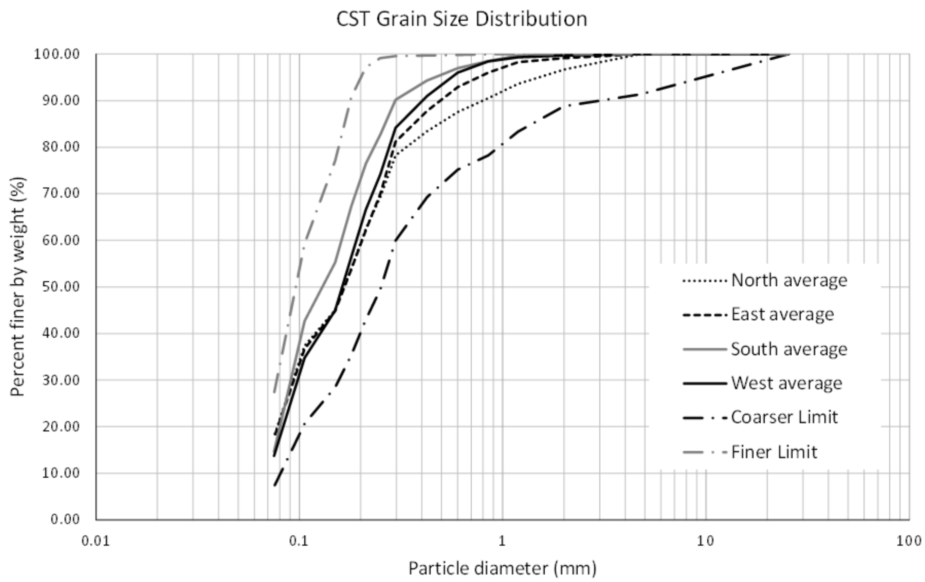

Figure 6.4 Grain size distributions of surficial CST collected from downstream dam slopes.

Once infilling is complete, the TSF will store more than 500 million m^3 of tailings over 14 km^2 to a maximum height greater than 60 m (AER, 2018). As of 2011 and 2016, 14% and 23%, respectively, of these dams had been reclaimed with the surficial addition of peat-mineral mix and locally common vegetation.

6.3 Methods

Three methods were used to gather information on the study site north of Fort McMurray: in-person field assessment, LiDAR data, and RGB digital stereo aerial photography. Large, recent erosional features were sought out along the perimeter dam using each data set: once identified their cause was determined based on geometry and characteristic geomorphic form, dimensions were taken where possible to calculate volume, and observations were recorded with respect to ease of collection throughout the process.

6.3.1 Field investigation

At the end of May 2017, fieldwork took place to identify erosional features in-person. Photographic documentation and mapping of the features was systematically completed along the 17 km of perimeter dam restraining the aboveground oil sands tailings. Large wind and water-formed erosion features covering a minimum of several square meters were of greatest interest since they pose a greater risk to the stability and reclamation of the dams post-closure compared to smaller erosional features. Erosion features were not individually dimensioned in-person as this was not practical for the entire structure.

6.3.2 LiDAR analysis

The most recent LiDAR data for the study site were taken in October 2016 and provided in .dwg format by the TSF owner and operator for the purposes of this study. The data were high resolution with a 95% horizontal accuracy of 40 cm, a fundamental vertical accuracy (95%) of 25 cm, and a minimum of 1 point/m^2. In order to visually represent the data points, a three-dimensional triangular irregular network (TIN) surface was created from the LiDAR points in the area of the TSF using AutoCAD Civil3D (Autodesk Inc., 2016). One-metre contours were generated from the TIN surface, giving information and appearance similar to that of a topographic map, and the LiDAR points were turned off for ease of viewing.

Within AutoCAD Civil3D, the perimeter dam was once again systematically navigated in search of anomalies within the contours that would represent erosional features. Each gully was given an identification number, then its average width, average depth, total length, and approximate surface area covered were measured. To quantitatively estimate the volume of CST removed within each gully a basic ‘V’ shape was assumed using the following equation:

$$Gully\ Volume = \frac{A_s \times d_{ave}}{2} \tag{6.1}$$

Where A_s is the plan-view surface area of the gully in square meters and d_{ave} is the average gully depth in meters. Figure 6.9 shows the surface area of representative gullies in grey. Depths were taken at each crossing contour from the gully edge, running perpendicular to the bottom, then the sum of all depths was divided by the total number of contours to get an average. Erosion features less than 0.3 meters in depth were not included in the database due to relative accuracy of the LiDAR data itself, as well as our definition of what constitutes a gully. Potential cause based on topographic indicators was recorded, and mass of CST eroded was calculated using dry density of the sand. Other calculations included total volume of soil loss from the TSF, soil loss totals for each dam section, and the average dimensions of gullies, as was overall gradient of the dam slope before and after gullying took place. These dimensions and measurements were plotted to identify trends in volume and location.

6.3.3 Digital stereo aerial photography analysis

Colour stereo aerial photographs were used in conjunction with ArcGIS (version 10.4.1) and PurVIEW (version 2.0.3.5c) softwares to view the TSF and terrain in three dimensions. Vertical 40-cm resolution photographs taken in August 2011 with an UltraCam XP camera and a 100-mm focal length from an altitude of 23,400 ft were used for visualization. PurVIEW is an application for ArcGIS that allows for stereo viewing with the ability to zoom in and out of imagery. The geo-referenced photos were overlapped and projected using a 120 Hz LCD monitor, while 60 Hz frames are viewed by each eye using LCD 3D vision glasses.

The TSF perimeter dam was systematically navigated in stereo at a scale of 1:750. Gully erosion and mass wasting features were outlined with a polygon along their perceived edges, and smaller rills were identified with a straight line. Each feature was given an identification number, then the length, average width, average depth, and planar surface area of gullies and mass wasting features were recorded, while length was recorded for rills. Volume of CST was calculated using Equation (6.1) for each gully. Eroded volumes for each dam section were totalled, average dimensions calculated, and absolute dimensions were graphed to determine new trends. In order to determine the mass of eroded material, volumes were multiplied by the bulk density of CST. Comments were also recorded for each feature with respect to characteristics and causation.

The purpose of using multiple methods to identify and quantify erosion was to evaluate the relative advantages and disadvantages of each in preparation for reclamation monitoring of TSFs in the region. It is therefore important to note that while the majority of perimeter dams surveyed at our study site were constructed to full height prior to 2011 when the digital stereo aerial photographs were collected, un-reclaimed areas on the TSF (or 86% of dykes) were under constant traffic and construction by large earth-moving equipment. By 2016 when LiDAR data were taken 77% remained un-reclaimed.

6.4 Results

6.4.1 Field investigation

During the 2017 field investigation, a number of gullies (some greater than 2 m deep at their deepest point) and many areas of rill erosion were identified. Additionally, wind-formed sand ripples and blown sediment were visible. Photographic documentation was used to capture the scale of erosional features in three dimensions.

Gullies were identified in several areas during the field investigation. Figure 6.5 (a,b) shows a large gully and downstream deposition of the eroded sediment in an alluvial fan-like form. This particular gully was formed by ponding water at the top of the north side of the dam that eventually found a path of least resistance to lower ground. Considering the grain size distribution of CST, this erosion would correspond to flow speeds equal or greater than 20 cm/s on the Hjulström-Sundborg diagram (Sundborg, 1956). These gullies have characteristic near-vertical sides and head scarps, but low gradient slopes along their centre lines. Deep gullies vary along the bottom from narrow and flat to broad and flat depending upon how much of the bottom has been filled with eroded sediment. Shallow gullies are more pointed along the bottom. Rills were also identified during field investigation. Figure 6.6 shows a series of rills 10–15 cm in depth running parallel to the TSF slope, distinguishable by the alternating coarse and fine sediments. Fine sediments line the base of the rill, while coarser sediment is found between rills.

Figure 6.5 Gully identified on north side of AOS tailings dam resulting from pooling water and concentrated flow (a, left), and resultant deposition of sediment in fan-like form (b, right).

Wind erosion was noted in the field, particularly on the upper portions of the dams. Figure 6.7(a) shows light coloured wind-blown CST with an area of deflation in the background and wind ripples clearly visible in the foreground. A 0.3-m long trowel has been placed adjacent to the wind ripples in Figure 6.7(b) to provide scale. These wind ripples are formed by saltation: a chain reaction process by which a sand grain mobilized by wind collides with other sand or silt-sized particles, displacing them into the air and continuing the process when they land on other sand grains (Sauer & Elder, 1986). Silt tends to be suspended in the turbulent air more easily than sand due to its small grain size, and this was evident on site with significant blowing sediment at heights greater than 1.8 m above grade.

Figure 6.6 Rills created by water erosion on north-east side of AOS tailings dam.

One 2-m deep gully was found in an area that had been reclaimed with organic-mineral growth medium and low-to-medium height shrubs and grasses. In general, rills and signs of wind erosion were less prevalent in the reclaimed areas than in CST-exposed dams.

Figure 6.7 a (left) and b (right) Deflation can be seen in the upper left on (a) and wind ripples on the bottom and right. (b) Wind ripples. Both photographs were taken on the south-east corner of an AOS tailings dam.

6.4.2 LiDAR analysis

In total, 190 gullies were identified from the 2016 LiDAR data, cumulatively equivalent to approximately 14,830 m^3, or 23,740 tonnes, of eroded soil. Six of these were on reclaimed areas of the dam. The mean gully length and width were 39.59 and 4.15 m, respectively, while mean depth was 0.89 m. Gully depth ranged from 0.35 (0.05 m deeper than our chosen threshold for gully definition) to 2.44 m. Gully statistics identified through LiDAR analysis are recorded in

Table 6.2. Due to the LiDAR precision, it was not possible to definitively identify rills or wind-blown erosion locations.

Table 6.2 Gully statistics acquired through 2016 LiDAR analysis of tailings dams

	Length (m)	Width (m)	Depth (m)	Area (m^2)	Approx. volume (m^3)	Mean slope prior to erosion	Mean slope post-erosion (%)
Mean	39.6	4.1	0.9	277.2	136.2	37.2	19.5
Standard Deviation	41.9	2.4	0.4	539.8	320.6	18.8	11.4
CV%	105.9	58.9	40.1	194.7	235.4	50.6	58.5
Min.	5.8	1.5	0.3	7.8	2.5	6.0	0.9
Max	337.0	20.0	2.4	5050.0	3640.2	90.9	60.4

Note: CV% = coefficient of variation, demonstrating the extent of variation in relation to the mean.

Gullies were initiated on dams with mean pre-erosion slopes between 6% and 91%, and areas with a high density of gully occurrence did not consistently correspond to areas with the steepest downstream slope gradient. As such, no critical slope threshold was identified for initiation of gullies. This is comparable to other AOS sand dams that have seen extensive gullying on downstream slopes graded to 4% overall (Booterbaugh, Bentley, & Mendoza, 2015). The trajectory of bottom slopes within gullies was generally towards nearly flat final slopes as shown in Table 6.2. The width-to-depth ratio ranged from 1.4 to over 18, with a mean value to 5.1, indicating that depth was not limited by internal structures, geotextiles, or less erodible soil layers, for example. No strong statistical correlation was found between gully depth, width, and area (Figure 6.8), which agrees with findings from undisturbed terrain in other regions (Hancock & Evans, 2006). This lack of statistical correlation also speaks to the variable mechanisms that are actively causing erosion on the site.

The data does tell us that most gullies are between about 0.3 and 1.5 m deep, and less than 100 m long. Soil moisture content increases with depth, therefore one hypothesis is that the sand reached a level of saturation at about 1.5 m depth that made it less erodible. On unreclaimed areas, there are few locations along the dam where the slope is continuous for more than 100 m, with most steep areas being broken up by an area of reduced slope (or a bench/platform) about every 50 m in the downslope direction. Total volume of soil loss generally increased with total gully length, albeit this correlation was slight. Soil loss volumes may therefore be more indicative of the initiation mechanism than length or width. Figure 6.9 illustrates that the majority of gullies are relatively low in volume, generally less than 50 m^3; these tend to be generated from the merging of smaller rills.

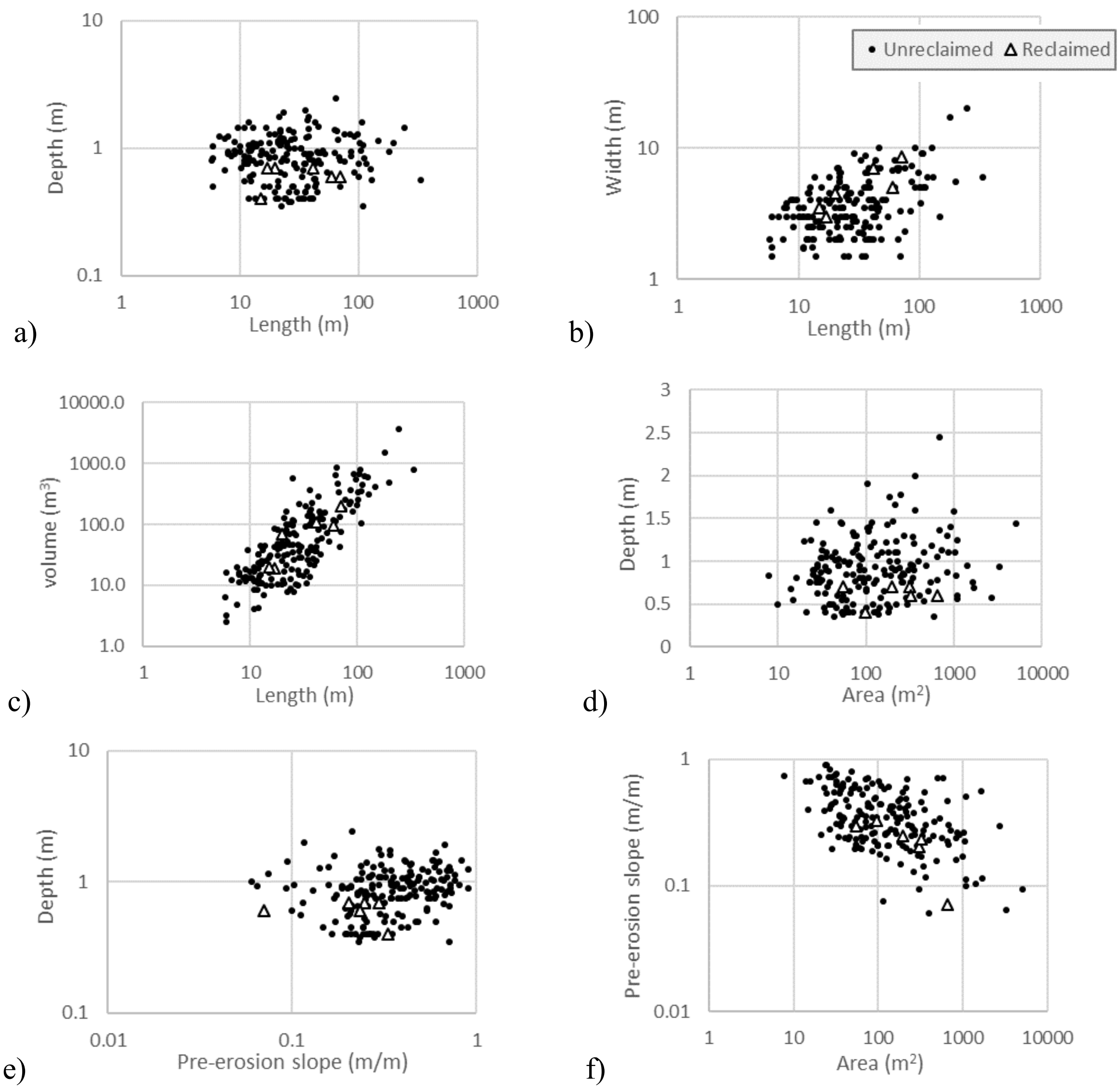

Figure 6.8 Gully length, width, depth, area, and pre-erosion slope characteristics for those found on reclaimed and un-reclaimed dam slopes Slight correlation between volume and length was found, although other properties demonstrated little correlation, perhaps due to the variation in cause.

Causes of the gullies were identifiable in many cases from the characteristic patterns made by topographic contours. Many large gullies were formed due to ponding of water on dam platforms which was eventually released. Ponding water is most likely a result of high-intensity precipitation events, since the infiltration capacity and permeability of CST is high (5×10^{-4} cm/s) (McKenna et al., 2010). Access roads to the top of the TSF were also common locations for gullying, as flow is collected and directed with CST road-side berms. Additional causes included seepage, indicated by a characteristic scalloped appearance to the terrain, and minor landslides possibly caused by over-steepened slopes, seepage, or toe erosion (see examples in Figure 6.10). Cross sections are similar to those seen during the field investigation with steep side slopes and head scarps.

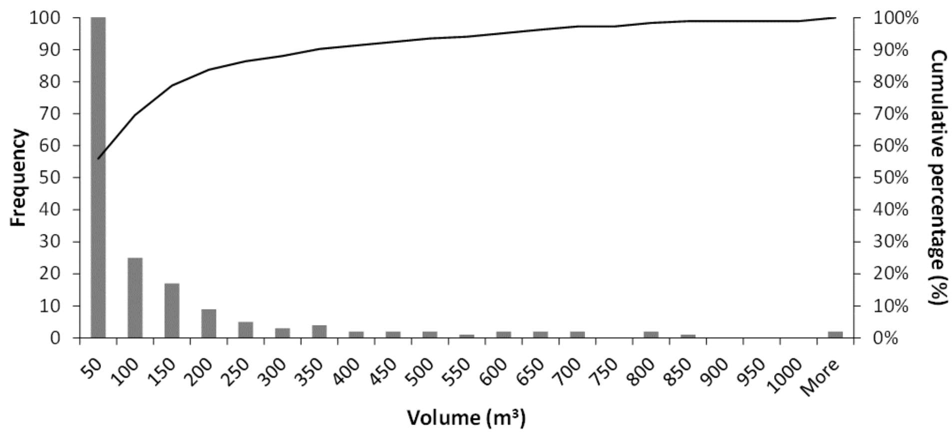

Figure 6.9   Histogram of measured gully volumes

Since tailings dams in the oil sands are regularly maintained, it is conservative to assume that the gullies measured were initiated within the last year. The yearly rate of erosion due to gullies and earth flows was therefore calculated based on the full 490 ha of downstream dam slope analyzed to be 48 Mg/ha/year (megagrams/ hectare/ year). Note that 1 megagram = 1 tonne. Broken down into unreclaimed and reclaimed areas we find that these rates shift to about 57 Mg/ha/year and 4 Mg/ha/year, respectively. This amount of soil loss corresponds to a 'very high' hazard classification for unreclaimed and 'very low' hazard classification for reclaimed areas according to Alberta Transportation and Agriculture and Agri-Food Canada (Table 6.3), two entities responsible for much of the erosion management and evaluation work in Alberta, Canada. A tolerable amount of soil loss is considered that which does not negatively affect hillslope productivity, considered in Canada to be generally less than 6 Mg/ha/year (Wall, Coote, Pringle, & Shelton, 2002). In comparison, erosion on abandoned and/or unvegetated mining landscapes in other regions has been measured between 93 Mg/ha/year in south-eastern Wales and 425 Mg/ha/year in northern Queensland, Australia, respectively (Haig, 1979; So, Yatapange, & Horn, 2002). With consideration for the high erodibility of CST sediments, these higher values may provide a general estimate of the scale of erosion possible in the case of mine site abandonment. Of the more than 190 gully and earth flow erosional features identified, six occurred on reclaimed dam slopes. Overall the drainage density of gullies was about 1.5 km per square kilometer of (downstream) dam slope.

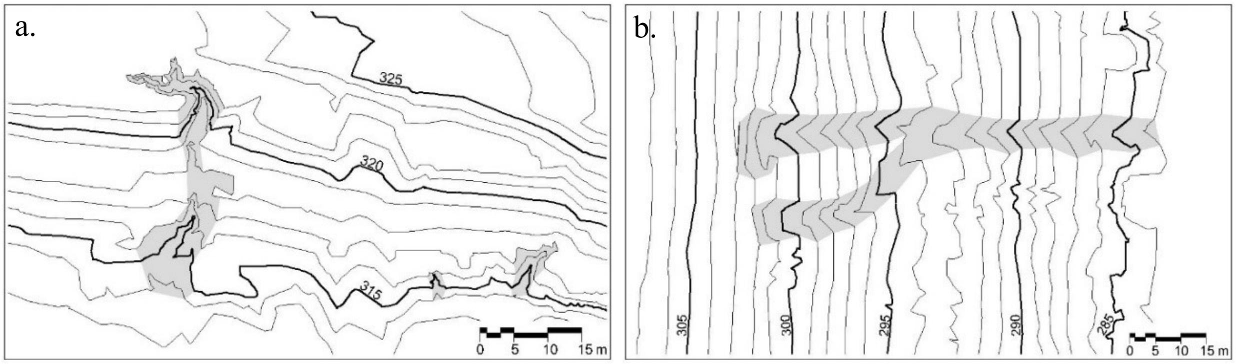

Figure 6.10 Gullies (shaded grey) identified through LiDAR analysis as viewed with a 1 m contour interval using AutoCAD. (a) On the left, pooled water caused the large gully here, while gullies shown in the right image (b) are caused by seepage.

Table 6.3 Hazard classification due to erosion. Adapted from (Government of Alberta Transportation, 2011; Wall, Coote, Pringle, & Shelton, 2002). Acceptable rates across Alberta are less than 6 Mg / hectare / year.

Soil Erosion Hazard Class	Soil Erosion Potential (Mg / hectare/year)
Very low (tolerable)	< 6
Low	6 - 11
Moderate	11 - 22
High	22 - 33
Very High	> 33

6.4.3 Stereo aerial photography analysis

A review of the 2011 digital stereo aerial photographs identified 141 erosion features, producing a cumulative soil loss volume of approximately 8731 m^3. Recall LiDAR was taken in 2016 such that the quantity of gullies is not indicative of the effectiveness of the identification technique used. Five of these features were caused by subsidence reminiscent of earth flows and all remaining were gullies, predominantly caused by localized seepage or surface ponding leading to concentrated flow. An additional 342 instances of rill erosion were identified totaling over 7100 m in length, as were large areas of wind-blown CST. Gullies were measured to have a mean depth of 0.73 m, up to a maximum of 2.66 m deep. The mean width was 2.95 m and the mean length was 44.30 m. The advantage of viewing stereo aerial photography is the ability to observe the terrain in three dimensions with image tone indicative of relative moisture content. Topographic measurements are less precise using stereo aerial photography alone; therefore, volume was not calculated. Erosion dimensions using this method should be regarded with respect to relative proportions and causation rather than their individual dimensions.

Gullies were distributed unevenly along the dam, with the majority visible on the north and east exposures. Uneven distribution may result from reduced visibility due to sun reflection on the south side, and extensive reclamation on the west side. The largest soil losses from individual features were associated with isolated earth flows, but gully erosion lead to the greatest cumulative soil loss. Gullies were caused by seepage that was clearly visible as dark regions horizontally aligned along the downstream dam face. The presence of moisture darkens the tone of surface material viewed in stereo aerial photography, making seepage areas and very dry areas easily identifiable, as seen in Figure 6.11(a, b). For comparison, Figure 6.11(b) is taken in the same area as Figure 6.10(b). On reclaimed areas, relative surface moisture is evident from vegetation coverage, type, and quality.

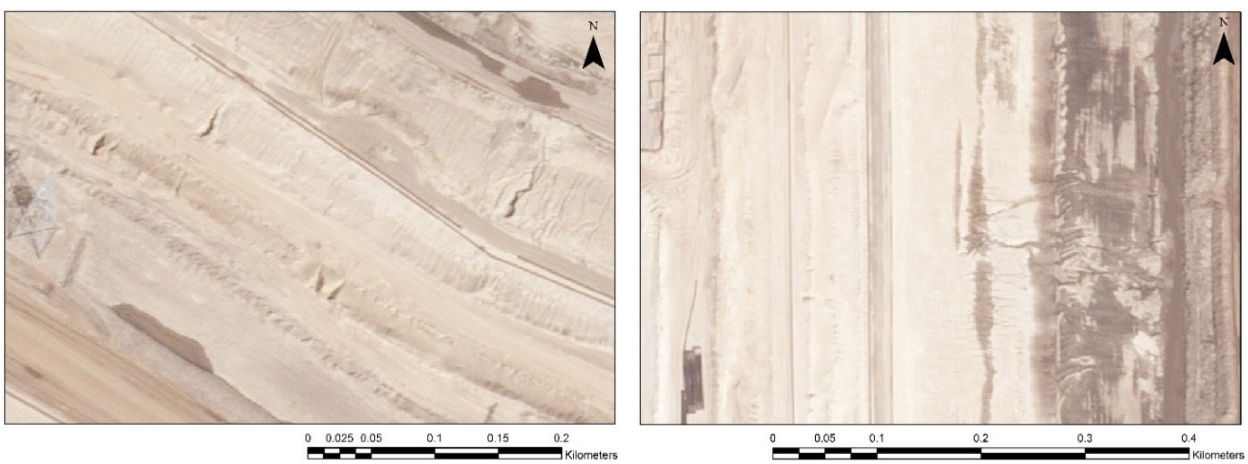

Figure 6.11 Erosion features visible on digital aerial photography. Gullies and large areas of rills are visible on the left (a). Wind-blown CST appears light in colour and seepage generating gullies appears dark in colour on the right image (b).

Wind-blown CST is clearly visible on the upper surface of the tailings impoundment and at selected locations on the east and south exposures. Precise depth calculation of wind-blown CST is not possible; rather, the occurrence in itself is important with consideration of long-term behaviour and monitoring. Similarly, the surficial extent of rill erosion discussed above can be measured reasonably well, but accurate depth measurements are not possible. Given that the upper limit of rill depth is about 30 cm and that rills tend to be consistent in their cross-sectional geometry, one could assume an average depth to broadly estimate soil loss volume.

6.5 Discussion

The inventory of erosional features completed on an oil sands tailings dam has identified that erosion due to wind and water is occurring on CST-constructed tailings dams. The dam inventoried is regularly maintained yet soil loss from water erosion was significant on exposed CST areas, and present but much reduced to a tolerable level on reclaimed areas. Water erosion is therefore a concern for the post-closure structure when maintenance will be less frequent, and when droughts and forest fires are more frequent. There are presently over 20 TSFs in the AOS, the majority of which are constructed with CST. All of the TSFs will need to be reclaimed, delicensed, and eventually returned to the Crown.

The overwhelming goal of reclamation for the majority of oil sands mine operators is exactly as follows, or a slight variation of the following:

> *'..to achieve maintenance-free, self-sustaining ecosystems with a capability equivalent to pre-development conditions, such that the developed and reclaimed lands can receive reclamation certification and be returned to the Crown.' (CNRL 2011; Golder Associates 2011; SCE 2011 and 2012; SEI 2011)*

To determine whether the former dams can be returned to the Crown, it is expected that monitoring will be necessary for an extended time frame, proving their performance does not pose a threat to human or environmental health (OSTDC, 2014). The OSTDC, composed of members from AOS consulting firms, dam operators, and the regulator, currently proposes a path towards dam closure that includes extended active monitoring prior to delicensing, and an additional extended passive monitoring phase prior to reclamation certification (Figure 6.1). It is expected that the majority of monitoring will take place remotely for efficiency and also due to the monetary and time cost of travel, time expected to navigate the large surface areas, potential disruption to completed reclamation works, and safety concerns given the region has a history of fatal wildlife encounters. Additionally, a plethora of information in addition to landform erosion data can be attained using the methods described above, which would otherwise require several diverse specialists in the field over a period of days or weeks.

6.5.1 Economics and degree of maintenance

Soil loss does not only impede reclamation works, but also has a cost and degree of effort associated with repair, dredging of channels, and material relocation. For example, unreclaimed areas of this dam lost nearly 57 Mg/ha (tonnes/ha) of CST while reclaimed areas lost about 4 Mg/ha. Using some rough assumptions for unreclaimed dams, we find:

- If gully repair costs are \$15/m^2, the annual repair of these gullies would cost \$926,000.
- Assuming all of the eroded CST is captured by channels at the base of the dam, and a dredging cost of \$10/Mg, this equates to about \$215,000/year.
- If 20 tonne gravel trucks are used to transport the material away at a rate of three round trips per hour and \$200/hr, this will require nearly 1400 trips and \$100,000.
- Total cost per year: \$1,241,000.

For reclaimed dams, we find:

- If gully and reclamation repair costs are \$100/m^2, the annual repair of these gullies would cost \$943,700.
- Assuming all of the eroded material is captured by channels at the base of the dam, and a dredging cost of \$10/Mg, this equates to about \$19,600/year.
- Using the same 20 T gravel truck to transport dredged material at a rate of three round trips per hour and \$200/hr, less than 100 trips and \$6,700 would be needed.
- Total cost per year: \$970,000.

Even though the reclaimed structure will have fewer gullies to repair, the cost of repair to a reclaimed structure is more (based on these estimated costs) due to the effort and increased complexity of the task. The cumulative costs for this reclaimed structure are more than \$270,000/year less and are likely to decrease more quickly than with an unreclaimed structure. Ongoing costs of this magnitude are likely to increase the financial security (bond) required by the mine owner as well and should be considered. While no mine owners are presently proposing to leave their CST dams exposed without a reclamation cover, this example demonstrates the importance of high quality reclamation such that maintenance efforts and costs are more quickly reduced.

6.5.2 Erosion identification and quantification methods

As of spring 2018, the AOS mining region has not been subject to precipitation events greater than a 1 in 6-year return period since the dam was constructed, yet the erosion present on un-reclaimed areas is significant. Of the three erosion identification methods used in this study, in-person field investigation is the least practical for use in the future reclaimed environment. Vehicle access routes were identified as common locations for erosion to occur on site and it is therefore preferable to minimize vehicle access following reclamation. TSFs composed nearly entirely of CST cover over 170 km^2 and the many overburden dumps proposed to be covered with CST will increase the extent of erosion monitoring. To ensure thorough coverage of their large surface area, remote methods of monitoring are thought to be a first line of defence.

Gullies were easily identifiable using LiDAR data viewed as a contour plan and precise gully measurements, including gully depth, were possible. While the dams are actively trafficked and undergoing changes, a systematic approach is necessary to analyse the topography. The advantage of LiDAR usage (given high-resolution data are used) is the ability to precisely quantify estimates of soil volume lost on reclaimed or un-reclaimed land. Language employed to date in regulatory documents regarding delicensing has lacked detail surrounding how dam owners might demonstrate that reclaimed land 'is compatible with the risk level of the surrounding environment' (OSTDC 2014) such that reclamation certificates can be issued with confidence. Comparison of the quantity of erosion on a tailings dam (using methods described above) to known values considered to be 'tolerable' in the natural environment is a definitive and quantifiable method of evaluating risk due to erosion and surface instability.

A variety of wind and water erosional features were easily identified by viewing digital stereo aerial photography in three dimensions. In addition to gullies, extensive areas of rill and wind erosion were easily characterized about five times faster than using LiDAR data; however, precise quantification and delineation of the extent of erosion was a challenge, particularly on the south side of the TSF where the light-coloured CST reflected the sun and reduced surface clarity on aerial photographs. The overwhelming benefit of using stereo aerial photography in this way was that the cause of erosional features was more easily identifiable. Surface water, due to pooled rain or seepage through the dam, is a major concern with respect to tailings dam stability and is clearly visible in photo tone. Table 6.4 summarizes the benefits of both LiDAR and digital stereo aerial photography methods.

Table 6.4 Summary of remote inventory and assessment methods

	Stereo Aerial photography	**LiDAR**
Erosion Identification	Fast	Slow
Wind erosion	Yes	No
Water erosion	Gullies, rills, mass wasting	Gullies, mass wasting
Erosion Classification	Yes	Limited
Erosion Quantification	Limited	Yes, with high resolution data
Erosion Causation	Clearly visible	Limited
Additional interpretation potential	Vegetation health, density, quality, diversity, and species identification. Limited water quality assessment.	TSF central pond surface settlement. Dam movement.

Since a major component of this work sought to quantify soil loss using LiDAR, it is important to attain high quality data such that size and shape can be determined and viewed with precision. Seepage and concentrated flow were identified as the cause of most water erosion on the study site. This was clearly visible on bare CST, but other indicators will be visible once vegetation is established. On densely vegetated areas, the altered topography from gully formation may not be visible due to canopy coverage; however, these areas by definition correspond to higher moisture contents and thereby different vegetation. Vegetation that grows in moist areas typically includes shrubs, grasses, and leafy deciduous species; often berries or other food eaten by wildlife grows in these conditions. Both the availability of food and water attracts animals to these locations. Moving forward stereo aerial photography can help inform where wildlife surveys, water sampling, and other monitoring activities are best focussed on the dams.

On closure, the TSF is considered to be indirectly connected to aquatic resources (as are most in the AOS) since a perimeter ditch collects sediment at the bottom of the dams prior to treatment and release into natural watercourses. Therefore, so long as the perimeter ditch is capable of collecting sediment local waterways and aquatic habitats are not impacted by sedimentation. In preparation for reduced maintenance and increased resilience, perimeter ditches surrounding the

TSFs will be widened to between 30 and 50 m channels on closure initiation. This width increase will accommodate large precipitation events, overland water run-off from the dams, deposition of eroded sediment, water conveyance to a treatment facility, and allow for reduced frequency of maintenance. These perimeter channels will be well armoured, inhibiting vegetation growth between the banks, and allowing for a clear view to areas of excessive deposition that would indicate the presence of large erosion features. Use of stereo aerial photography to view perimeter channels as an initial step will provide a quick indication of locations requiring more detailed investigation. Water colour is also visible in channels using the digital stereo aerial photography, and this can be indicative of water quality surrounding and within mining landscapes (Woo et al., 2013). For example, with calibration, water colour can be compared to the Munsell chart to estimate pH remotely.

6.5.3 Sustainable mine reclamation

The Brundtland Report defines sustainable development as 'development that meets the needs of the present without compromising the ability of future generations to meet their own needs' (World Commission on Environment and Development, 1987). Tailings dams in the AOS retain tailings with a range of chemical and physical challenges. The sequestration of these materials such that their impact on the surrounding environment is minimized is imperative to the sustainability of reclamation practices. An initial geomorphic approach to the design of these tailings ponds and waste storage facilities is optimal and has been widely practiced in the coal mining industry where different reclamation challenges exist (Martin-Duque et al., 2015; Sawatsky & Beersing, 2014). The use of geotextiles has been proposed as an erosion control measure, but such 'engineered' measures are not in line with the objective of a long-term geomorphic approach that uses natural processes and tailings material characteristics as fundamental design considerations (Martin-Duque et al., 2015; McHarg, 1969). The exception to this is in the establishment of vegetation where readily biodegradable fibers are used to establish initial vegetative coverage in a wind-erosion prone environment.

This study provides confirmation of the short-term success of reclamation works undertaken, and an insight as to what might happen should erosion penetrate through the reclamation cover into CST. Sustainability of the mining sector is dependent upon a long-term reclamation strategy, reinforced at all stages by holistic government policies and regulation. Any long-term approach must by definition include consideration for geomorphology. Adaptation of downstream dam slopes for future mine sites based on site-specific geomorphic tendencies and landscape evolution modelling is a responsible first step. For existing tailings dams with little flexibility, long-term annual monitoring (at a minimum) using both LiDAR and digital stereo aerial photography can yield essential information on structure behaviour, and contribute to a definitive long-term reclamation strategy.

6.6 Conclusion

From the authors' experiences in North and South America, the long-term geomorphology of tailings dams and their retained contents is largely unknown, and perhaps as a result this is not often discussed among stakeholders. It is of critical importance that geomorphic forces on tailings dams be well understood prior to closure, such that behaviour can be anticipated and controls can be put in place to prevent negative outcomes. Erosion has previously been evaluated on small-scale plots at AOS tailings dams using simulated precipitation, and in conjunction with evaluation of various reclamation covers; however, the importance of long (and short)-term wind and water erosion processes within entire catchments should not be overlooked. This research sought to identify existing erosion features on reclaimed and un-reclaimed tailings dam slopes, to quantify the problem, and to determine the underlying causes of erosion.

This research has shown that large geomorphic features can develop in less than one year without maintenance or statistically significant precipitation events, on unreclaimed (bare CST) and to a lesser, tolerable extent on reclaimed dams. This has substantial implications for the post-mining landscape, for the reclamation of 176 km^2 of TSFs in the AOS, and more broadly on the long-term stability of taller sand tailings dams located internationally. Over 190 gullies were identified in the study area using LiDAR data analysis, corresponding to a conservative soil loss estimate of 57 Mg/ha/year on unreclaimed areas and 4 Mg/ha/year on reclaimed; this corresponds to 'very high' and 'very low' hazard classifications, respectively. Onsite photographic documentation of erosion in the form of smaller rills and wind ripples was conducted, and these features were also identified using digital stereo aerial photography. A fundamental benefit of using digital stereo aerial photography was the ability to determine the cause of erosional features, which may allow for preventative measures and controls to be installed prior to slope instability or failure.

As owners, operators, and regulators prepare for the delicensing and reclamation of tailings dams in the oil sands, staged monitoring has been proposed to evaluate the behaviour of the structures and their impact on the surrounding environment. This staged monitoring will allow for the determination of when delicensing a dam can occur, when reclamation certificates may be granted, and when liability for the TSFs will revert to the Crown. The findings of this research encourage the use of LiDAR and digital stereo aerial photography analysis in conjunction as a path forward throughout active and passive stages of monitoring. Digital stereo aerial photography may be used: (1) preventatively to locate areas of seepage, water pooling, or blowouts due to wind, (2) to determine the cause of existing erosion features, and (3) as a precursory evaluation of other environmental aspects such as water or vegetation quality. LiDAR analysis can be used to precisely quantify erosion, and to determine when the dam's erosion hazard class has reached a tolerable level by local standards. While it would be ideal to have one type of data that provides all of the above information, data collectors and purveyors typically have instrumentation to collect both LiDAR and digital stereo aerial photography at the same time. Simultaneous collection of both forms of data is optimal for analysis purposes and cost effectiveness.

This work provides evidence of the geomorphic processes that are actively taking place on above ground tailings dams in the AOS such that industry may be better prepared to manage erosion during reclamation. The results show that significant soil loss from unreclaimed dams is occurring on actively maintained tailings dams, predominantly through water-based erosion due to seepage and pooling surface water. Should erosion of reclamation covers expose underlying CST on the dam slopes, soil loss, maintenance effort, and reclamation costs could be high. Reclaimed areas were noted herein to meet a very low hazard class, and therefore require a low degree of maintenance at this time. The remote investigation methods used herein demonstrate that neither data format is solely capable of providing all necessary information for future monitoring. Instead both formats are proposed in conjunction to provide a holistic and measurable understanding of geomorphic processes and reclamation success.

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7.0 Landscape evolution models (LEMs)

The Universal Soil Loss Equation and its many related equations provide a quick and easy estimate of annual soil loss through empirical means, but fails to provide sufficient information on location of erosion and deposition, and information on long term changes. Direct measurement using remote methods is beneficial to attain reliable quantities of soil loss and active processes. In contrast, landscape evolution models seek to predict long-term, three-dimensional geomorphic changes, filling major gaps of USLE and providing detailed spatial and temporal predictions of change.

This chapter provides an overview of landscape evolution modelling as well as a few of the more common LEMs and their application. The CAESAR-Lisflood (C-L) LEM used in Chapters eight, nine, and ten is reviewed in detail providing an overview of how it works, fundamental equations used, and input/parameterization requirements.

With a growing number of mines closing amid higher than expected reclamation costs and underwhelming landscape performance, there is uncertainty on the part of mine-owners, regulators, and other stakeholders with respect to long-term performance. Ongoing maintenance, additional financial draws, and sub-standard environmental/water quality are a few of the concerns and long-term consequences of inferior landform and drainage design and construction. Methods for checking the long-term performance of landform designs are necessary to optimize the landform design and construction process, and to achieve the best results possible.

7.1 Background

CEMA (2010) states that “establishing vegetative cover on the reclaimed landscape is the optimal mitigation measure to minimize soil erosion”. While vegetation is an important aspect of erosion control, constructing a landform with geomorphically mature topography can prevent erosion as well; particularly over long time frames and as vegetation changes take place due to natural conditions such as pests & disease, forest fires, and large storm events.

The Universal Soil Loss Equation (USLE), the Water Erosion Prediction Project (WEPP), and related equations are helpful in providing average annual soil loss predictions from land subject to rill and inter-rill erosion; however, they have several shortcomings as listed in Section 3.4.

One such shortcoming is that they assume constant topographic elevation. Landscape evolution models (LEMs) are intended to fill some of these gaps by providing spatial information on sediment erosion and deposition in three-dimensions and over timeframes from one year to over 10,000 years. This ability to provide estimates of future geomorphology over long timeframes is a key element, as regulators and society increasingly expect post-mining waste landforms and caps to be designed and constructed for extended design lives (see Chapter one). Landscape evolution models provide an opportunity to test landform and drainage designs over elongated timeframes, thereby evaluating the viability of a design.

7.2 History of LEMs

Landscape Evolution Models simulate geomorphology over long timeframes using cellular automata (CA), first developed by von Neumann (1951, 1966). CA breaks down three-dimensional spaces into a series of cubes which hold information on the physical environment corresponding to that particular region (Barkwith et al., 2015). The concept for application of CA to landscape evolution and erosion began with Culling (1960) in which the average volumetric sediment transport rate per unit slope was described as a function of land-surface elevation, the distance down slope, and of process, material, and climate, shown in equation (7.1) (Culling, 1960; Tucker & Hancock, 2010). Since this time a number of geomorphic transport functions, like Culling's, have been developed. When these are used in combination with laws of mass continuity, geomorphic transport functions can be used to describe how landscapes evolve (Tucker & Hancock, 2010).

$$q_{s,ave} = -K_c \frac{\partial n}{\partial x} \quad (7.1)$$

For equation 7.1, $q_{s,ave}$ is the average volumetric sediment transport rate per unit of slope width, n is the land elevation at the surface, and x is the distance down slope.

Numerous LEM's have been developed since the 1970's as computer processing speed increased (Coulthard, 2001). LEMs use digital elevation models (DEMs) as their landform base and therefore have advantages over more traditional methods of erosion prediction such as RUSLE or the lesser known WEPP in that they are multi-dimensional. LEMs also provide a more accurate estimation of slope profiles as a result of dynamic surface adjustments (Hancock, 2016). Many LEM's have been created in the last 30 years, as described in Table 7.1; however, few have undergone sufficient field testing to be considered well-validated (Coulthard, 2001; Willgoose, 2018b).

LEMs are an important progression because previously hydrology and geomorphology were considered independently when in reality they are linked processes: landform affects hydrology within a catchment, and the hydrology can alter the landform (Willgoose, 2005 and 2018b). Depending on the intended length of time to be simulated, the type of processes to be modelled should change. For example, a model that is used to simulate discrete storm events does not need to consider the impact of soil creep on catchment morphology but creep would play an important role in a model that simulates 10,000+ years (Coulthard, 2001). Sediment transport and water flow require numerous complex equations to simulate the processes as they occur, particularly over the long time frames of interest; as a result simplifications have been made. One example of this is the D4 routing algorithm for surface water, meaning water leaving a cell can only enter adjacent cells located in cardinal directions - whichever is the lowest elevation. In reality water can take more than one path and in any direction.

LEMs use digital elevation models to represent terrain topography. Since different processes will dominate over different timeframes, and not all cells will change as rapidly, there are three different approaches that have been taken to date to represent terrain. The first uses a triangular irregular network (TIN) DEM that automatically creates additional nodes in locations where more change takes place (stream channels, for example). This method also reduces the likelihood of mis-parameterization by relying too heavily on cell size. The second option is to use a regular gridded DEM of large cells and a sub-grid for active areas; this option is used by SIBERIA and GOLEM. The last method is incorporated into CAESAR-Lisflood, and uses a regular gridded DEM of small cells, but dedicates the majority of modelling time to active cells, then checks and adjusts non-active cells at regular intervals (Coulthard, 2001).

LEMs can be broken down into two broad categories based on temporal scale: those that use discrete time steps to simulate individual events (CAESAR-Lisflood, CHILD), and those that model evolution according to long-term spatially calibrated erosion and discharge parameters (SIBERIA). In reality, event return period and event intensity (time distribution of a rainfall event) are variable, and corresponding discharges from channels or hillslopes vary across a landscape, based on infiltration, slope, rate of flow, etc. (Huang & Niemann, 2006). Event intensity directly affects the discharge intensity, and this variability has at least equal if not greater impact on the amount of erosion experienced than the mean precipitation quantity (Dick & Ghavasieh, 2015; Tucker & Bras, 2000). Tucker and Hancock (2010) have come to the conclusion that while estimates based on steady state precipitation and discharge do have applicable uses (small catchments or those with elongated storm events, for example), "hydrodynamic variability can have an impact on landscape dynamics and should normally be incorporated in models" (Tucker & Hancock, 2010). The majority of LEMs are simplified to operate under steady state flow, such that discharge is either calculated based on drainage area, or discharge is routed instantaneously through the watershed over one time step (Coulthard et al., 2013). The latest iteration of the CAESAR LEM (CAESAR-Lisflood, also referred to as C-L), has incorporated hydrodynamics which improves accuracy of discharge volumes, rates, and sediment transport. While C-L can be forced to run in steady state, this has been found to increase sediment yield (Coulthard et al., 2013).

Table 7.1 Summary of some LEMs. From Coulthard, 2001; Tucker, Lancaster, Gasparini, & Bras, 2001; Tucker, 2010; Willgoose, 2005; http://csdms.colorado.edu/wiki/Model:GOLEM#

Model Name (Programming Language)	Geomorphic Orogenic Landscape Evolution Model, **GOLEM** v.5.14 (C)	Channel-Hillslope Integrated Landscape Development, **CHILD** v.R9.4.1 (C++)	**SIBERIA** v.8.30 (Fortran 95)	Cellular Automata Evolutionary Slope and River-Lisflood, **CAESAR-Lisflood** v.1.9b (C#)
Developer, affiliation.	Started in 1991 by Greg Tucker, Michigan Institute of Technology, USA.	Started in 1997 by Nicole Gasparini, Stephen Landcaster, & Greg Tucker. More contributors since 1997. Dept. of Civil & Environmental Engineering, MIT (initially). Now University of Colorado, USA.	Started in 1986 by Garry WIllgoose at MIT, USA. Now of Telluric Research and University of Newcastle, Australia.	Started in the late 1990's by Tom Coulthard at the School of Geography, University of Leeds, UK. Now at Department of Geography, Environment and Earth Science, University of Hull, UK.
Inputs	Single C file with gridded DEM values.	ACSII files for topography (TIN), rate coefficients, switches for activating options/ formulas	Gridded DEM (.rst2) Boundary file (.bnd) Calibration parameters (β_1, β_3, m_1, m_3, n_1) Optional region files for variable erosion	Surface DEM (.txt) Optional bedrock DEM (.txt) Precipitation file (.txt) Grain size distribution (max. nine sizes) About 30 parameters

Outputs			Single file (.rst2) with geomorphic statistics and topography at user-defined intervals.	Spatial distributions of elevation, elevation change, d_{50}, water velocity, water depth, etc. (.txt) and water and sediment discharge by grain size fraction over time (.dat)
Spatial and temporal scale modelled, run time	A few km^2 to sub-continental areas. 1000 - 10,000,000 years. Run time unavailable.	Meters to 100 km^2. Single storm – millions of years Run time: minutes to days.	Meters to 100 km^2. A few years to 10,000’s of years. Run time: minutes.	Meters to 100 km^2. A few years to 10,000’s of years. Run time: hours to weeks.
Limitations	Simplified 2D, raster grid structure. Few calibration examples available.	Constant rainfall intensity throughout storm. Most applicable to long time frames. Use of variable spatial scale via Triangular Irregular Network (TIN). Calibration to engineering applications is difficult. No suspended sediment load, landslide or eolian transport. Moderate testing and calibration completed.	Site calibration required over minimum one year in order to achieve site specific outputs. Steady-state precipitation and discharge	Some components are still undergoing testing. Slow modelling speeds can restrict the timeframes simulated. Data processing to determine geomorphic statistics and graphs can be complex. No tectonic uplift modelled. D4 flow routing

SIBERIA was the first LEM to be used to assess the geomorphic stability of a landform design in the post-mining environment (Hancock, Lowry, & Coulthard, 2016; Willgoose & Riley, 1998). Since this time, SIBERIA, CAESAR, and CAESAR-Lisflood have been used to provide insight as to the geomorphic evolution of encapsulated mine waste with respect to their form and function. Loading of adjacent environments and atmospheric exposure of undesirable mine waste due to gully formation are of particular concern and are drivers for this work. Waste dumps at the Ranger Uranium Mine in Australia have been modelled extensively to predict gully development, long-term geomorphology, safety and waste encapsulation timeframes, and to compare model outputs between CAESAR and SIBERIA (Coulthard, Hancock, & Lowry, 2012; Evans, 2000; Hancock, Lowry, & Coulthard, 2015; Hancock et al., 2016; Willgoose & Riley, 1998).

7.3 CAESAR-Lisflood

The CAESAR LEM was initially developed in the 1990's and has undergone several revisions over the years. The most significant change was the replacement of an existing flow sweeping code with the Lisflood-FP flow model in 2012 (Coulthard et al., 2013). With this change, the name of the model versions using Lisflood FP hydrodynamic routing code have been changed to "CAESAR-Lisflood". In addition to this flow model, C-L integrates a hydrologic model, fluvial erosion/deposition model, and slope processes such as creep and slope failure due to over-steepening. C-L is a deterministic model, such that any variation in outputs is due directly to variation in inputs or parameters (Coulthard & Van De Wiel, 2007). Just as geomorphic and fluvial systems are non-linear in behaviour, C-L has also demonstrated this behaviour via spatially heterogenous sediment and soil moisture, hysteresis, capacity-limited sediment entrainment, bed armouring, vegetative bank stabilization, etc. (Coulthard, Kirkby, & Macklin, 1998; Coulthard & Van De Wiel, 2007). This has several consequences, first that small changes to inputs may produce disproportionate outputs, since the results of the system are not a direct sum of its parts, and secondly that short term results do not form the basis of long-term predictions (Coulthard & Van De Wiel, 2007; Lane & Richards, 1997; Phillips, 2003). In essence, the model simulates the cumulative effects of a number of different moving parts subject to moving inputs.

7.3.1 CAESAR-Lisflood versus SIBERIA

C-L is a reduced complexity LEM meaning that it works by simplifying the actual mechanisms present that alter the shape of land over time. For example, precipitation inputs (typically historic hourly rainfall) are applied to the surface, and what does not infiltrate (based on grain size distribution) will flow over the surface. Velocity dictates which grain sizes are dislodged and transported, as well as when they are deposited. While other mechanisms realistically contribute to these processes, over long time frames a simplified method is considered to be a reasonable estimate. This approach is in contrast to that used in SIBERIA, perhaps the best-known and most well-documented LEM available. SIBERIA uses site measurements from field plots or flume data to calibrate input parameters (sediment transport coefficient, β_1, runoff coefficient, β_3, channel initiation threshold coefficient, β_5, etc.). Parameters that describe the terrain are then fitted to the characteristics of the DEM. SIBERIA changes landscape (DEM) form based on rates of change over long time frames: while periods as brief as one year are required for field measurements, this assumes that the landscape has been subject to a conditioning effect from exposure to previous climate. This approach produces much faster modelling times as compared to C-L, but also less flexibility.

C-L was chosen for use in this research because it simulates the precise intensity, duration, and frequency of convective storms that occur in the AOS, and because the inputs required were more readily attainable than those required for SIBERIA. Since the AOS receives between 400-800 mm of rainfall annually, the sediment transport parameter β_1 in SIBERIA can be set based on particle size distribution and generic parameters used for all others; however, this approach does not generate site specific outputs and was therefore not proceeded with.

While a landscape evolution model is impossible to validate over long future time frames, it is possible to validate models used for undisturbed terrain over historic time periods by comparing outputs to the current landform shape (Welsh, Dearing, Chiverrell & Coulthard, 2007; Coulthard, Macklin, & Kirby, 2002; Coulthard, Lewin, & Macklin, 2005). Short time frames are also possible to validate through comparison with site measurements of water discharge, soil loss, and geomorphology. Where short-term predictions are verified through site measurement, there is more confidence in the long-term model results. CAESAR-Lisflood and SIBERIA have been also been cross-evaluated at sites across Australia (Hancock, Lowry, & Coulthard, 2015; Hancock, Lowry, Coulthard, Evans, & Moliere, 2010; Hancock, Coulthard, Martinez, & Kalma, 2011). Due to the different inputs for each of the models, end geomorphology that correlates between the two has provided confidence in results.

7.3.2 Fundamental equations

This section presents the equations used in C-L to alter surficial water and soil distribution. There is no official user manual for C-L, but documentation of the model is abundant and has been used below to summarize its mathematic foundation. The determination of parameters outlined in this section will be further discussed in section 7.3.3.

C-L uses a DEM to discretize topography into a regular grid where each cell has unique properties that change over time. The spatial resolution of the grid depends on the features and processes of interest. For each cell the following equations are applied.

7.3.2.1 *Water flow and routing*

Water is added to the DEM surface in C-L via rainfall in catchment mode. Equations (7.2) to (7.5) show how soil moisture in each cell is used to calculate whether overland flow (water discharge) can occur from that cell (Coulthard & Van de Wiel, 2007). Water discharge for each cell, Q_{tot}, is calculated in catchment mode using an adjustment to the 'Topography based hydrological model', or 'TOPMODEL' (Beven, 1997; Beven & Kirkby, 1979). A rainfall (r) record specified by the user is read by the model and when rainfall occurs ($r > 0$) the following equations are applied:

$$Q_{tot} = \frac{m}{T}\log\left(\frac{(r-j_t)+j_t\exp\left(\frac{rT}{m}\right)}{r}\right) \tag{7.2}$$

Where m, or the "m-value", is a user-defined parameter related to vegetation coverage and soil transmissivity carried over from TOPMODEL (Beven & Kirkby, 1979; Welsh, Dearing, Chiverrell, & Coulthard, 2009), T is time step in seconds, r is rainfall rate in mm/hour, and j_t is the soil moisture storage as calculated below with Equation (7.3).

$$j_t = \frac{r}{\left(\frac{r-j_{t-1}}{j_{t-1}}exp\left(\frac{(0-r)T}{m}\right)+1\right)} \tag{7.3}$$

Where j_{t-1} is the moisture storage in soil for the previous iteration. If there is no precipitation ($r = 0$), then the following are used:

$$Q_{tot} = \frac{m}{T}\log\left(1+\left(\frac{j_tT}{m}\right)\right) \tag{7.4}$$

$$j_t = \frac{j_{t-1}}{1+\left(\frac{j_{t-1}T}{m}\right)} \tag{7.5}$$

The m-value is one of the most important parameters within C-L because it controls the rate of change of soil moisture, which in turn affects the time it takes for water to move through the soil and how quickly water moves through the watershed (i.e. the flood hydrograph). Sensitivity testing was completed prior to running any simulations, verifying that the model is sensitive to alteration of this parameter. For example, if the m-value is adjusted to represent dense forest (m-value = 0.016), erosion reduces to almost no erosion. This is similar to reducing the C-factor in

RUSLEFAC to represent dense forest (C-factor=0.01), resulting in very low erosion (Section 5.5.6).

For each time step and for each cell the Q_{tot} is multiplied by the contributing drainage area to find the discharge to that cell as a result of upstream discharge. This value is solely used for comparison with a user defined Q_{min}: if the value is greater than Q_{min} then water depth for that cell is calculated, otherwise no water depth calculation takes place for the cell. Information on setting a Q_{min} value is found in Section 7.3.3.

Note that there are three modes that can be used in C-L: catchment mode, reach mode (or both together), and tidal mode. This description is restricted to equations relevant to catchment mode. Q_{min} plays an additional role in reach mode which may impact the value chosen for it.

The Lisflood-FP flow model (Bates, Horritt, & Fewtrell, 2010), then determines how water is routed from cell to cell, restricted to adjacent cells in the four cardinal directions. The discharge, Q, to each cell in the cardinal directions is calculated using the following equation (7.6):

$$Q = \frac{q_{t-1} - g h_{flow} \Delta t \frac{\Delta(h+z)}{\Delta x}}{\left(1 + g h_{flow} \Delta t n^2 |q_{t-1}| / h_{flow}^{10/3}\right)} \Delta x \tag{7.6}$$

Where q_{t-1} represents the flow between cells for the previous iteration (m^2s^{-1}), g is gravitational acceleration (ms^{-1}), h_{flow} is the user defined minimum allowable depth of flow between cells (m), t is time (s), $\frac{\Delta(h+z)}{\Delta x}$ is the slope of the water surface, x is cell width, and n is Manning's roughness coefficient ($m^{1/3}s^{-1}$). h_{flow} assists with model run speeds by preventing discharge at very low gradients. At this point the water depth in each cell is updated using the following equation (7.7):

$$\frac{\Delta h^{i,j}}{\Delta t} = \frac{Q_x^{i-1,j} - Q_x^{i,j} + Q_y^{i,j-1} - Q_y^{i,j}}{\Delta x^2} \tag{7.7}$$

Where i and j are individual cell coordinates. Water depth is used to determine cells are "active" and those that are not according to the user defined parameter, d_{min}. When water depth is greater than the d_{min} value then the cell is considered active and fluvial erosion and deposition can occur in that cell. When a cell is inactive slope processes (creep and slope failure) continue to operate and are checked for every 1000 iterations (Meadows, 2014).

Cell size and water depth can affect the stability of the model, so the time step used in these calculations can be as small as fractions of a second. To aid in stabilization an additional condition is built into the model called the Courant-Freidrichs-Lewy (CFL) condition that ensures a wave cannot cross more than one cell per time step (Coulthard et al., 2013). The time step controlled by the CFL condition is determined as follows:

$$\Delta t_{max} = \alpha \frac{\Delta x}{\sqrt{gh}} \quad (7.8)$$

The Courant number, α, is user defined coefficient within the range of 0.3 and 0.7 (Bates et al., 2010). Stability in C-L is further controlled by limiting flow from one cell to another with the user defined Froude number (Fr) (see Section 7.3.3).

Model efficiency is improved by allowing the time step to increase when little fluvial erosion is taking place: when the difference between input discharge, Q_{tot}, and output discharge is less than the user defined Q_{diff}, the time step increases as a steady state condition is assumed. The time step during steady state is then determined based on the amount of fluvial erosion occurring.

C-L uses a grain size distribution with up to nine size classes in order to transport sediment according to size. Soil layers are used to represent layers that would naturally be present, although each layer contains the same particle size distribution. As erosion occurs, the upper-most, or active, layer may become armoured based on the flow rate and soil sizes removed, and any material "hiding" due to shadow effects. The thickness of soil layers, L_h, are user-defined, and their alteration over time due to erosion and deposition is illustrated in Figure 7.1. Active layers change when they reach 25% or 150% of the original thickness defined (Meadows, 2014). In each (unaltered) layer all nine grain sizes are present in the proportions defined at model start up.

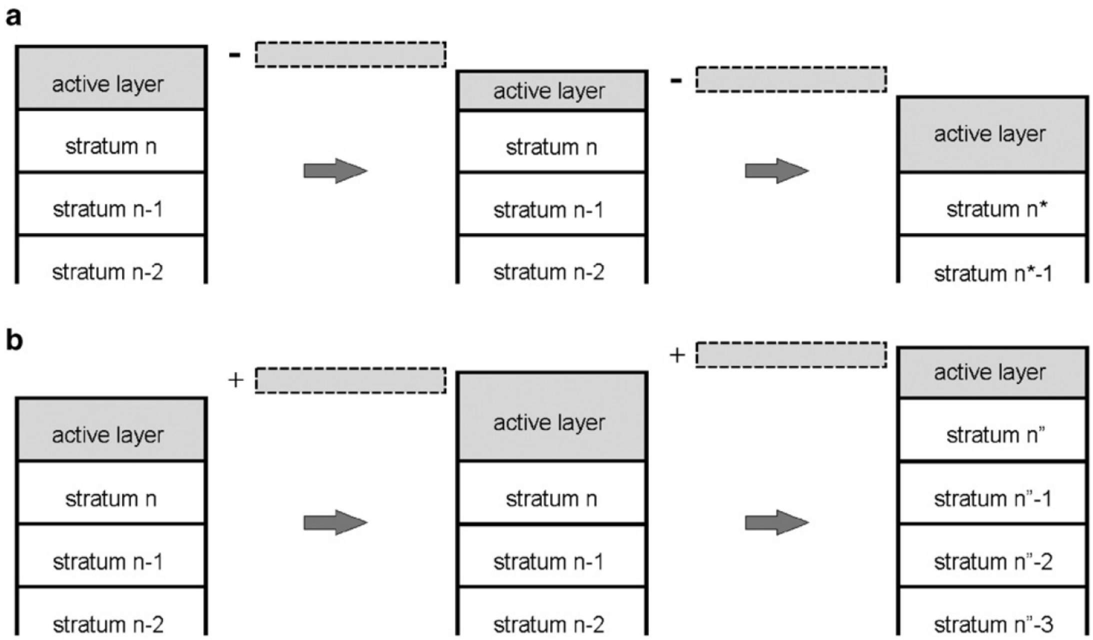

Figure 7.1 Illustrated changes to the active layer via (a) erosion and (b) deposition. Stratum layers are named according to their distance from the active layer: during erosion when stratum n becomes the new active layer, n-1 becomes n, etc. and during deposition when the active layer becomes stratum n", n becomes n"-1, etc. From Van de Wiel, Coulthard, Macklin, & Lewin, 2007.*

7.3.2.2 Suspended sediment transport

Sediment transport occurs as bedload, and optionally, the finest sediment size class can be treated as suspended load when water flow speed is high enough. Suspended sediment is routed to cells with lower bed elevations than cell water elevation according to flow velocity, $V_{i,k}$ (where *i* is the smallest sediment class size and k is the direction of the neighbouring cell of interest) (Van de Wiel et al., 2007):

$$V_{i,k} = \frac{U_k}{\sum U} V_i \tag{7.9}$$

Where U_k is flow velocity in direction of cell k, U is flow velocity, and V_i is flow velocity of the smallest sediment class size. The volume of suspended sediment is deposited according to fall velocity, v_f, using equation (7.10) for each iteration or time step, Δt (seconds):

$$V_{dep} = \kappa v_f x^2 \Delta t \tag{7.10}$$

Where κ is the concentration of suspended sediment, and x is cell size (m). The volume of suspended sediment transported must be less than the total volume of the smallest sediment size class in the active layer, making suspended sediment transport limited.

7.3.2.3 Bedload sediment transport

Bedload sediment transport is determined using one of two capacity-limited transport equations: Wilcock and Crowe (2003) or Einstein (1950). Wilcock and Crowe (2003) was developed using predominantly gravel, with 0.2 - 34% sand, and particle sizes ranging from 0.5 to 64 mm. Einstein (1950) was developed using relatively uniform grain sizes greater than 0.061 mm in diameter (#250 mesh) and up, and is typically used for uniform sediments and fine sediments. These criteria are used to determine the applicability of sediment transport equations for the application. In both transport equations the bed shear stress, τ, is required (equation (7.11)):

$$\tau = \rho C_d u^2 \tag{7.11}$$

Where ρ is water density (kg m^{-3}), u is flow velocity (m s^{-1}), and C_d is a drag coefficient that is calculated using equation (7.12):

$$C_d = gn^2h^{0.33} \tag{7.12}$$

Where g is gravitational acceleration (ms^{-1}), n is Manning's roughness coefficient ($m^{1/3}s^{-1}$) as above, and h is water depth.

If Wilcock & Crowe (2003) is determined to be most appropriate for use, then the transport rate for each grain size class, q_i (m^3 s^{-1}), is determined using equation (7.13):

$$q_i = \frac{F_i U_*^3 W_i^*}{((\rho_s/\rho)-1)g} \tag{7.13}$$

Where F_i is the fractional volume of sediment (of grain size class i) in the active layer, U_* is shear velocity, W_i^* correlates the transport rate of this fraction of sediment to the total transport rate, and the ratio of sediment to water density is ρ_s/ρ. To calculate shear velocity, U_*, equation 7.14 is used:

$$U_* = (\tau/\rho)^{0.5} \tag{7.14}$$

Where bed shear stress, τ, is calculated as above.

W_i* requires a series of calculations as outlined in equations (7.15) to (7.20):

$$W_i^* = \begin{cases} 0.002\emptyset^{0.75} & \text{for } \emptyset < 1.35 \\ 14\left(1 - \frac{0.894}{\emptyset^{0.5}}\right)^{4.5} & \text{for } \emptyset \geq 1.35 \end{cases} \quad (7.15)$$

$$\emptyset = \frac{\tau}{\tau_{ri}} \quad (7.16)$$

Where τ_{ri} is the critical shear stress for the i-th particle size class, as determined by equations (7.17), (7.18), (7.19), and (7.20):

$$\tau_{ri} = \tau_{rm}\left(\frac{D_i}{D_{s50}}\right)^b \quad (7.17)$$

$$\tau_{rm} = \tau_{rm}^* \rho g D_{s50} \quad (7.18)$$

$$\tau_{rm}^* = 0.021 + 0.015\exp[-20F_s] \quad (7.19)$$

$$b = \frac{0.67}{1+\exp\left(1.5 - {}^{D_i}/_{D_{sm}}\right)} \quad (7.20)$$

Where τ_{rm} is the critical shear stress for the mean sediment size of bed sediment, τ_{rm} is the dimensionless value of this same variable, D_i is the grain size of the i-th fraction. D_{s50} is the D_{50} value of the bed surface (mm), F_s is the percentage of sand on the bed surface, and D_{sm} is the mean grain size on the bed surface.

In the C-L application of Wilcock & Crowe (2003), the equations have been adapted to include silt sized particles (it was intended for primarily gravel particle sizes with some sand); however, this remains an untested component (Van de Wiel et al., 2007).

Alternately, if Einstein (1950) is deemed more appropriate, equations (7.21), (7.22), and (7.23) are used to calculate transport rate of sediment:

$$q_i = \frac{\emptyset}{\sqrt{\frac{\rho}{(\rho_s - \rho) g D_i^3}}} \quad (7.21)$$

$$\emptyset = 40\left({}^{1}/_{\varphi}\right)^3 \quad (7.22)$$

$$\varphi = \frac{(\rho_s - \rho)D_i}{\tau/g} \tag{4.23}$$

Where φ is a bedload transport rate (dimensionless), D_i is the particle size for the i-th class (mm), and ∅ is the ratio of resisting to pushing forces.

Once the sediment transport rate for the time step is determined using either Wilcock & Crowe (2003) or Einstein (1950), sediment volume for the particular time step used at that point is determined by multiplying the rate by the time step. Time step (d*t*) is determined by the user defined maximum elevation change per time step, ΔZ_{max}, and calculated using equation (7.24):

$$\Delta t = \frac{\Delta Z_{max} \Delta x^2}{q_{max}} \tag{7.24}$$

Where Δt must be less than or equal to one hour, and q_{max} is the maximum sediment transport rate for the time step.

7.3.2.4 Lateral erosion

Lateral erosion results from rivers that have a braided and/or meandering flow pattern, and has been included in C-L. Since the landform designed and studied in this work is isolated from outside water sources, flow in the channels is likely to be sporadic and therefore lateral erosion has not been integrated into the model. Integration of this component would require calibration to existing radii of curvature in the channels, which have yet to be constructed. The lateral erosion components in C-L have been fully explained in Meadows (2014) and Van de Wiel et al. (2007).

7.3.2.5 Slope processes

Slope processes considered in C-L include creep and slope failure, as well as several additional slope erosion parameters that are still undergoing testing and have consequently not been used.

Creep (in meters) is accounted for using a constant, user-defined value, as calculated using equation (7.25):

$$Creep = \frac{SC_{rate}T}{\Delta x} \tag{7.25}$$

Where S is slope, C_{rate} is a user defined rate of soil creep in meters per year, T is time in years, Δx is cell size in meters. While it has been recognized that creep is variable over time and that non-linear equations provide better transport rate approximations, the volume of soil moved via creep is low over extended time frames when compared with other transport modes (such as landslides or fluvial erosion) making this linear estimation reasonable (Martin, 2000; Slingerland, Beier, & Wilson, 2018).

Slope failure is triggered in C-L when cells are arranged to create a slope greater than the threshold defined by the user. When over-steepened slopes are identified, sediment is transferred downslope until the gradient is below the threshold.

7.3.2.6 Vegetation

Vegetation acts as a mitigation factor in C-L, such that as vegetation "grows" to a fully grown state (user defined in years), erosion is linearly decreased until it reaches a steady background rate (user defined proportion). Vegetation is removed entirely from a cell when the user-defined vegetation critical shear strength is exceeded via flowing water. Once the shear strength reduces to a level below this threshold value, vegetation begins to grow in the cell once again.

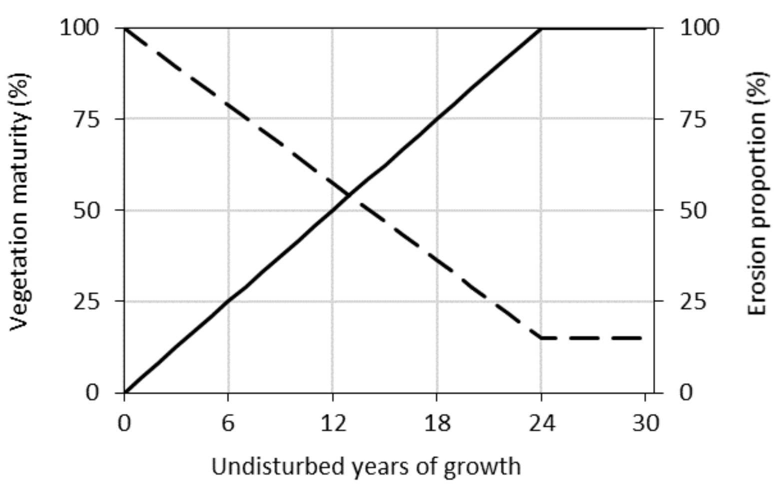

Figure 7.2 Relationship between vegetation maturity (solid line) and corresponding proportion of erosion (dashed line) permitted to occur. Adapted from Slingerland et al., 2018.

7.3.2.7 Limitations and assumptions

Since C-L is a reduced complexity model there are a number of assumptions made. Conservation of mass from one cell to the next is a basic assumption found in nearly all hydrologic and geomorphic models that use cellular automata. This is a reasonable assumption when we have no obvious sinks in the model or system. The landscape topography is represented with a DEM, for which each grid cell will have a single value associated with it. The assumption is that the values calculated for each cell are in turn representative of the entire area covered by that cell. For example, each cell will have one soil moisture value, one water table, etc. For this reason, it is important to choose the grid size based on the features of interest. In terms of channel flow, no turbulent flow is assumed to occur, which would impact spatially variable erosion, for example. This is not realistic in stream modelling, or in extreme storms, but is a necessary assumption for model speed and simplicity.

With regard to the oil sands specifically, limitations include the following:

- The fluid modelled is assumed to be water, therefore any chemical effects due to salt concentration, seepage or dispersion for example, are ignored.
- Surface topography is assumed to be stable up to a critical user-defined angle; no differential settlement is integrated to the model despite the likelihood of this for several years over areas of fine tailings storage.
- CST tailings can generate near-vertical gully walls on occasion, and this is likely impossible to model while still attaining similar overall gully shape and eroded soil volumes from the model.
- Vegetation is given one critical shear number throughout the model, which is not realistic for an upland landform with variable moisture conditions. In reality, many shrub and woody species have higher critical shear forces than herbaceous vegetation, for example, that is more easily removed by flowing water or debris.
- Multiple particle size distributions are not included, making a layered system (gravel over sand, for example) or rock armour impossible to input.
- Evaporation in the AOS is highly variable throughout the year, but is treated in C-L as a constant.

With an understanding of the above limitations, adjustments to the model inputs can be made such that the outputs more accurately reflect conditions on site, and are interpreted with a greater understanding of their relative reliability.

7.3.3 Inputs

The following tables describe the parameters and options in CAESAR-Lisflood with respect to hillslope and channel fluvial erosion and slope morphology. C-L also contains a soil development model and an eolian erosion model that were not used in this research and are therefore excluded from the descriptions below. Terrain is represented using a gridded DEM in ACSII format, between 200,000 and 250,000 cells to run optimally. Hancock (2005) has found that cell sizes 10 m were able to adequately represent slope shapes and gradients, and LEMs have been run successfully on DEMs with cells ranging from 20 cm to 50 m (Coulthard, Hancock, & Lowry, 2012; Coulthard & Macklin, 2001). Historic precipitation records are typically used and looped to meet the length of simulation. This assumes that past climate trends will persist into the future (in simulations for future), and poses a limitation in that exceptional storms may not be captured in the historic record.

Table 7.2 Sediment tab parameters

Parameter definition		Purpose	Recommended value
	Bedrock erosion threshold	Determines when to lower elevation of bedrock.	-
	Bedrock erosion rate	Tells model the rate bedrock should lower when threshold is exceeded.	-
	Suspended sediment? Smallest grainsize is treated as suspended.	Allows or disallows sediment to move suspended in flow.	-
v_f	**Fall velocity**: Velocity that allows sediment to fall out of suspension.	Used to calculate deposition of suspended sediment	-
	Sediment transport law: Wilcock and Crowe or Einstein-Brown	Tells model how to calculate flow rate.	-
	Maximum velocity used to calculate Tau	Rarely necessary, but over very steep slopes, this can limit the sediment transport.	Default: 5 m/s
ΔZ_{max}	**Maximum erode limit**: maximum depth of sediment eroded or deposited in a cell for each iteration / time step.	Helps with numerical stability by preventing excess sediment transfer. Also affects time step /iteration.	0.02 m. DEMs with cells 10 m or less should be set at 0.01 m. Increase with greater cell size.

L_h	**Active layer thickness:** thickness of a single active soil layer.	Defines thickness of active layer	0.1 to 0.2 m. At least 4 times the maximum erode limit.
λ	**In-channel lateral erosion rate:** River and channel lateral erosion, cross-section morphology. For loose, unconsolidated sediment shallow and wide channels are typical because sediment is easily eroded.	Controls how wide or narrow the channel becomes based on how cohesive the sediment is.	Typical values are 10 - 20 for most river types (larger for wide, lower for narrow).
	Lateral erosion included: whether channel erosion can occur.		None. Requires field calibration and lengthens modelling time.

Table 7.3 Hydrology tab parameters

Parameter definition		Purpose	Recommended Value
	Rainfall data file time step: Length of time each line of precipitation represents.	Tells model how to read precipitation input file.	60 minutes
m	**'m' value:** mimics the water transport and storage dynamics in soil associated with vegetation. Large values produce low flood peaks with a long duration hydrograph, similar to that seen with forested soil. Small values produce higher, flashier peaks as seen in a grassland landscape.	Dictates length and slope of the recession portion of the hydrograph used throughout model run time.	0.005 to 0.02. Typically chosen based on relative forest cover across (0 to 0.02) value range. May also be calibrated using a storm/runoff hydrograph.

Table 7.4 Vegetation tab parameters

Parameter definition		Purpose	Recommended value
τ_{crveg}	**Vegetation critical shear:** Value of horizontal shear stress that removes vegetation.	Vegetation will be removed by fluvial erosion when values exceed this threshold	None. Estimate from strength of vegetation grown.
T_{veg}	**Grass maturity:** length of time for vegetation to reach maturity, in a linear fashion.	Site-specific vegetation growth rates.	None. Estimate based on known or measured times.
	Proportion of erosion that can occur when vegetation is fully grown (0 - 1): Determines how vegetation maturity affects the in-channel lateral erosion rate and the lateral (bank) erosion rate.	Decrease in river/ channel erosion with vegetation maturity.	Ranges from 0 (no erosion) to 1 (full extent of erosion occurs).

Table 7.5 Slope processes tab parameters

Parameter definition		Purpose	Recommended value
C_{rate}	**Creep rate:** diffusive soil creep function.	Simulates creep on hillslopes.	Default value is 0.0025

	Slope failure threshold: angle in degrees above which landslides occur.	Impedes formation of over-steepened slopes	None. Estimate or measure using DEM, LiDAR, field study.
	Dynamic slope fail angle, varying according to soil saturation?	Leads to shallower slopes at higher saturation.	-
E_r	**Soil erosion rate:** adaptation of USLE approaches leading to more erosion at base of slopes.	Untested. In theory this refines hillslope erosion to USLE rate.	-
	Erosion varies according to soil saturation?	Untested	-

Table 7.6 Flow model tab parameters

Parameter definition		**Purpose**	**Recommended value**
Q_{diff}	**Input / output difference allowed**: difference permitted between water which should be coming out of model and water that is actually coming out of model. If Q_{out} equals Q_{in} then model is running in steady state and iterations speed up until this is no longer the case.	Run time optimization, adjusts time step.	None. Default is 1 m^3/s. Value is ideally close to the watershed low flow value.
Q_{min}	**Min Q for depth calculation:** threshold above which a flow depth in a cell is measured in catchment mode. Low (0.01) values mean stream heads initiate higher in the catchment, increasing run time and possibly erosion. Stream heads initiate lower in the catchment with high values, decreasing run time.	Run time optimization, depth calculation	Historically 0.1 m^3/s for 10 m cell size, 0.5 m^3/s for 50 m cell size. This is currently under review. Recommended that Q_{min} remain constant regardless of cell size (recent research).
Q_{max}	**Max Q for depth calculation**: used in reach mode where water is added up to this limit to every cell less than this limit.	Run time optimization	None. Default is 1000 m^3/s.
d_{min}	**Water depth threshold over which erosion will happen:** Flow depth at which erosion begins to be calculated in a cell.	Run time optimization, fluvial transport calculation	0.01 m typically. Larger values can be used on cells > 50m, smaller values for high resolution DEMs.
S_{edge}	**Slope for edge cells:** slope on exit cells out of model	Allows calculation of flow out of model	Mean valley floor slopes, adjusted to inhibit edge erosion
	Evaporation rate: applied every day the model is running.	Evaporation from soil surface and pools of water	Daily average evaporation rate
α	**Courant number:** controls model stability and operation speed. Ranges between 0.3 and 0.7 with larger numbers increasing speed but decreasing numerical stability.	Model stability and speed	0.3 to 0.7. Low resolution DEMs (50 m cells) may use larger numbers, high resolution DEMs may use smaller numbers. (Typ. 0.4 for cells 10 m or less)
h_{flow}	**hflow threshold:** relates water surface elevation between two cells.	Prevents moving water when low gradients exist between cells. Run time optimization.	Default value is 0.00001 m.

Fr	**Froude # flow limit:** limits the amount of flow allowed between cells per time step. Excess Froude #'s lead to checker-boarding effects in the DEM output.	Model stability and speed	Default value is 0.8. Values up to 1 may work. Can use lower values when modelling deep flows (lakes) at fine cell size.
n	**Manning's n:** roughness and sinuosity coefficient.	Used to calculate flow rate and bed shear stress.	None. Calculate or look up values from tables.
	Spatially variable Manning's n?	Variable roughness.	Untested.

7.4 Discussion and application

In Chapter Three a geomorphic design for the closed surface of a tailings pond was developed using long-term stable slopes, measured cross-sectional width of stable vegetated swales, etc. as found in nature. This method is common in the oil sands, however, the long-term stable slopes and swales measured are composed of very different substrates from those composing the TSF and SEA.

The natural analogue approach is common practice in design of natural environments and even in waste rock dump design, although it is considered preferable to "check" the designs via landscape evolution models, especially when the natural analogue is located remotely. It seems especially pertinent to "check" designs in the AOS given that design basis values are taken from remote locations and different substrates. Using a LEM to evaluate a landform design also allows for comparison of design alternatives, adjustment, and ultimately for design and construction of a mature landform with the best long-term performance possible. Ideally, trial landforms can be built well before reclamation work begins for field testing and comparison as well.

A growing movement of "design for closure", "cradle to grave" construction methods, and other "sustainable mine" concepts universally point towards early closure planning, and working towards a set closure plan from the outset of mine planning. Since re-shaping of dam slopes during reclamation is not generally considered feasible, a case is to be made for designing dam slopes using a LEM from the very beginning (Figure 7.3). Using this approach, topography generated using the traditional design methods are first evaluated with a LEM. If the structure meets long-term erosion and geomorphic stability targets then it can proceed. If it does not then the dam is re-designed until all short-term and long-term requirements are achieved, as demonstrated through properly parameterized and calibrated modelling software.

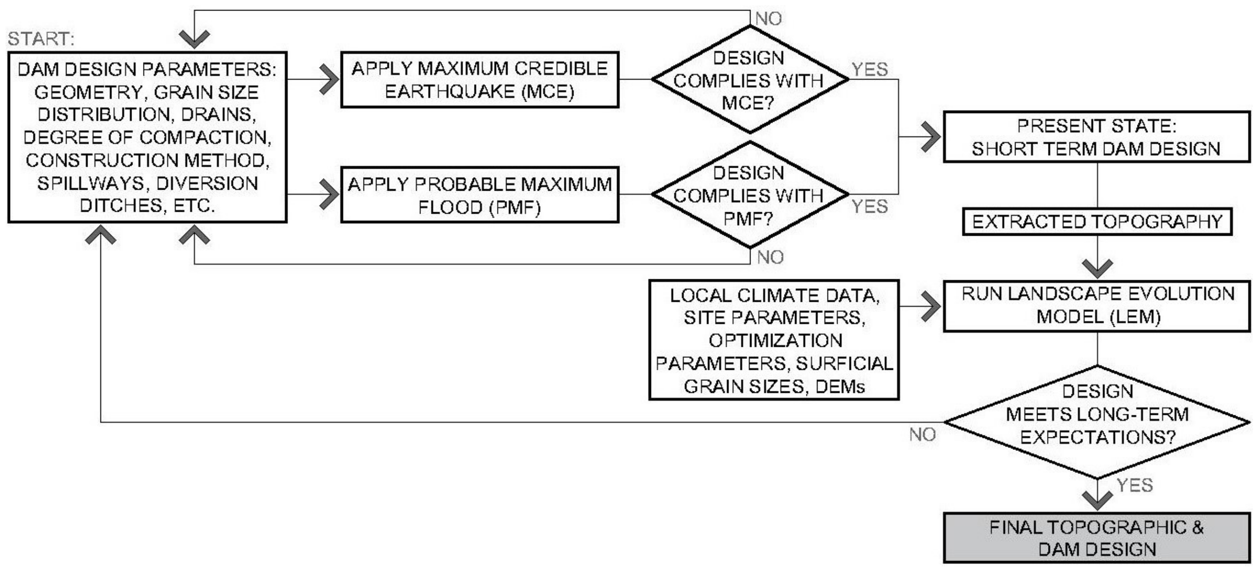

Figure 7.3 Process model for integration of LEM assessment into tailings dam design, from Slingerland, Isidoro, Fernandez, & Beier (2018)

The method proposed in Figure 7.3 would generate a dam design that meets short-term stability, seepage, and long-term geomorphic stability guidelines. In order to attain a reclamation certificate in Alberta it is expected that mining companies will need to demonstrate, using legally defendable methods, that their former mine site and its component landforms will perform similarly to a natural landform, posing no contamination hazard over very long timeframes. In Australia the Ranger Mine has been charged with demonstrating that no tailings will be exposed to the atmosphere for a period greater than 1,000 years (Willgoose & Riley, 1998). Attaining legally admissible evaluations of post-mining landform designs will likely be necessary in the future, both to demonstrate long-term performance to opponents of development and to determine negligence/ liability in cases of poor landform design and waste containment (Willgoose 2018a). The use of LEMs in the initial design process may become professional due diligence for any geoscientist or engineer engaged in mine closure design and planning, particularly where regulations for design life or reclamation certification exist.

7.5 Summary & conclusions

Landscape evolution models have developed to a point where, despite simplification of the processes modelled, they have demonstrated replication of natural hydrologic and geomorphic processes. Due to the extended design life that is expected by regulators to ensure safety of closed post-mining environments, and especially due to the risk posed by tailings dams, it is logical that we use the tools available to begin checking if designs meet their targets. This may include running designs previously completed through a fully parameterized LEM, or more preferably, by integrating LEMs into the initial dam design process which that a design can be identified early on that meets both short and long-term stability requirements.

8.0 LEM application to the AOS

The AOS mine previously described in Chapter Three is scheduled to end production in the middle of the twenty-first century. Steps towards closing their external tailings storage facility and south expansion area have begun, with the proposed TSF conceptual design (as per Chapter Three) accepted with revisions as recommended by subsequent studies. This chapter analyses the long-term geomorphic stability of the preferred conceptual closure topography for the TSF from Chapter Three and the infilled SEA ‘plateau’ using the CAESAR-Lisflood landscape evolution model (LEM), version 1.9b.

8.1 Goals of landscape evolution modelling

The process of developing a topographic design for the SEA and TSF highlighted a gap in knowledge regarding how to design a geomorphically stable landform with new soil for long time frames. In Chapter Three the design approach used methods and information available at the time (2015), which included design of slopes and channels using measurements of those in equilibrium on surrounding undisturbed terrain. This was a logical approach given that the post-mining environment is presently, and will continue to be, subjected to the same climatic forces as the natural terrain adjacent to it. However, geomorphology is dependent upon more than climate patterns alone: it is also shaped by the soil and its various properties that make it more or less erodible due to grain size distribution, permeability, moisture content, etc.

The tailings that make up much of the closure landscape, including the TSF dyke, infill, and cap are dominated by fine grained sand and silt-sized particles. These tailings have been noted for their erodibility and resulting reclamation challenges as early as the 1970’s (Syncrude 1978). In contrast, the natural soils in the vicinity of the mine are mostly coarser glacial outwash sand (Figure 3.1) overlain by metres of peat and organic deposits which provide erosion resistance (Turchenek, 1982). It is therefore inconsistent to apply the gradients, slope lengths, and shape characteristics of geomorphically stable local terrain to a landscape constructed of uniformly fine-grained particles.

The goals of conducting landscape evolution modelling on the TSF and SEA are numerous. Primarily, it is of interest to determine if the use of LEMs, particularly CAESAR-Lisflood, have potential for use in the northern Alberta climate where much of the year precipitation falls in the form of snow. CAESAR-Lisflood has never been used in northern Canada and has been used only once before to the authors knowledge in an environment subjected to winter climate. Data inputs that would typically be used in their raw format will therefore need to be altered to address winter conditions.

This work seeks to assess:

- the geomorphic performance of tailings storage facilities constructed of CST,
- if and how the proposed closure design for the TSF and SEA are impacted by precipitation over long time frames such that vulnerabilities can be identified,
- how much deposition can occur before proposed perimeter channels are blocked,
- if ongoing maintenance is required, what the return period might be, and what is the estimated time to reach equilibrium of erosion?
- how we might improve the design of sand dams in the Athabasca oil sands for closure.
- is the CAESAR-Lisflood model sensitive to cumulative climate change effects and how do these effects alter erosion patterns over 100 years? (Chapter Nine)

Three separate simulations were run in order to assess the above points. The first included the entire TSF and SEA (Figures 8.1 and 8.2) for 200 years. The goal this simulation using this set of LEMs was to understand general trends in morphology, the type and spatial extent of medium-term geomorphic changes, where erosion-prone areas were located, and what the long-term challenges in terms of fluvial processes might be to maintenance of a functional drainage regime and landform. The second included the 1 km dam section (Figures 8.3 and 8.4) at high resolution for 1000 years in order to determine longer term slope characteristics and gully dimensions. The third included two simulations using the 1 km dam section, each for 100 years: one using historic climate parameters and the other using projected climate parameters. Traditionally, landscape evolution modelling for the purpose of geomorphic prediction has used historic climate; this last simulation (pair) seeks to determine how geomorphology might be affected by climate change, and is detailed in Chapter Nine.

8.2 Model inputs

As discussed in Chapter Seven, the CAESAR-Lisflood model requires data inputs in the form of a DEM used to represent the surface topography, a DEM to represent bedrock topography (or in this case, the lower limit of erosion), a typical grain size distribution for the landform surface that has been separated into nine groups maximum, and a precipitation record that is both historically long (in order to capture as wide a variation as possible) and sufficiently detailed to capture storm intensities.

8.2.1 Digital elevation models

LiDAR data at a 40 cm horizontal resolution and 25 cm vertical accuracy (flown on October 10, 2016) was provided by Shell Canada Ltd. for the purposes of this research. The LiDAR was first edited to:

1. Remove unnecessary features such as culvert overpasses (which show up as blockages in perimeter channels when viewed as a topographic map)
2. Level the topography surrounding the TSF in order to accurately measure the extent of any sediment transported perpendicular to dyke slopes.
3. Remove the central pond topography from the TSF and replace it with the proposed closure topography
4. Remove the central pond topography from the SEA and flatten the area according to the perimeter dyke crest topography.
5. Expand the perimeter ditches from 3.5 - 7 m width to 36 - 48 m width perimeter channels, as is presently planned for the site.
6. Extend the TSF central outlet to drain out the top of the DEM.

The LiDAR was then converted to a geo-referenced .dem file in AutoCAD Civil 3D with 1 m resolution and in order to capture maximum detail. This meant that the total area captured included over 28.5 million individual cells. CAESAR-Lisflood runs optimally on DEMs up to 200,000 - 250,000 cells after which point the program tends to slow, or in extreme cases stalls due to computer memory exceedance. ArcMap was used to resample the .dem file to a lower resolution such that the number of total cells was less than the recommended upper range of 200,000 - 250,000 while capturing as much detail as possible. A grid size of 10 m has previously been found to sufficiently capture shape and curvature of a natural catchment (Hancock, 2005), but ultimately an appropriate grid size is one that conveys topographic characteristics of interest in the modelling (Wechsler, 2007; Willgoose, 2018). A 12 m x 12 m cell size was used as it resulted in a DEM with 198,465 cells total (425 cells wide by 467 cells high) and 1.89 megabytes in size. Considering the width of designed drainage pathways and scale of the TSF more broadly, a 12 m cell size was adequate in order to understand the overall changes in form. The DEM was then converted to an ACSII .txt file readable by CAESAR-Lisflood. Further refinements in this format were made using MS Excel and RasterEdit software to remove pits and obstructions to drainage. MS Excel proved to be the most efficient method of editing .txt DEMs as it allowed for quick extension of slopes using algorithms and rapid duplication of cell elevation values. The resulting surface DEM retained topographic characteristics present in the original LiDAR file, but processing to a 12 m grid size had an overall smoothing effect such that features smaller than this size were lost. A graphic visualization of the surficial DEM is shown in Figure 8.1.

A bedrock DEM (Figure 8.1) was constructed to the same dimensions as the surface DEM. This was completed by lowering the surface DEM by 1 m in AutoCAD Civil 3D, and connecting elevations between the two perimeter channels using straight-line contours. This created a hard limit such that no more than 1 m of erosion in the perimeter channels and landscape surrounding the TSF was permitted (where deposition is expected to predominate). This also allowed for erosion within the TSF and SEA down to a maximum depth of the channel base. The same process of file conversion and resampling was then used in order to create a bedrock .txt DEM.

The same process was used to construct a 2.5 m cell size DEM covering a single portion of a dyke, and the underlying “bedrock” or limit of erosion (Figure 8.2). This area on the east TSF dyke (592 by 386 cells) was used to gain a more detailed view of changes to the landscape. The goal simulations using this set of LEMs was to determine the (1) long-term “steady-state” slope of the downstream dam face (as such an extended flat area was retained at the top and bottom of the dam face) and (2) high resolution soil loss from a typical dam slope and gully dimensions.

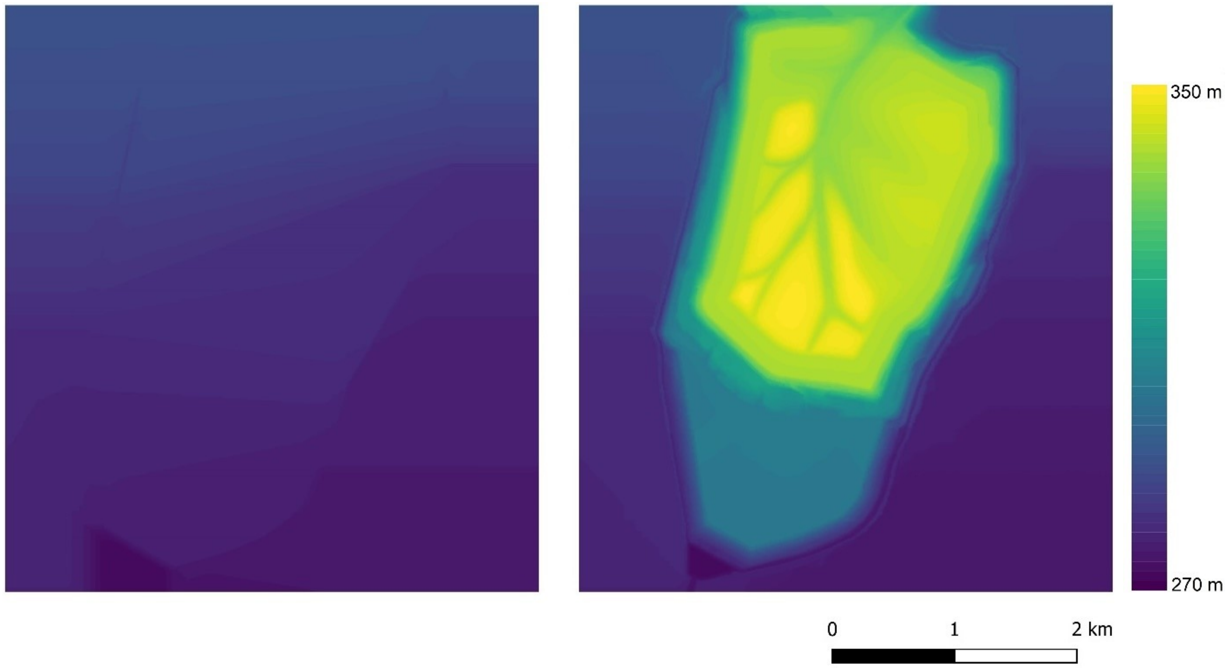

Figure 8.1 Bedrock DEM (left) and surface topography DEM (right) used in the first simulation (200-years), both with north to the top of the page.

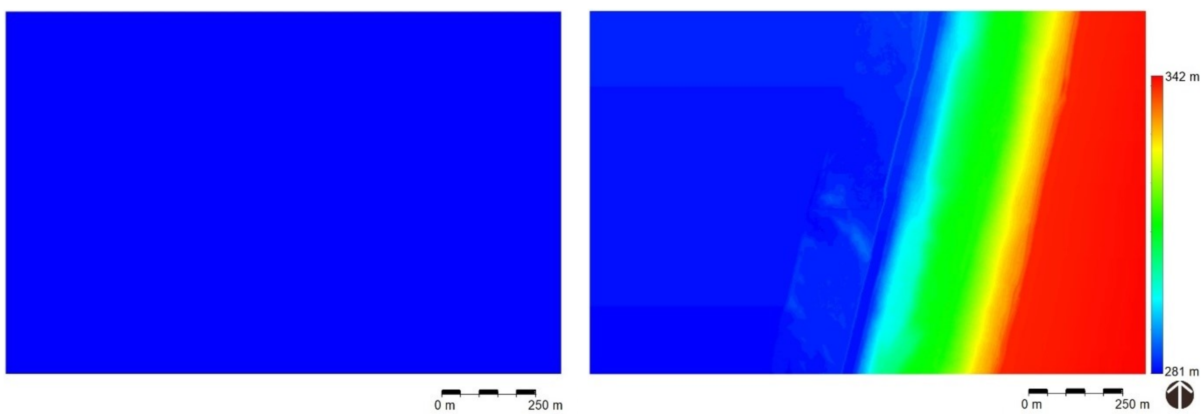

Figure 8.2 Bedrock DEM (left) and surface topography DEM (right) used in 1000-year and 100-year simulations, both with a cell size of 2.5 m and dimensions of 592 x 386 cells.

8.2.2 Grain size distribution

Samples were gathered in the spring of 2017 from locations around the TSF shown in Figure 5.3 and Table 5.1. The process used is described in Section 5.3. Particle size distribution is shown in Table 8.1 and Figure 5.4. The distribution was then reduced to nine classes for use in the CAESAR-Lisflood LEM, shown in Figure 8.3. Ranges are not permitted in C-L, therefore median grain size for a range is used. Ranges were taken from the sieves used in mechanical analysis, and proportion of soil captured by the sieves was measured relative to total soil.

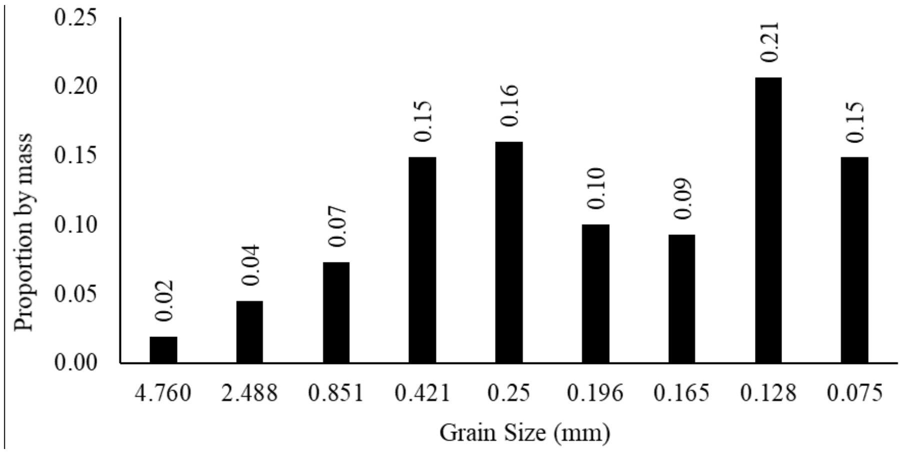

Figure 8.3 Particle size classes used in CAESAR-Lisflood simulations.

8.2.3 Precipitation record

CAESAR-Lisflood operates with two possible modes of water input to the system: catchment mode, reach mode, or both. In reach mode, water is introduced to the model via point sources just as water enters a portion of stream from a point. Reach mode assumes that runoff is generated from point sources such as a lake, spring, or upstream river. In contrast, the TSF forms an isolated upland feature fed by precipitation, and perimeter channels are fed by overland flow, interflow, and groundwater seepage from the TSF. Under these circumstances the use of 'catchment mode' is more appropriate; catchment mode is dependent upon precipitation inputs applied uniformly to the entire DEM.

The use of catchment mode for simulation requires a precipitation record, preferably recorded at an hourly interval and for as long a time frame as possible, within reason for the purposes of the modelling. The longer the data set, the wider the range of precipitation events captured. However, in consideration of climate change projections, recent climate patterns are a better predictor of future climate than patterns from 100 years ago, therefore a balance must be found. Previous studies have used available precipitation records from nearby weather stations, then looped the data repeatedly in order to achieve the desired length of modelling time; a survey of these studies is provided in Table 8.2. For example, if 10 years of hourly precipitation data are available and the model is to simulate 100 years then the 10-year data set would be repeated (looped) 10 times to create an hourly 100-year data set.

Table 8.1 Particle size distribution of samples. No sieving was done for WM and WL as these were overburden.

Mechanical analysis of CST: MRM ETF

Site Location No.	Sample Depth (mm)	U.S. Standard Sieve No. (*mm*) - percent retained 1" 25.4	#4 4.75	#10 2.000	#16 1.190	#20 0.850	#30 0.600	#40 0.425	#50 0.297	#60 0.250	#70 0.212	#80 0.180	#100 0.150	#200 0.075	#140 0.106	<200
NT	0-150	100.00	100.00	97.81	96.62	95.49	94.44	92.55	89.35	82.61	76.66	69.07	59.53	24.61	50.46	8.13
	150-250	100.00	100.00	98.74	97.97	97.15	96.12	94.14	90.61	82.86	76.60	67.94	57.40	19.62	47.06	5.63
NM	0-150	100.00	100.00	92.78	87.39	82.52	77.80	72.24	65.90	56.09	48.68	40.16	32.63	12.89	26.88	4.99
	150-250	100.00	100.00	94.46	88.09	82.08	76.25	69.41	62.78	52.96	46.48	37.78	29.47	10.67	23.25	4.39
NB	0-150	100.00	100.00	97.46	94.05	90.48	87.65	83.88	78.85	70.06	63.37	55.26	47.56	22.89	40.77	11.18
	150-250	100.00	100.00	98.74	97.50	95.51	92.84	88.24	81.86	70.86	62.74	53.15	43.58	16.95	35.81	6.62
NET	0-150	100.00	100.00	97.52	94.10	90.40	84.96	80.01	74.70	67.19	61.82	54.03	44.78	18.15	36.58	6.68
	150-250	100.00	100.00	100.00	99.90	98.94	96.71	91.63	82.91	68.85	60.36	50.29	39.08	12.50	29.83	4.09
NEB	0-150	100.00	100.00	99.53	99.13	97.77	96.21	93.23	88.63	80.42	74.56	66.07	54.77	20.43	43.81	6.93
	150-250	100.00	100.00	99.83	99.30	98.62	97.45	95.41	91.99	85.42	80.24	71.84	59.54	20.00	47.00	6.27
ET	0-150	100.00	100.00	97.22	94.86	91.65	88.28	83.76	78.11	67.23	58.64	49.77	41.52	18.07	34.52	6.94
	150-250	100.00	100.00	97.55	95.35	92.47	89.17	84.42	77.94	64.12	52.69	42.34	33.56	13.82	27.29	5.32
EM	0-150	100.00	100.00	100.00	100.00	99.17	97.31	93.22	88.01	79.82	74.34	67.89	59.87	27.14	51.41	9.91
	150-250	100.00	100.00	100.00	100.00	98.72	96.42	91.64	84.95	74.76	68.20	60.86	52.54	21.97	44.07	7.86
EB	0-150	100.00	100.00	100.00	99.72	97.39	92.80	84.96	75.36	62.11	55.17	47.24	37.99	11.56	29.47	3.18
	150-250	100.00	100.00	100.00	99.56	96.69	93.48	88.88	82.69	71.49	64.00	54.75	43.81	13.13	33.55	3.93
SET	0-150	100.00	91.36	90.22	89.00	86.76	83.89	79.23	73.29	63.50	56.10	46.26	35.93	9.75	26.31	3.09
	150-250	100.00	100.00	98.03	95.97	92.05	87.04	79.28	68.45	57.45	49.04	38.36	28.49	7.13	20.66	2.05
SEB	0-150	100.00	100.00	100.00	99.74	98.69	97.17	94.03	88.87	78.89	70.44	58.83	46.92	16.47	36.87	5.08
	150-250	100.00	100.00	100.00	99.83	98.70	97.30	94.39	89.38	79.46	70.99	59.31	47.27	16.34	37.24	4.96
ST	0-150	100.00	100.00	100.00	100.00	99.92	99.83	99.71	99.54	99.12	97.13	88.91	71.29	14.59	51.88	1.87
	150-250	100.00	100.00	100.00	100.00	99.94	99.82	99.61	99.13	98.05	96.37	90.75	77.10	18.40	59.29	2.41
SM	0-150	100.00	100.00	100.00	100.00	99.32	98.05	94.57	87.27	73.89	64.32	52.76	41.25	10.88	31.07	2.41
	150-250	100.00	100.00	100.00	100.00	97.89	96.28	93.20	87.30	75.61	66.23	54.40	42.47	10.83	31.86	2.33
SB	0-150	100.00	100.00	99.04	98.11	96.30	93.83	89.93	84.94	76.64	70.06	62.09	53.87	19.64	45.60	5.64
	150-250	100.00	100.00	100.00	99.88	97.43	94.07	89.02	82.75	72.48	64.54	54.97	45.58	13.59	36.47	3.34
SWT	0-150	100.00	98.85	88.79	83.35	78.24	75.19	72.16	69.15	63.70	58.73	50.97	41.19	11.74	32.10	3.21
	150-250	100.00	92.99	76.48	60.41	49.77	43.84	38.87	34.66	28.93	25.17	19.33	13.53	3.52	9.51	2.24
SWL	0-150	100.00	100.00	100.00	99.86	98.68	97.51	95.76	93.17	88.55	84.25	77.83	68.94	22.01	57.00	4.54
	150-250	100.00	100.00	99.94	99.60	98.72	97.59	95.63	92.09	84.51	77.42	68.23	57.65	15.22	45.58	1.99
WT	0-150	100.00	100.00	98.81	97.61	96.62	95.69	94.23	91.80	86.03	79.72	69.05	55.57	14.94	42.59	3.56
	150-250	100.00	100.00	99.88	99.78	99.63	99.29	98.29	96.20	91.11	85.81	75.36	60.67	15.15	45.57	3.94
WM	0-150															
	150-250															
WM2	0-150	100.00	100.00	100.00	99.83	98.52	94.18	84.46	71.77	56.59	47.70	38.84	31.00	12.49	25.16	4.16
	150-250	100.00	100.00	100.00	100.00	98.90	94.93	86.92	76.87	62.85	53.08	42.45	32.74	12.26	25.81	3.75
WL	0-150															
	150-250															
NWT	0-150	100.00	100.00	99.47	98.55	96.54	93.58	88.52	81.53	69.20	57.80	43.66	32.13	8.50	23.54	2.54
	150-250	100.00	100.00	99.94	99.17	97.09	93.80	88.25	80.98	68.25	57.07	42.42	30.59	7.16	21.82	1.91
NWL	0-150	100.00	100.00	98.62	93.42	87.01	78.69	69.28	59.96	49.45	42.97	35.36	28.76	11.25	23.13	4.92
	150-250	100.00	100.00	86.18	70.41	59.92	48.86	38.65	30.15	21.92	17.86	13.88	10.82	4.24	8.496468	1.92
AVERAGE		100.00	99.56	97.55	95.48	92.94	89.96	85.57	79.84	70.61	63.61	54.54	44.51	14.75	35.25	4.58

Within the AOS region weather stations with publicly available data are operated by Environment Canada and the Regional Aquatics Monitoring Program (RAMP). RAMP provided the longest and most consistent set of hourly data taken from their 'Aurora C1' climate station located near the mine site. Hourly precipitation data was available with occasional gaps from January 1, 2003 through to August 30, 2017 (15 years). The data was quality controlled and compared with other local stations to ensure general agreement. Any periods with irregular or no data were replaced with hourly precipitation data from Environment Canada's Mildred Lake climate station, based upon congruence with C1 data from immediately before and after the gap. Hourly precipitation data from September 2017 through to the end of 2017 was attained from the Fort McMurray 'A' station.

CAESAR-Lisflood does not differentiate between precipitation that falls in the form of snow or rain. Preliminary sensitivity testing was conducted in order to determine whether adjustment for winter conditions would impact the model results using three precipitation options on a basic shallow 'v'-shaped DEM: (1) the 15 year precipitation data set without any adjustment; (2) the 15 year precipitation data set with precipitation falling over the winter removed (this varied by year, measured by consistent temperatures below 0°C); and (3) the 15 year precipitation data set with no precipitation over winter, and snow melt calculated as water equivalent applied in spring. Option (1) and (2) generated very few changes to the DEM, while option (3) generated minor changes. It was therefore determined that CAESAR-Lisflood was sensitive to minor variation in precipitation inputs and that adjustments for winter conditions would be necessary in order to accurately evaluate morphology. Since option (3) was most realistic, it was then used throughout the 15-year data set.

Hydrologic modelling in northern environments is particularly challenging where snow accumulation/redistribution is dictated in part by terrain topography and snow melt is strongly influenced by slope aspect (Woo, 2000). In order to account for snow melt and winter conditions, system simplifications are necessary, and temperature data is required at an hourly or daily interval. Temperature data dictates when precipitation is set to zero, and when snow melt should begin. Temperature data was collected primarily from RAMP's Aurora C1 (and occasionally Environment Canada's Mildred Lake, as necessary) station until the end of 2012, followed by Fort McMurray CS from 2013 to the end of 2017. Gaps in climate data, and coordinating where irregularities began, is a particular challenge in attaining a consistent and reliable data set. Identifying the most consistent locations and minimizing sources is an important aspect of generating a trustworthy data set.

Snow accumulation near the study site has been measured by RAMP for an extended time frame and this was determined through trial and error to be the most representative method of determining snow melt. The daily difference in snow depth measurements was converted to a water volume using equation (8.1) and applied as precipitation to the day over one hour, in addition to any rainfall measured. (Note: Additional sensitivity testing with respect to the length of snow water equivalent took place, but little to no erosion occurred when the SWE was distributed across multiple hours of the day.)

$$SWE = \frac{d\rho_s}{\rho_w} \times \frac{10mm}{cm} \tag{8.1}$$

Where SWE, or snow water equivalent, is in mm, *d* is snow depth (cm), ρ_s is snow density (g/cm^3), and ρ_w is water density (g/cm^3). Where no snow density measurement was available, the average from 1997 - 2015 was used, which was 0.243 g/cm^3 as calculated from all RAMP values. In autumn once temperature was below 0 °C, precipitation was set to zero (as it would be in the form of snow, therefore no fluvial erosion is possible) and in spring, snow melt initiation typically corresponded to an average daily temperature above -1 °C, the base temperature for snow to melt in Fort McMurray (Hassan, Sekhon, Magai, & McEachern, 2012). Figure 8.4 illustrates the adjustment of quality controlled precipitation data for winter conditions using this method, which is similar to the method previously used by (Welsh, Dearing, Chiverrell, & Coulthard, 2009) in the French Alps. Over the fifteen-year period, the minimum, maximum, and average length of time it took for the snow to melt was three days, 34 days, and 14.7 days, respectively. Since this was calculated from snow depth from day to day, there was no maximum and no minimum SWE applied to a day. In some instances, there were gaps between days with any melt occurring due to low temperatures.

An initial 15-year amended precipitation record was formed once snow melt and winter conditions were accounted for as described above, for the entire data set. This 15-year record was then looped to create an hourly record for the necessary time period, and statistical 24-hour storms were inserted for a 1:25, 1:50, 1:100, and 1:1000 (for the 1000-year simulation only) event according to their return period, or probability (for example, a 1:25-year event was placed once every 25 years). This was done for ease of standardization and as a basic first attempt, despite the probability of exceedance, P_e, Equation (8.2). Other methods previously used to generate long sub-daily precipitation records for use in LEMs are outlined in Table 8.2.

$$P_e = 1 - \left[1 - \left(\frac{1}{T}\right)\right]^n \tag{8.2}$$

Where P_e is the probability of an equal or greater event, T is the return period, and n is the number of years in review period.

Typically, a ‘Type II’ storm distribution is used in Alberta to achieve hourly distribution of precipitation for a statistical storm event, or occasionally a synthetic ‘nested storm’ where no distribution is identified. These distributions do not accurately represent large storms in Fort McMurray (the Natural Resource Conservation Service (NRCS) Type II distribution is particularly conservative), and using a triple-peak distribution typical of the Fort McMurray region (Dick & Ghavasieh, 2015) has been used instead (Figure 8.5) for statistical 24-hour storm inputs. This triple-peak storm was found by Dick and Ghavasieh (2015) to most closely correspond to measured large storm events and runoff from typical AOS catchments, including areas of natural terrain and a sand tailings dam. Historical IDF curves were attained using the IDF_CC tool (Simonovic, Schardong, Sandink, & Srivastav, 2016) for the Fort McMurray ‘A’ climate station (Figure 8.6).

In summary, generating a precipitation dataset required several steps: (1) quality control of hourly precipitation data for the 15 years of continuously available data, (2) adjustment of precipitation record based on winter conditions (continuous temperature less than 0 °C in autumn, and calculation/addition of SWE from snow melt once temperatures reached greater than -1 °C in spring), (3) looping adjusted precipitation dataset to form an expanded dataset for desired length of simulation, and (4) inserting statistical storms according to their basic annual probability and distributing rainfall using a triple-peak across 24 hours.

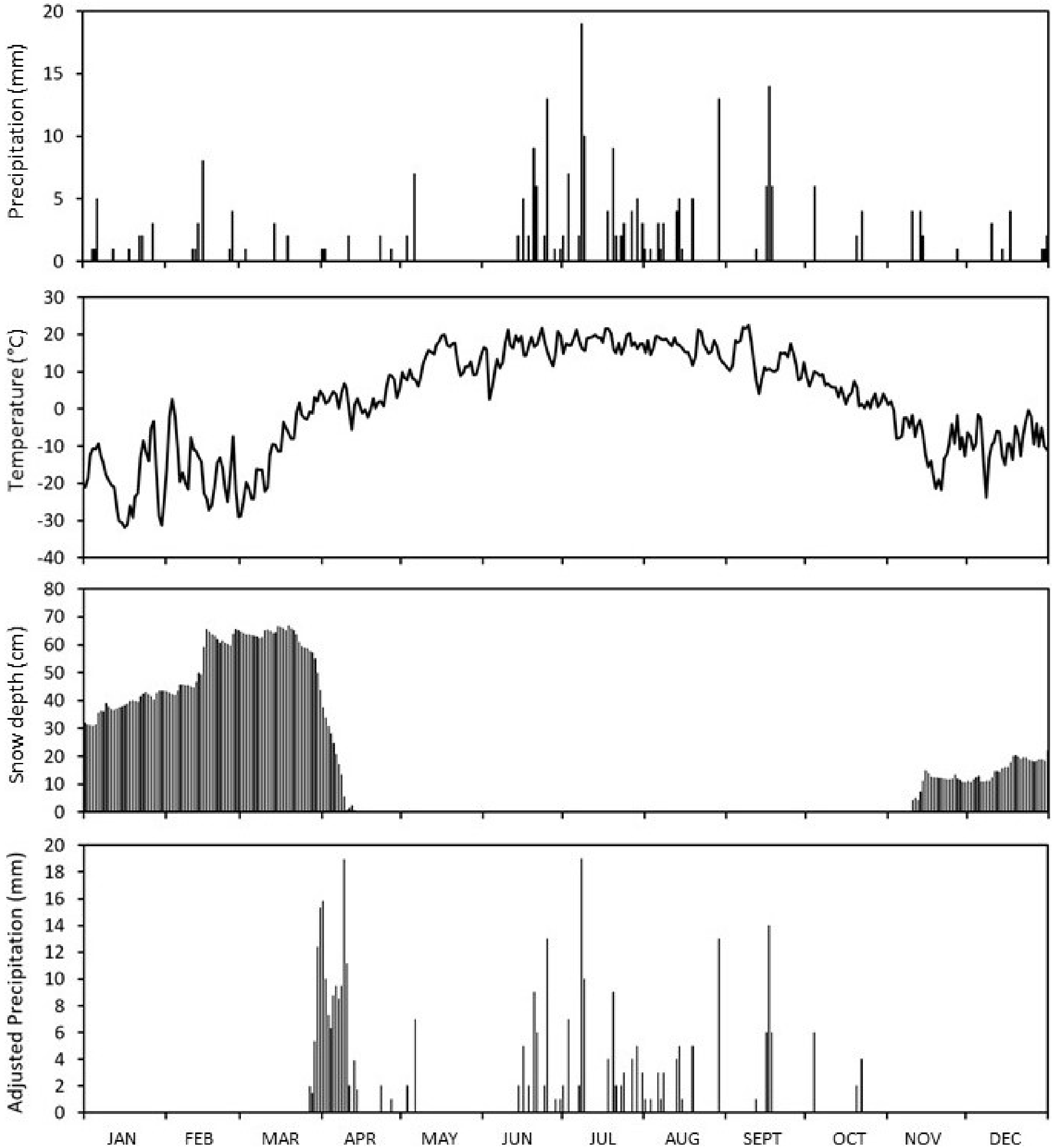

Figure 8.4 Illustration of precipitation data adjustment for winter conditions and snow melt. The adjusted precipitation was input to CAESAR-Lisflood for simulations.

Table 8.2 Previous methods of precipitation dataset generation for use in LEMs.

Publication	Initial data set length	Total run time	Measured data (M) or reconstructed data?	Study location
Coulthard, Macklin, & Kirby (2002)	10 years of hourly data.	9200 years BP	Proxy wetness index from a peat bog sampled at 50-year intervals, then normalized to values between 0.5 and 2.25 to create a rainfall index. 10 yr data set was looped 5 times to create 50-year dataset. Each 50-year loop was multiplied by the index, accounting for changes in flood magnitude.	UK
Coulthard, Lewin, & Macklin (2005)	10 years of hourly data.	9000 years BP	10-yr data set was looped 5 times to create 50-year dataset. Two proxy surface wetness indices from peat bogs in northern England (6300 cal. BP to present) and Scotland (6300-9000 cal BP). These records were combined, interpolated and resampled at 50-year intervals. Normalized values b/w 0.75 to 2.25 created a wetness index. 50-year loop was then looped again with wetness index multiplied to it.	UK
Welsh, Dearing, Chiverrell & Coulthard (2007)	14 years of hourly data.	180 years BP	14 years was simplified to a 5-year template, then repeated back 180 years (to 1826) and manually adjusted to meet known monthly totals (ignoring IDF). Snow storage/melt calculated using temperature data & freeze/thaw thresholds.	French Alps
Hancock (2009)	23 years of hourly data.	1000 years	Measured. 4 scenarios tested: A) years 1-22 (dry) looped. B) years 1-22 (dry) looped twice then year 23 (heavy rain) added to make a set of 45 years close to 1:50 return period. C) all 23 years looped. D) years 1-11, then wettest (year 23), years 12-22, then wettest again (year 23) = 24-year loop.	Tin Camp Creek, close to ERA Ranger Mine
Hancock, Lowry, Coulthard, Evans, & Moliere (2010)	22 years of hourly data.	10,000 years	Measured	Tin Camp Creek, close to ERA Ranger Mine
Hancock, Coulthard, Martinez, & Kalma (2011)	< 7 years of hourly data.	1000 years	Measured	NSW, Australia
Coulthard, Hancock, & Lowry (2012)	1 year of 10-minute data.	20 years	Measured	ERA Ranger Mine, Jaiburu
Lowry, Coulthard & Hancock (2013)	22 years of hourly data.	A) 45 years. B) 1000 years.	Measured. 2 scenarios: A) 22 years repeated twice with one extreme (exceeding 1:100 return) rainfall in year 45. B) 22 years looped without extreme event.	ERA Ranger Mine, Jaiburu
Coulthard, Neal, Bates, Ramirez, Almeida, & Hancock (2013)	40 years of hourly data	40 years	Measured	UK
Hancock, Lowry, & Coulthard (2015)	22 years of hourly data	1000 years	Measured	ERA Ranger Mine, Jaiburu
Barkwith, Hurst, Jackson, Wang, Ellis, & Coulthard (2015)	2 years of daily data	2 years BP	Measured	UK
Coulthard & De Wiel (2017)	30 years of hourly data	210 years	Reconstructed with UKCP09 weather generator for climate change impact assessment.	UK

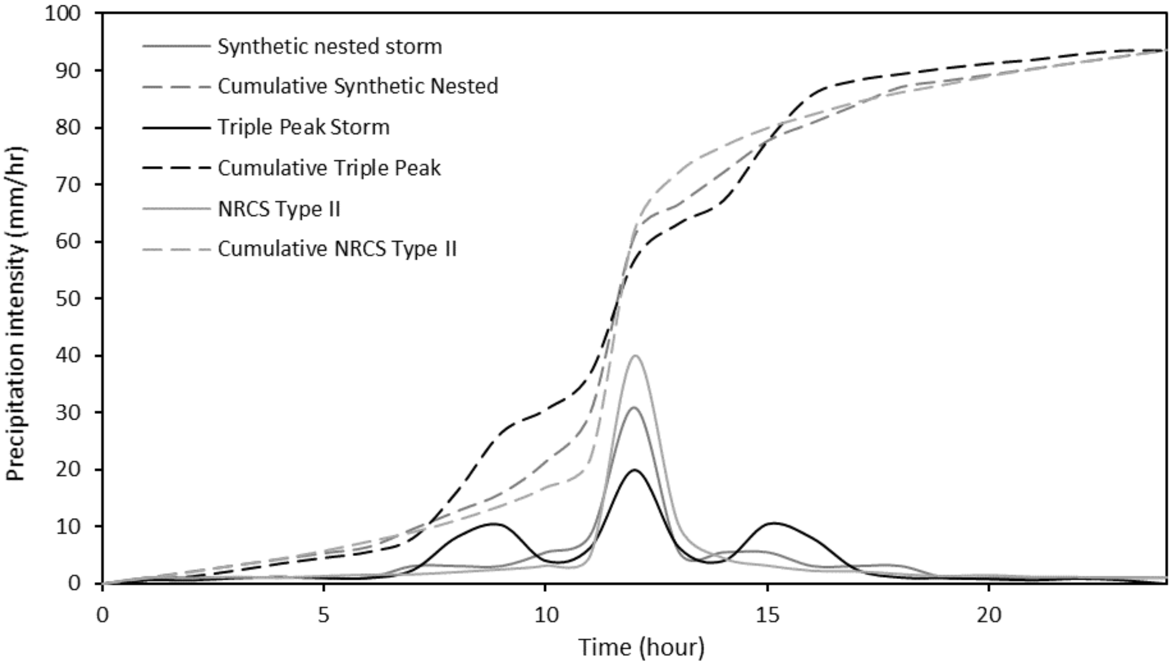

Figure 8.5 Example hyetographs for the historic 1:100 year, 24-hour storm in Ft. McMurray using the NRCS Type II distribution typically used in the region, the synthetic nested storm distribution used in areas where no distribution is specified, and the triple-peak distribution fitted to Ft. McMurray by (Dick & Ghavasieh, 2015).

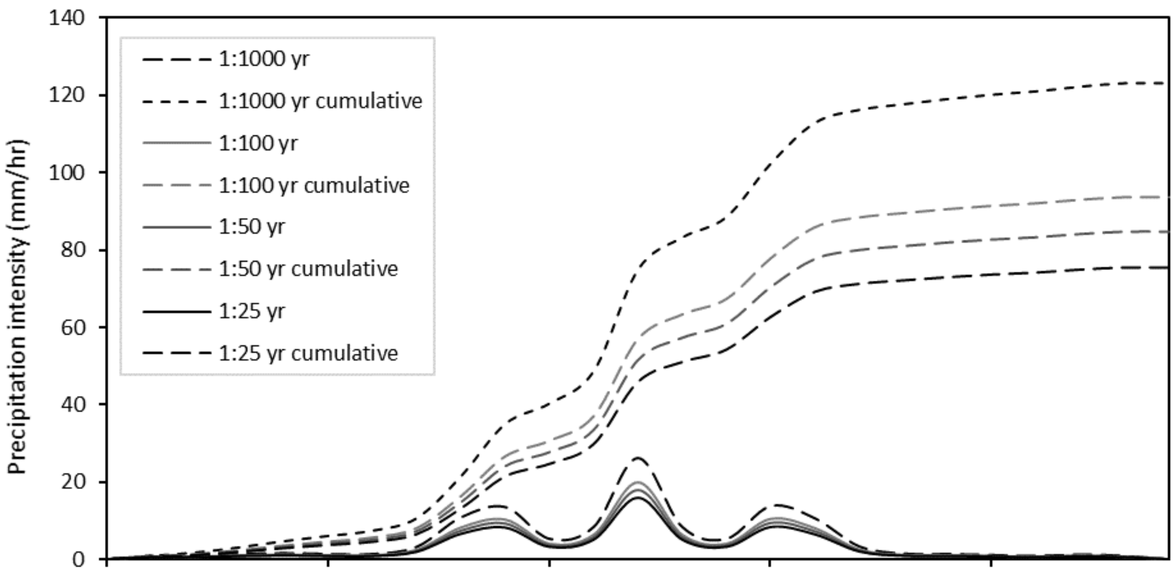

Figure 8.6 Hyetographs used for historic 24-hr storms in Ft. McMurray

8.2.4 Parameterization

A number of parameters are required to further refine model calculations, as discussed in Chapter Seven. Several of these parameters are discussed below.

8.2.4.1 Sediment

In addition to the grain size distribution, other parameters and choices need to be made with respect to how the model manages sediment. Parameters used are listed in Table 8.3 below. Two bedload transport equations are available for use in CAESAR-Lisflood: The Einstein bedload transport equation (Einstein, 1950) and the Wilcock & Crowe equation (Wilcock & Crowe, 2003) that was developed using gravel-dominated sand-gravel mixtures. Both models tend to over-estimate bedload transport, but this can be minimized by using the appropriate model for your particle size distribution. Einstein-Brown (1950) was developed based on flume data taken with relatively fine sediment (smaller than #250 mesh, or 0.061 mm), making it more appropriate for use with oil sands' CST than Wilcock & Crowe (2003). Importantly, if one were to attempt to evaluate the results of CAESAR-Lisflood with SIBERIA, as has been done previously, it is best to use Einstein-Brown since this is the same fluvial sediment transport equation used in SIBERIA.

Table 8.3 Sediment tab parameters

Parameter		Recommended Value (if any)	Value used	Notes / justification
	Bedrock erosion threshold	-	0 Pa	N/A
	Bedrock erosion rate		0 m/Pa/yr	N/A
	Suspended sediment? (y/n)		yes	
v_f	Fall velocity for suspended sediment	-	0.004398 m/s	Calculated for finest fraction (average particle size of 75 microns) using Stokes' Law
	Maximum velocity used to calculate Tau on steep slopes	Default: 5 m/s	5 m/s	N/A
ΔZ_{max}	Maximum erode limit (per time step)	0.02 m. DEMs with cells < 10 m should be set at 0.01 m. Increase with cell size.	12 m DEM: 0.02 m 2.5 m DEM: 0.01 m	
L_h	Active layer thickness	0.1 to 0.2 m. At least 4 times the maximum erode limit.	0.1 m	Lower depth suitable for DEM sizes used

λ	In-channel lateral erosion rate	Typical values are 10 - 20 for most river types (larger for wide, lower for narrow).	20	Due to the physical, non-cohesive nature of CST, the highest typical value was used.
	Lateral erosion (L.E.) included? y/n	-	no	This parameter is most applicable to reach mode: waterways with constant flow.
Λ	If L.E.=Yes. Lateral erosion rate	Braided rivers: 0.01 - 0.001 (typ.) Meandering channels or channels with little lateral erosion: 0.0001	undefined	N/A
N_{smooth}	If L.E.=Yes, Number of passes for edge smoothing filter	-	undefined	N/A
N_{shift}	If L.E.=Yes, Number of cells to shift lateral erosion downstream	-	undefined	N/A
ΔV_{max}	If L.E.=Yes, Max. difference allowed in cross channel smoothing	-	Undefined	N/A

8.2.4.2 Hydrology

Within the hydrology parameters are several options relating to rainfall input, tidal variables, and reach variables as discussed in Chapter Seven. For the study herein only the rainfall input variables are applicable (Table 8.4), particularly the m variable that was estimated through comparison of natural vegetation coverage in the AOS (assumed to be equal to an m-value of 0.016, or soil found under dense forest cover) to reclamation forest cover and grassland (assumed to have an m-value of 0.005) (Welsh et al., 2009). Sample images of this comparison are shown in Figure 8.7.

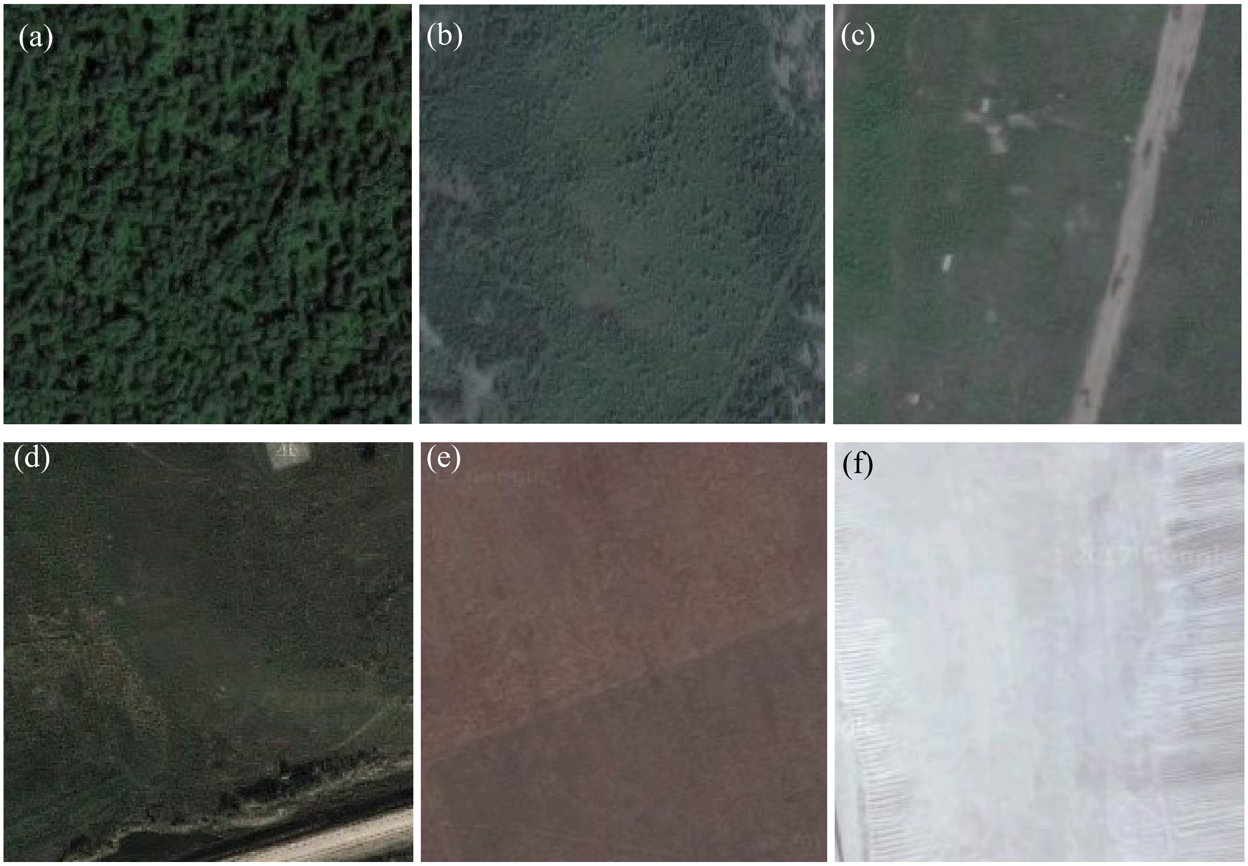

Figure 8.7 300 m square patches of land from north of Fort McMurray. (a) Dense Forest (m = 0.016); (b) natural mixed forest and grassland (m = 0.012); (c) Revegetated dyke (m = 0.01); (d) Revegetated scrub & grassland (m = 0.007); (e) Revegetated grassland (m = 0.005); (f) un-vegetated dyke crest (m = 0). Images from Google Earth.

Table 8.4 Hydrology parameters

Parameter		**Recommended Value (if any)**	**Value used**	**Notes / justification**
	Rainfall data file time step	60 minutes	60 minutes	
m	m-value	0.005 to 0.02. May be calibrated using storm hydrograph. Values have been chosen from relative forest cover across value range.	0.01	This will change over time as organic matter accumulates and vegetation grows.

8.2.4.3 Vegetation

Within the vegetation parameters are three variables that need to be estimated or measured where possible. These parameters, especially the time to grass maturity and proportion of erosion that can occur at full maturity, have the effect of decreasing erosion as vegetation grows. This was fully explained in Section 7.3.2.6 and in Slingerland, Beier, & Wilson (2018).

Table 8.5 Vegetation parameters

Parameters		Recommended Value (if any)	Value used	Notes / justification
τ_{crveg}	Vegetation critical shear	Standardized value is 180 Pa. Estimate from strength of vegetation grown.	177.23 N/m^2	Alberta Transportation (2003) Appendix F states that vegetation retardance Class A (>600 mm, good stand including native grass mixture) has maximum permissible shear stress of 177.23 Pa (Page F-42) (Alberta Transportation, 2003). This is in line with standard program value.
T_{veg}	Grass maturity	None. Estimate based on known or measured times.	24 years	(May et al., 2011) found that tree cover increased linearly until final sampling 24 years after planting, shrub cover increased for 6 - 9 years before levelling off, and both forb and grass cover decreased steadily from time of planting to final sampling.
	Proportion of erosion that can occur when vegetation is fully grown (0-1)	Ranges from 0 (no erosion) to 1 (full extent of erosion occurs).	0.15	- An erosion-free state is possible for at least three years once dams are vegetated if fertilization applications continue (Rowell, 1979). - Syncrude's SWSS shows evidence of gully formation on reclaimed tailings pond dykes. - Previous field trials at Suncor TID produced little erosion during maximum 2-hour simulations of large rainfall events (i.e. 1:1000) (Sawatsky, Dick, Ekanayake, & Cooper, 1996).

8.2.4.4 Slope processes

Within the slope processes parameters, movement of sediment downslope and factors affecting that process are described. Creep is a slow, quasi-continuous movement of large sediment volumes on shallow slopes, while mass wasting is typically considered to be rapid, intermittent movements of large sediment volumes on steep (>30%) slopes (Martin, 2000).

Table 8.6 Slope process parameters

Parameters		Recommended Value (if any)	Value used	Notes / justification
C_{rate}	Creep rate	Typical value is 0.0025	0.0025 m/year	Not measured due to time requirements and constant site activity. Minimal impact from creep is expected over the relatively short timeframes modelled (i.e. < 1000 years).

	Slope failure threshold		40°	Angle of repose for fine sand (0.21 mm) was measured to be 40 degrees (Kleinhans, Markies, de Vet, in 't Veld, & Postma, 2011). Slopes viewed in tailings sand on site were measured both steeper and shallower than this median angle.
	Dynamic slope fail angle, varying according to soil saturation? y/n		yes	
E_r	Soil erosion rate		-	This parameter has not yet been tested or calibrated by the developers; therefore, it has not been used herein.
	Soil erosion varies according to soil saturation? y/n		yes	

8.2.4.5 Flow model

Within the flow model parameters there are both inputs required to control model run time / optimization as well as surface water characteristics.

Evaporation was a required input in the form of m/day. Morton's potential evaporation, as calculated from 1972 - 2009 for a land environment at the upwind edge of a lake in the Fort McMurray area, are recorded in (Alberta Government, 2013) with a mean annual value of 831 mm. Given that CAESAR-Lisflood does not generally have precipitation inputs from November to mid-March (245 days approximately from March to the end of October), only the months with precipitation were included in the average daily rate used in the model (bolded, Table 8.7). The total mean PE from March to October was 844 mm, giving an average over March-October of 0.0034 m/day.

Table 8.7 Potential evaporation estimates in mm from (Alberta Government, 2013)

	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sept	Oct	Nov	Dec	Tot.
Mean	-3	0	**27**	**97**	**156**	**169**	**172**	**135**	**70**	**18**	-2	-4	835
Min	-8	-8	0	49	115	132	132	99	41	9	-9	-11	698
Max	-1	6	62	153	196	202	212	185	114	27	3	1	987

Traditional geomorphic design does not rely on engineered methods such as heavy armouring or geotextiles, but instead on design to meet localized stability requirements of materials and climate that are interacting. The geomorphic design for the TSF plateau (Chapter Three) was completed with this in mind, such that vegetated swales might be used. Surficial soils were assumed to be composed of CST in line with a worst case scenario, and are reflected in calculation of Manning's roughness and sinuosity coefficient, *n*. In theory, one could increase Manning's *n* to represent rip rap if this were included in the design along flow routes, however this leads to a risk of reducing erosion in areas where unintentional concentrated flow exists.

Table 8.8 Flow model parameters

Parameters		**Recommended Value (if any)**	**Value used**	**Notes / justification**
Q_{diff}	Input / output difference allowed	Close to the watershed low flow value. Standard value: 1 m^3/s.	1 m^3/s for TSF 0.2 m^3/s for dam section	No overall flow values known for the dams and perimeter ditches.
Q_{min}	Min Q for depth calculation	Historically 0.1 for 10 m cell size, 0.5 for 50 m cell size. This is currently under review and it is presently recommended that Q_{min} remain constant regardless of cell size for the same area.	0.022 m^3/s (0.025 m^3/s for single slope)	About 2/9 of perimeter channels are blocked, therefore drainage is restricted to 2/9 of possible drainage area -> 0.1*2/9 = 0.022 used for TSF. Single slope never blocked entirely, so 0.025 was deemed adequate.
Q_{max}	Max Q for depth calculation	-	1000 m^3/s	Parameter used in reach mode
d_{min}	Water depth threshold over which erosion will happen	Typically 0.01 m. Larger values can be used on cells > 50m, smaller values for higher resolution DEMs.	0.005 m	
S_{edge}	Slope for edge cells	-	0.005	
	Evaporation rate	-	0.0034 m/day	See Section 8.2.4.5 explanation.

α	Courant number	0.3 to 0.7. Low resolution DEMs (50 m cells) may use larger numbers, high resolution DEMs may use smaller numbers. (Typ. 0.4 for cells 10 m or less)	0.4 for 12 m DEM 0.3 for 2.5 m DEM	
h_{flow}	h_{flow} threshold	Default value is 0.00001 m.	0.00001 m	
Fr	Froude's # flow limit	Default value is 0.8. Values up to 1 may work. Lower values can be used when modelling deep flows (lakes) at fine cell size.	0.8	
n	Manning's n, coefficient of roughness and sinuosity.	None. Calculate or look up values from tables.	0.0345	Uniformity coefficient, C_u, for CST is 1.6, or very well sorted. For uniform sediment, C_u <3: $n = \frac{{d_{50}}^{1/6}}{21.2}$

8.3 Refinement and optimization

Once model inputs were formatted appropriately, and parameters were calculated and identified, model refinement occurred. Model refinement was required to fine-tune those values that optimize the program in terms of run-time speed and efficiency. If the model runs too quickly there is a risk that erosion or deposition will be missed; if too slow then run time may be prohibitively lengthy. The process of refinement, while time consuming, is quite clear in its results and with practice model optimization is a simple process. Rough parameter values can be estimated by the DEM cell size in most cases, but refinement of the value is required for optimization. Model refinement was done using a systematic testing of consecutive values varying +/- one order of magnitude where applicable, then further by trial and error.

Inputs requiring optimization include:

- Input/ output difference allowed, Q_{diff}
- Minimum Q for depth calculation, Q_{min}

- Maximum Q for depth calculation, Q_{max}
- Water depth threshold over which erosion will occur, d_{min}
- Courant number, α
- Froude's number (flow limit), *Fr*

Ultimate values used for these inputs are listed in Table 8.8.

8.4 Results

The results of three simulations have been outlined in two conference papers and one journal paper:

- Slingerland, N., Isidoro, A., Fernandez, S., Beier, N.A. (2018). Geomorphic analysis for tailings dam design in consideration of a 1000-year closure design life. In *Proceedings of the 2018 Planning for Closure Conference*. Santiago, Chile, Nov. 7-9. Pp. 1-9.
- Slingerland, N., Beier, N.A., Wilson, G.W. (2018). Landscape evolution modelling of large sand tailings dams. In *Proceedings of the 12th International Mine Closure Conference*. Leipzig, Germany, Sept. 4-7. Pp. 341-348.
- The 100-year simulations of the 1-km dam section with and without climate change have been submitted to 'Earth Surfaces Processes and Landforms'. A preprint can be found in Chapter Nine.

Results from the 1000- and 200-year simulation conference papers are presented below.

8.4.1 1000-year simulation of a 1 km dam section

8.4.1.1 Qualitative geomorphic assessment

Geomorphic changes to the TSF were evaluated using erosion quantities, cross-sections of the dams, and sediment discharge to the environment over time. Qualitatively the morphology of the structure was well established within approximately 60 years. After this time erosion and deposition continued to exaggerate the established features, but no new features were formed. Gullies were most frequently formed in locations of concentrated flow such as horizontally concave dam sections. Gullies as deep as 20 m were initiated along lower reaches of the dam, then quickly eroded backwards. The near-flat gully bottoms were subsequently slowly lined with additional soil.

The profile below (Figure 8.8) shows the development of a gully in the dam where the majority of soil erosion occurs by year 50. Eroded soil is deposited in the perimeter channel, which is filled to the point that it is no longer functional. Stability re-analysis would be necessary here to assess the factor of safety for the revised geometry.

The central watershed was subject to minimal erosion outside of the drainage network base, which was not armoured. This work confirms that directed and concentrated flow managed through sub-watershed creation (i.e. the TSF central watershed) leads to less erosion than undirected sheet flow as seen on the unaltered dam surfaces. Where possible, surface water should be directed towards drainage swales which are more erosion resistant due to lower slope gradient and greater vegetation size and density, and sub-watersheds should be sized in accordance with soil and climate characteristics.

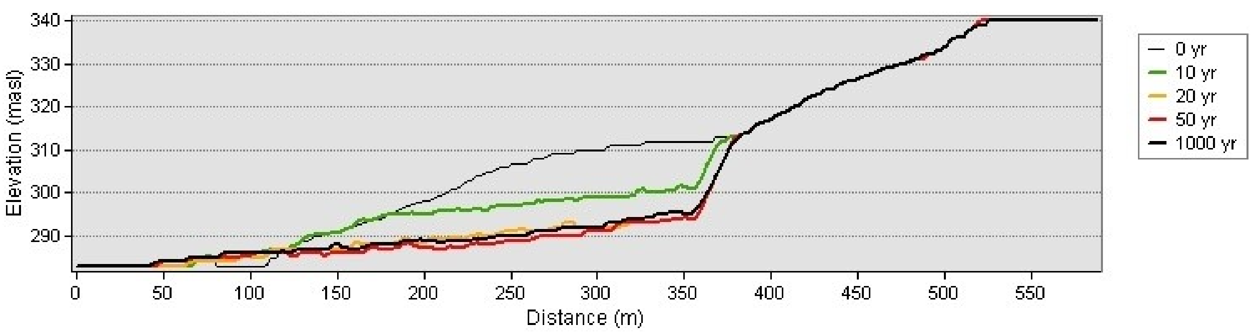

Figure 8.8 Model results: section through a gully formed on an AOS sand dam with toe berm over 1000 years

8.4.1.2 Quantitative geomorphic assessment

Quantitatively, sediment loads transported off site via the perimeter channel were initially high then decreased to less than 10 m^3/year after 55 years of simulation (Figure 8.9). This can be attributed to several factors: 1) geomorphic equilibrium in some areas is reached and erosion is reduced, 2) the perimeter channel collecting runoff was entirely blocked by deposited sediment in one location and partially blocked in two others, and 3) erosion rates decrease dramatically as simulated vegetation "grows" and reaches full maturity due to model assumptions (i.e. full maturity at 24 years). Given no further maintenance of perimeter channels, depositional fans can render the drainage system non-functional. When channels are clear, the importance of settlement ponds is demonstrated in the large volumes of sediment discharged off site.

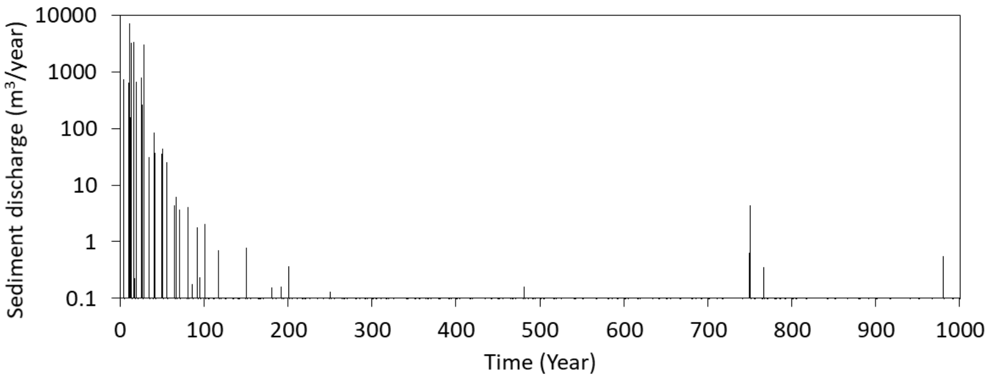

Figure 8.9 Sediment discharge from perimeter channel at toe of dam section.

Cumulative soil volume loss from the 40-ha crest-to-toe dam section (Figure 8.10) corresponds well to qualitative observations of off-site sediment transport and to the morphology timeline in Figure 8.8. A plateau in cumulative soil loss is reflective of geomorphic equilibrium, filling of perimeter channel, and model assumptions (i.e. vegetation growth).

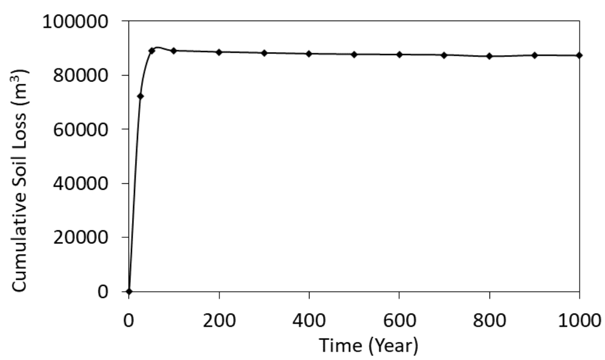

Figure 8.10 Soil loss from the dam (soil eroded from the slope) over 1000 years.

The hypsometric integral (HI) is a quantitative method of describing geomorphic form, written in equation (8.3). Hypsometric integrals (also known as the 'hypsometric index' or 'elevation / relief ratio'), provide a generalized description of relief and can be used to evaluate the type of landform change that is likely to occur. This method is considered beneficial in that it quantifies the geomorphology, but provides no other details that a qualitative assessment provides.

$$HI = \frac{mean\ elevation - minimum\ elevation}{maximum\ elevation - minimum\ elevation} \qquad (8.3)$$

In general, low HI's (less than 0.3) are considered mature, or stable, while high HI's (greater than 0.6) are especially immature and geomorphically unstable. In terms of landform processes, Willgoose and Hancock (1998) consider HI's less than 0.5 to be dominated by fluvial erosion processes, and HI's greater than 0.5 to be dominated by hillslope processes such as landslides and creep. The initial HI prior to any simulation is 0.532 and after 1000 years this has been reduced to 0.426. This indicates that while the slope is relatively stable, it is still maturing and is considered an actively developing area.

In applying the proposed design methods in Figure 7.3, if the equilibrium topography found herein complies with long-term erosion and stability goals then this timeline information can be used to estimate the extent of maintenance on the structure for post-closure budgeting. At sites with inert materials, annual soil loss can be compared to acceptable background levels to determine when the dam is behaving similarly to local natural terrain; this is a factor in dam delicensing under some regulators.

8.4.2 200-year simulation of a TSF and buffer zone

TSF morphology was evaluated using erosion and deposition quantities and rates, cross-sections, and sediment discharge over time. In terms of geomorphology, the majority of changes along the external dykes occur in the first 60 years as large gullies develop and progress retrogressively inward through the dyke. The sediment eroded via these gullies was then deposited at the bottom of the slope, blocking off perimeter drainage routes and the majority of sediment transport out of the model. Gullies along the dyke were 20 meters deep in some locations and gullies were more prevalent in areas where flow was concentrated. Changes to the plateau were minimal after approximately 30 years; incision of the main drainage channels were observed nearly to their entire length and to a depth of over 10 m in some locations.

An analysis of sediment discharge rates summarized in Figure 8.11 shows how the removal of sediment reduces over time, eventually reaching an equilibrium around year 42. Some portion of this would typically be attributed to initial preferential removal of fines by the model; however, there is negligible change in the surficial D_{50} that would indicate surface armouring, which makes sense given the uniform grain size distribution. Simulation of landscape evolution on a natural landscape would typically require a “spin-up” period in order to achieve natural armouring of the surface; however, in the case of this sand dam the entire surface is newly constructed of uniform sand over the last 10 years and no measurable armouring has occurred on the ring dyke to date, eliminating the need for spin-up. The initially high sediment discharge rates seen in Figure 8.11 are more likely due to the narrow grain size distribution and fine texture of surficial sediments that makes them highly transportable. Occasional spikes in sediment discharge can be seen at year 16, 41, 50, 66, 80, 91 and 100 where statistical precipitation events were applied to the DEM. These statistical events produce greater erosion than we see when unamended historic precipitation is applied due to the additional water depth, velocity, and erosivity of larger storm events.

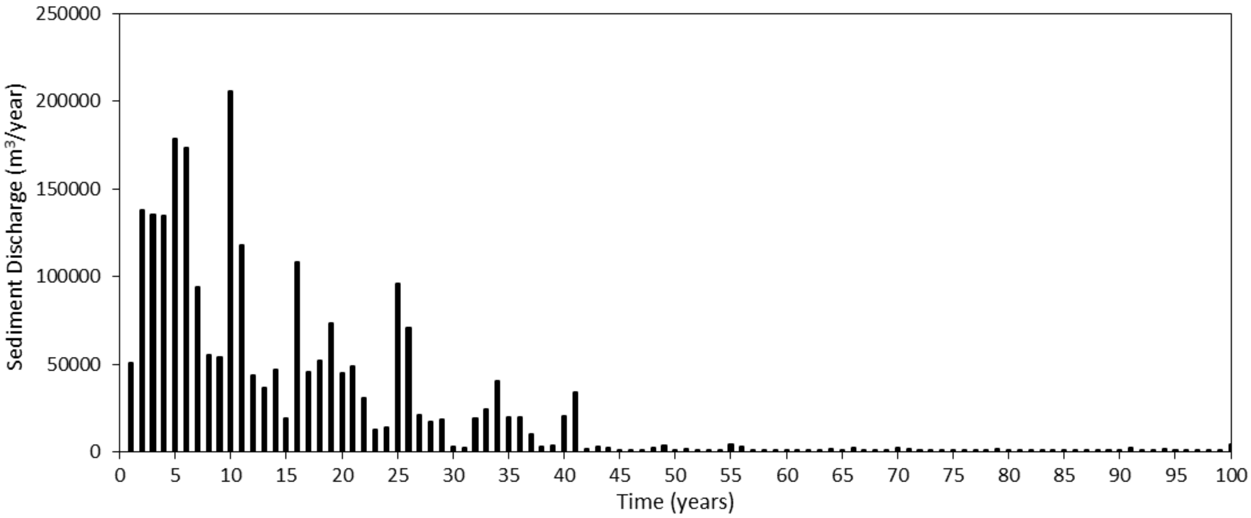

Figure 8.11 Annual sediment discharge from entire TSF over the first 100 years of simulated landscape evolution. Note: 50,000 m^3 of CST is approximately equal to 80,000 tonnes.

Vegetation plays a significant role in reducing erosion and mass wasting (landslides) in natural environments, and the CAESAR-Lisflood model does a good job of mimicking that through parameterization. The reclaimed landscape behaves differently from the natural environment, and long-term erosion measurement on fully vegetated reclaimed sand dykes will need to continue in order to gain more certainty with respect to future estimation. Parameterization of vegetation components drew from available research that was predominantly medium-term (less than 25 years) in nature, and the simulations completed indicate reduced erosion once vegetation is established. Major gullies were initiated prior to vegetation reaching full maturity and none established after this point within the simulation, however new branches of existing dendritic gullies did continue to develop.

Diffusive erosion, or “creep”, is typical of upper slopes resulting in incremental changes over long time periods. While non-linear transport equations more accurately approximate creep, transport rates even on steeply sloping terrain over 10,000+ years are low in comparison to other erosion modes, such as landslides or gullying; a linear approximation is therefore often sufficient over short and long time frames (Martin, 2000). As expected, after 200 years of landscape evolution modelling minimal evidence of degradation due to creep processes exist. Smoothing of contours and of the remnant angular topography generated by gullies are the dominant contributions of diffusive erosion processes to this simulated landscape.

The initial formation of gullies on the TSF dyke was observed to begin near the bottom of the dyke in most cases: the bottom half of a slope typically has higher moisture content in the soil and overland flow transitions from dispersive flow in favour of more centralized, efficient flow paths. As concentrated flow progresses down a slope it gains speed and erosive power. Development of gullies following this process occurred on dyke slopes without topography that would lead to significant pooling or concentration.

The other observed method of gully development arises from surface water being directed and concentrated in one location, saturating a plateau and eventually finding the downward path of least resistance, eroding the surface via overland flow. In nearly all locations with laterally concave slopes (where overland flow is directed down a central valley), large gullies were formed. In contrast, on laterally convex corners of the perimeter dyke (where overland flow is directed divergently) there are few indications of gully formation even after 200 years of simulated evolution.

While this simulation was not intended to measure precise sizes of gullies due to the large cell size, they were nonetheless measured for comparison with models of higher resolution. In total, nearly 40 gullies developed that were at least 100 m in length and 24 m in width. All of these were initiated in the first 30 years of simulated time. The longest gully was over 1250 m long reaching well into the central tailings storage area and had eight dendritic-patterned branches feeding into the main corridor. This gully, and other larger gullies, were deep: this gully in particular eroded sediment to a maximum depth of 19.90 m across the surface plateau of the SEA: This would certainly have penetrated the tailings contained by the CST cap and pose significant risk to dyke stability. Correspondingly, deposition of sediment extended in some instances well over one kilometer beyond the perimeter channel wall.

Figure 8.12 illustrates the development of a gully along the eastern downstream slope of the TSF dyke. The initial profile at T = 0 years has an overall gradient of 14%. At 50 years a gully has already been initiated in the lower reach and developed in the upstream direction about 275 m.

By year 100 the gully has further developed 80 m and sediment is being deposited at the toe of the slope. The gully continues to expand over the next 50 years, continuing to deposit sediment at the bottom of the slope. Stabilization of the slope is evident in the 200-year profile, as it deviates only slightly from that of the profile generated in year 150. This process of eroding upper reaches and depositing in lower reaches has the effect of reducing the slope to less than 8% in the lower half, creating an elongated lower concave slope and a short, steep convex slope at the top. This is in line with theories of hillslope evolution which define mature hillslopes (previously eroded slopes that are presently in equilibrium) as having an 'S'-curve in which the lower concave portion is heavily elongated (Toy & Hadley, 1987). This mature profile provides an alternate design option for long-term stability of sand dykes.

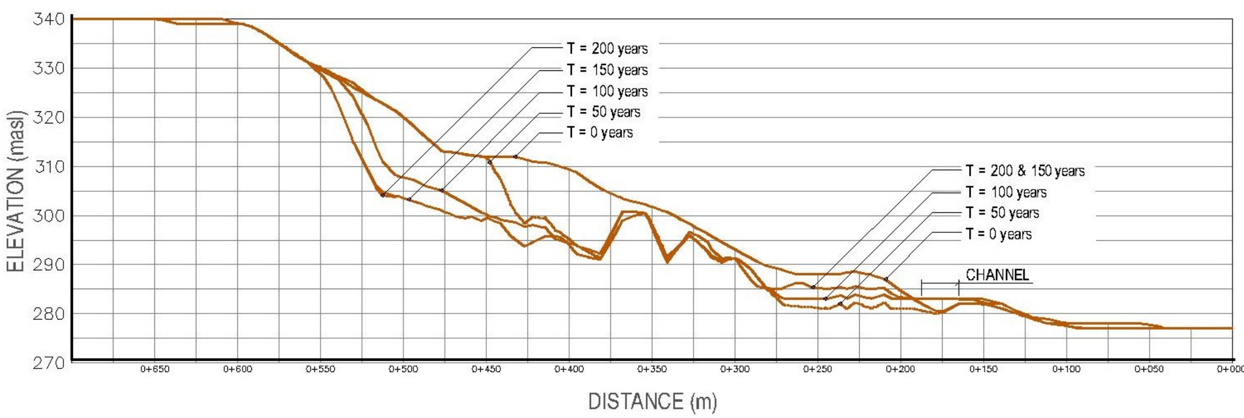

Figure 8.12 Surface profile of an eastern (downstream) portion of a sand dyke prior to landscape evolution modelling (time = 0 years), and after 50, 100, 150, and 200 years of simulation. 3x Vertical exaggeration, profile is not to scale.

Of particular interest in the evolution of these anthropogenic landforms is the point at which they no longer function and will require outside intervention. Intervention is necessary when the landscape fails to function as intended and poses a threat to either environmental or human health, or to the economy of a region or entity. This information is nearly impossible to evaluate but is of general interest given the roughly 20-year timelines for delicensing to occur and the goal of maintenance-free conditions. At the base of the east dyke in Figure 8.12, deposition of soil eroded from the upper reaches occurs due to gully formation. The perimeter channel installed around the dyke is evident at T = 0 years, the fictional "end of construction date", spanning just less than 30 m in width. As simulated time progresses through the first 50 years, the channel width expands, and sediment is washed downstream within the channel by fluvial processes. Over the next 50 years, from year 50 to year 100, soil removed by the retrogressive gully formation is deposited in the channel to the point where the channel is completely filled. This continues as an alluvial fan develops at the base of the gully, moving outward. The result of this channel blockage is that overland flow from the dyke that is captured by the channel backs up until it overtops the channel banks. When flow is high this subsequently erodes the outside channel wall and drainage water is diverted onto the surrounding landscape buffer. This phenomenon occurred at several locations within the modelled landscape after being subjected to small rainfall events that were less than a statistical 1-in-25 year storm. The largest depositional fans generated were greater than one kilometer in radius from the deposition initiation point (Figure 8.13).

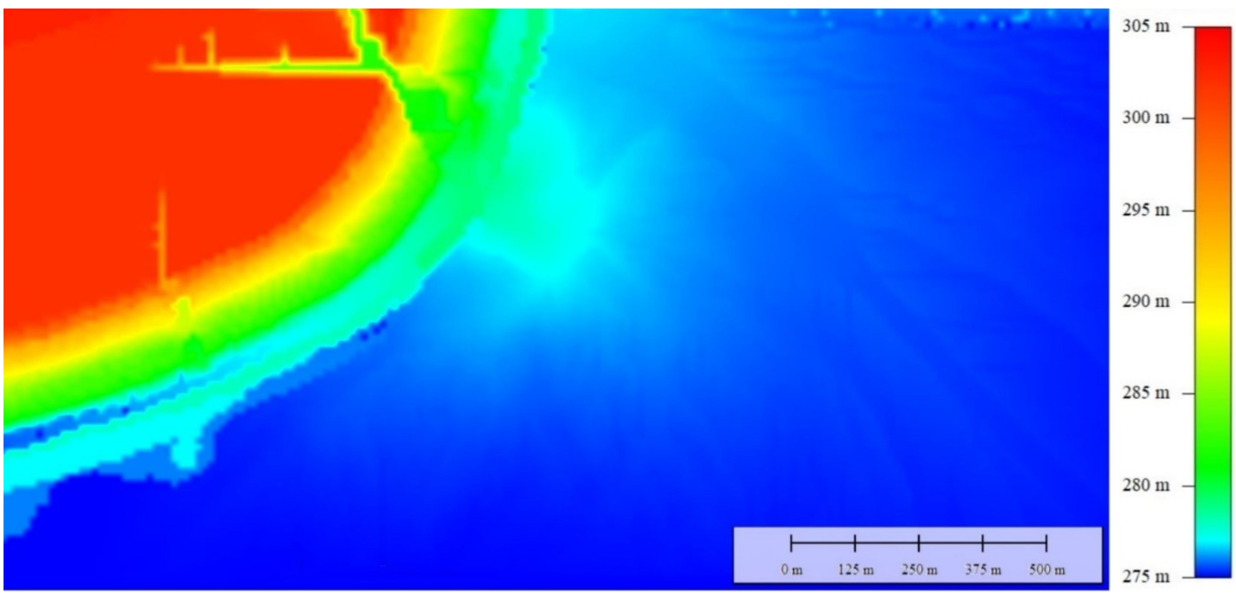

Figure 8.13 DEM following 200 years of simulation. A gully in the upper left has eroded the dam and deposited CST in a fan extending to the lower right corner of the image.

8.5 Model evaluation

An important aspect of numerical modelling is evaluation of model results. Evaluation of the CAESAR-Lisflood model results was attempted using four different methods, each of which is discussed below with respect to the 1 km dam section.

8.5.1 Average annual discharge comparison

CAESAR-Lisflood provides and average water discharge (Q_w) over a user-defined timestep throughout the simulation. As no measurements from the landscape catchment are available for comparison, equation (8.3) was used to estimate discharge and this value was compared to the values provided by the model. This method has been previously used by (Hancock, 2009).

$$Q_w = C_r R A \tag{8.3}$$

C_r is the unitless runoff coefficient, R is average annual rainfall in meters, and A is the total catchment area. Over the single dam section, the overlapping range of runoff coefficients previously determined by Alberta Transportation (2003) and Sawatsky et al. (1996) for an oil sands tailings dam were used (see Section 9.5.2 for further detail); this corresponded to 0.05 – 0.33. The dam section model results compared well within the range provided by equation (8.3) for the first 25 years (Table 8.9). The same comparison was attempted with the 1000-year simulation. While the 1000-year average annual model discharge was outside of the range provided by equation (8.3) it was within the same order of magnitude of the upper limit.

One theory for this lack of correlation is that the frequency that large statistical storm events were input into the precipitation data set is statistically greater than expected (refer to equation (8.2)). The greater frequency of storm events simulated in the model will correspond to greater overall annual discharge. In comparing discharge from the first 25 years to 1000 years of simulation, average annual discharge is shown to increase, therefore it is also of interest whether the runoff coefficient estimation is best done over an entire season or over one year, rather than from individual events.

Table 8.9 Water discharge predictions for a 1 km dam section using Equation (8.3) compared to those from CAESAR-Lisflood for historic parameters over the first 25 years and over the full 1000 years of simulation.

Timeframe of dam section simulation	**Average annual discharge prediction (m^3 $year^{-1}$)**	
	Eq. (8.3)	**C-L**
20 years	28,746 - 189,724	57,673
1000 years	28,746 - 189,724	279,520

This discharge comparison was not attempted with simulations for the entire TSF since the available runoff coefficients were attained from individual dam sections (at a different site) that were comparable to our modelled dam section. No runoff coefficients were available for upland landforms or upland and dam combinations on the scale of the TSF simulated.

8.5.2 Short-term sediment loss

LiDAR was used to compare actual sediment loss from the landscape to sediment loss over short time frames in CAESAR-Lisflood. Using LiDAR data from 2016, soil loss was calculated from the mostly un-vegetated downstream dam slopes across the entire TSF and SEA to be approximately 48.5 tonnes / hectare (Chapter Six); when separated into reclaimed and exposed CST slopes we get 17 and 124 tonnes / hectare, respectively. Due to the periodic maintenance conducted on the dams, this is estimated to be a roughly annual rate. Using DEM outputs from CAESAR-Lisflood, the average annual soil loss from the 1 km dam section was found to be 41 tonnes/ hectare for the first ten years of simulation, which encompasses the linear transition from bare CST to over 40% vegetation. This calculation was done by isolating the downstream slope in the output DEM representing elevation change, calculating the volume of soil removed over the area isolated, then converting that volume of CST eroded to tonnes using an average dry density of 1600 kg/m^3. These values demonstrate good agreement between measured and modelled erosion features due to gullying. Table 8.10 provides a summary of the estimates and measured values compiled in this study.

Table 8.10 Summary of soil loss predictions for the CST dam from the methods employed

Surficial CST Treatment	Method	Erosional feature measured	Annual Soil Loss Rate (Tonnes/ha)	Hazard Class
Bare	RUSLEFAC	Sheet erosion, rills	124	Very high
	LiDAR	Gullies	57*	Very high
Reclaimed & Revegetated	RUSLEFAC	Sheet erosion, rills	17	Moderate
	LiDAR	Gullies	4*	Very low
Bare to Revegetated Transition	CAESAR-Lisflood 1.9b (first 10 years)	Sheet erosion, rills, gullies	41	Very high

**LiDAR is considered a measured quantity while all others are predicted estimates.*

8.5.3 Comparison of erosional features

A comparison of gully position, size and shape characteristics, and number of gullies have previously been used to evaluate LEM results (Hancock et al., 2000). Note that this purpose of this modelling is not to predict with exact precision the time and form, but more so the general trajectory of a landform and any areas of concern. Gully characteristics were compared between the dam section modelled (early in the simulation) and those measured from LiDAR data of the actual dam topography in 2016. It is anticipated that dam maintenance and surficial re-grading would have been done at least once per year, making the 2016 LiDAR roughly indicative of erosion formed within one year.

Results are shown in Table 8.11 and Figure 8.14, showing a general correlation. Model-generated gullies were generally deeper and larger in area than measured in the LiDAR, but the length, width:depth ratio, and post-erosion slope from the base of the gully were within the range of those measured with LiDAR. Gully depth in the field is likely restricted by moisture content in the soil, while area is impacted by the near-vertical sides in some instances; C-L is not capable of integrating either of these features. Gully position and overall shape were similar as well, shown in Figure 8.15, indicating that despite DEM processing, erosion-prone features were maintained and predictable by the CAESAR-Lisflood LEM. Gully width is affected by the slope failure threshold (Table 7.5) that was set at a median angle relative to those observed in the field. Meadows (2014) used the steepest angle measured, which would lead to narrower gullies with less soil loss.

Table 8.11 Characteristics of measured gullies from LiDAR data compared to model outputs after 5 years' simulation.

	Number of gullies	**Length range (m)**	**Width range (m)**	**Average depth (m)**	**Width/ depth ratio**	**Post-erosion base slope (%)**
West dam, LiDAR. Un-reclaimed with annual maintenance.	21	9.0 - 200.0	2.5 - 10.0	0.5 - 1.4	1.8 - 12.5	1.1 - 41.5
1 km west dam section, following five years simulation	4	21 - 149	7.2 - 9.0	1.1 - 2.8	2.7 – 8.2	2.4 - 17.7

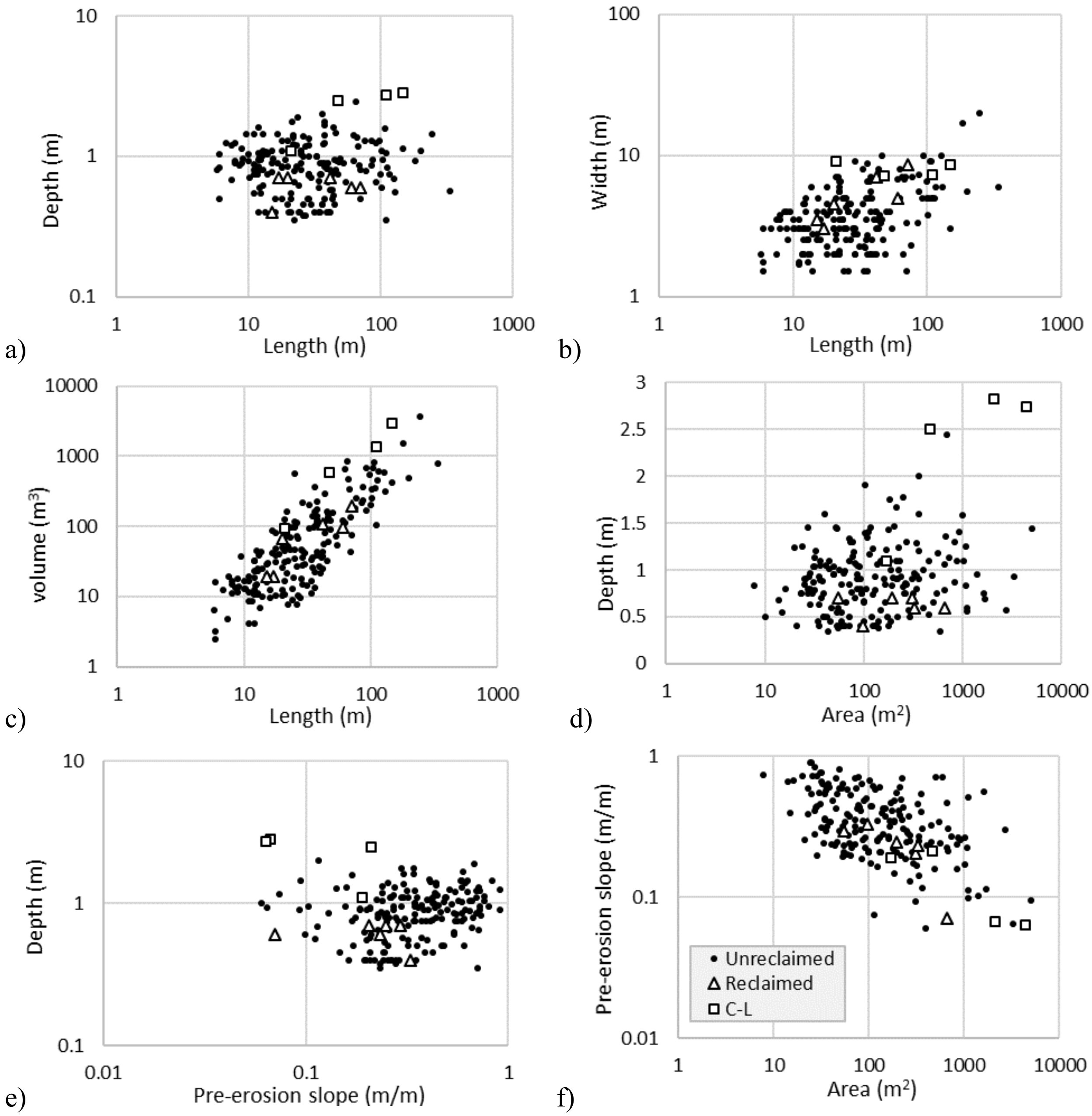

Figure 8.14 Gully characteristics from Chapter Six compared to those simulated with CAESAR-Lisflood

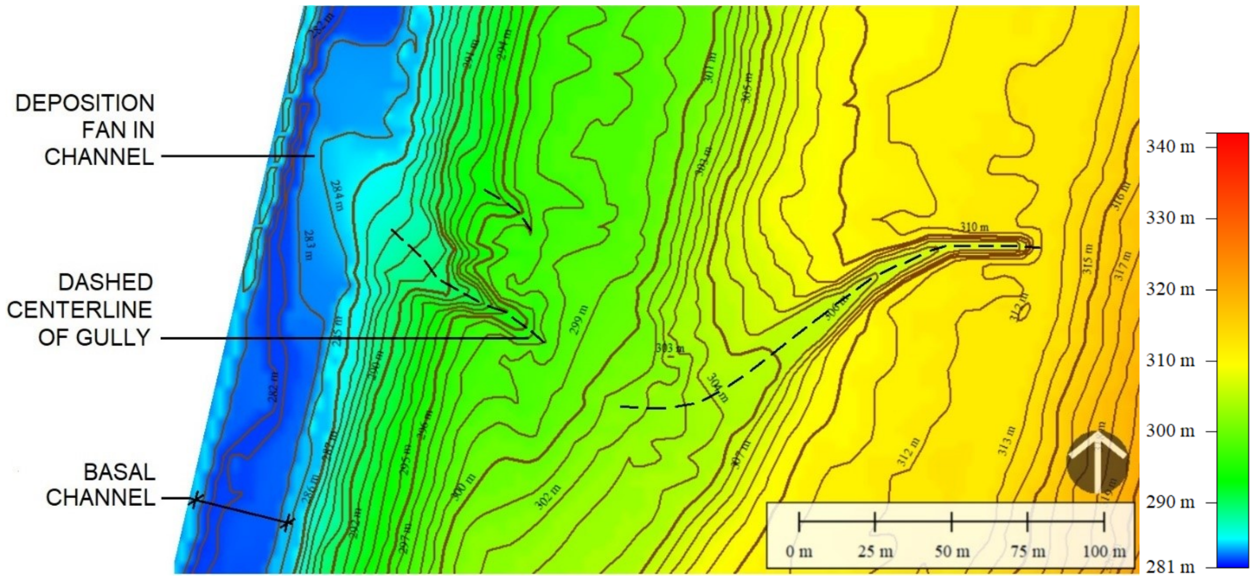

Figure 8.15 Topography produced after five years of simulation

8.5.4 Cross-referencing results with different LEM

Cross referencing of model results with another LEM that uses different inputs and calculations has been used to evaluate LEM's in the past (Coulthard et al., 2013; Hancock, Lowry, Coulthard, & Moliere, 2010; Hancock, Coulthard, Martinez, & Kalma, 2011). The most widely used LEM over the past 25 years is SIBERIA. This model does not simulate individual processes like CAESAR-Lisflood, but uses calibrated parameters related to drainage basin size, erosion rate constants, sediment discharge (bedload and suspended sediment), runoff rate constants, etc. and moves a landform slowly towards a natural shape characterised by input parameters. Correlation with SIBERIA (version 8.3) was attempted by calculating the input parameters, however it was demonstrated that the model works best with site calibration and further efforts are needed in this area in order to use SIBERIA on CST landforms. The comparison was therefore not possible at this time.

8.6 Discussion

The goal of modelling the TSF as a whole (including reclaimed and geomorphically designed surface, as well as the dams) was to understand changes to the structure in a more general sense, and areas of concern. Cell size was 12 m for the TSF/SEA models, therefore performance of perimeter channels, large gully formation, areas of susceptibility, as well as relative susceptibility of surface versus dam slopes were possible to evaluate. Modelling at this resolution also provides insight as to soil loss quantities for the structure as a whole which is important for sizing of channels and settlement ponds. The one-kilometer dam section was simulated in order to gain more detailed information about the ability of CAESAR-Lisflood to predict the development and type of erosional features, and to determine if the overall slope would change (it did not).

In terms of fluvial erosion and mass-movement, the dominant process that developed on the TSF and dam simulations was gullying. Gullies formed on the bottom half of downstream dam slopes, as would be expected due to higher soil moisture, accumulation of water, and concentration of flow, before deepening and then extending back into the dam. Gullies tended to reach maximum depth then slowly progress into the dam while depositing eroded sediment on the gully bottom.

No gullies were formed on the geomorphically designed surface plateau of the TSF (Chapter three), however the main drainage path was eroded at the base. This finding is important as nearly all re-grading/geomorphic design work for TSF closure occurs on the upper plateau area, while dam slopes are not adjusted from their short-term design for the operational period. This modelling has demonstrated that the dams - not the surface plateau - are the greatest cause of long-term geomorphic instability and their design should be re-assessed to create a maintenance-free landform.

With respect to the geomorphic design developed in Chapter three, all of the erosion was located within the bottom of the main drainage pathways. Small check dams were designed along these low-gradient (0.5% slope) drainage ways to further slow the movement of water and create shallow ephemeral pools, while also providing an opportunity for vegetation diversity. The challenge in modelling these with CAESAR-Lisflood is the lack of multiple grain size distributions: in reality these check dams would be constructed of rip-rap or large boulders, while the model simulates the check dams as CST. As a result, the check dams are quickly eroded. Despite the very shallow slope along the main drainage ways, erosion was still predicted along the path due to the large water volumes and erodible sediment. While these check dams should be re-modelled using a more representative grain size to better understand their usefulness in flow rate reduction, it is possible that the main drainage channels will need to be armoured or an additional outlet added and the design altered.

The depth to which gullies form will determine the success or failure of the cover system used. CAESAR-Lisflood is not intended to model very short timeframes (the model takes time to route water and saturate cells); however, our comparison of actual gully depth under roughly annual re-grading to the simulation after five years is similar albeit slightly deeper than seen in the field. In this sense, CAESAR-Lisflood can be used to estimate the length of time without maintenance for cover systems to be compromised due to erosion. In the 200-year simulation, gullies developed to an eventual depth of nearly 20 m, eliminating the upper layer of vegetation on the dams and exposing tailings. On the dam surface where a 4 m cap of CST was proposed over sensitive tailings, the cap remained intact for the full 200-year simulation. This suggests that thoughtful geomorphic design in conjunction with cover or cap design can produce more lasting results than cap or cover design alone. It also provides a method of assessing design life of caps or covers with respect to erosion and location-specific climate.

About 50-60% of the gullies that formed in both the large- and small-scale simulations did so in areas that were made more susceptible to erosion by their topography. It was therefore possible to predict where gullies would form in at least half of the instances, primarily in locations of horizontally convex or concentrated flow and along access roads. These insights allow for complete topographic re-design of these areas or for inclusion of rip-rap and other armouring strategies in these locations. The other 40 - 50% of gullies developed in areas with minor topographic inconsistencies, eliminating the possibility of preventative localized topographic redesign or armouring.

The overall slope of the dam did not change dramatically, although hypsometric integrals indicate that the landform remains in a state of active change at 1000 years. Soil loss rates from the dam are steady state and within acceptable limits for the province of Alberta at 1000 years, and therefore the slope is expected to continue its gradual process of maturation for an extended timeframe.

The 200-year TSF model included a wide buffer, which was frequently flooded entirely by runoff from the TSF as perimeter channels were overtopped due to blockage/filling with sediment. This is important because the TSF is bounded by sensitive features residing about 200 m from the channel edge on either side: on one side a river and on the other a provincial highway. The role of continued maintenance is therefore considered a key aspect to protecting the surrounding environment and ensuring a functional drainage system. In consideration of the simulated landform evolution using historic climate inputs adjusted for winter conditions, it is recommended that regular monitoring and maintenance take place for the first 50 years following reclamation, and that inspections additionally take place immediately following rainfall events greater than a 1 in 5-year return period and following spring snow melt. Remote methods previously outlined in Chapter six may provide a safe and efficient option as compared to in-person field inspections.

It has often been said that "all models are wrong; some are useful", and LEMs are certainly a prime example. There is currently no method of confirming the form and evolution of a landform 100, 200, or 1000 years into the future; however, by refinement of parameters and input data and by evaluating short-term results LEMs generate an evidence-based best guess.

8.7 Summary and conclusions

CAESAR-Lisflood has not previously been used in Canada's north, and more broadly has only been used once to the authors knowledge in an area subject to winter conditions. A primary goal of this work was to determine if the model was capable of simulating the unique climatic and substrate conditions that contribute to shaping the AOS region, in particular its mine waste landforms. This was accomplished through testing and adjustment of rainfall files until one method of accounting for winter conditions produced erosional features similar to what develop on CST structures over relatively brief time frames.

The application of CAESAR-Lisflood to tailings structures in the AOS has the potential to aid in closure design of mine waste structures, particularly in light of regulatory requirements globally moving toward 1000-year (and longer) design lives for mine waste structures. Current closure and reclamation plans in the AOS account for relatively short time frames (commonly about 20 years) in order to monitor their waste structures prior to target reclamation certification dates. 20 years of monitoring is insufficient (given the return period of large storm events) to determine or inform as to the behavior of a waste landform for the next 1000+ years. The only presently available method to evaluate a landform or a landform design with respect to its ability to withstand natural forces over 100, 200, or 1000+ year timeframes is to use a well-calibrated and/or parameterized LEM, such as CAESAR-Lisflood or SIBERIA. The demonstrated use of

CAESAR-Lisflood in the AOS region should therefore be of interest and importance to both mine owners and regulators.

Furthermore, the proposed timeline of about 20 years to undertake both active maintenance and passive monitoring prior to reclamation certification in Alberta is not supported by this research. All simulations of the TSF and component dams as a part of this research have demonstrated that large-scale erosion is likely to continue at high rates for extended time frames. Mitigation techniques such as armouring are not feasible across the entire structure due to cost, and about half of all gullies are unpredictable due to initiation from minor topographic inconsistencies. A minimum timeframe of about 50 years for active monitoring and maintenance is more in line with the findings of this research, followed by passive monitoring and eventual delicensing; however additional testing with adjustment of statistical storms would further refine this number.

9.0 Erosion assessment under two future climate scenarios

In Chapter Eight, the CAESAR-Lisflood LEM was tested using a medium-resolution DEM of the entire TSF/SEA simulated for 200 years, and using a high-resolution DEM of a 1 km dam section simulated for 1000 years. While climate change is regularly integrated into stability models for mine closure in northern regions, particularly where permafrost exists, it has been common practice to use historic climate information when preparing model inputs for landscape evolution models, as done in both simulations in Chapter eight. However, given continual reminders of climate change in the prevalence of forest fires, flooding events, etc. in northern Alberta and internationally, it is of interest to determine how the geomorphology of sand dams may be impacted. It is also of interest whether the differences in results are significant enough to warrant using climate projections within LEM inputs moving forward.

Climate change projections are available is greatest detail for the next 100 years, and as such the simulations run in this chapter are for a timeframe of 100 years. The 1 km dam section was run through three separate simulations: a base-case of 100 years with historic climate parameters, and two simulations of 100-years using projected climate change parameters integrated in different ways.

Section 9.0.1 first outlines the adjustments made in detail not presented in the journal article. Section 9.1 and all subsequent sections in the chapter consist of this LEM and climate change work as presented in a journal article submitted in 2018:

Slingerland, N., Beier, N.A., Wilson, G.W. (Submitted December 2018). Modelling tailings dam evolution post-closure: Erosion assessment under three future climate representation. *Earth Surface Processes and Landforms.*

9.0.1 Preamble: Hydrology and flow model adjustments

Two precipitation data sets were used for this portion of the modelling: one set with historical statistical storms, and a second identical dataset where the depth of statistical storms were altered according to climate change projections and corresponding IDF curves, as attained from Simonovic et al. (2016). Some background on climate change adaptation for the precipitation data set is outlined below, as it is not discussed in depth within the paper that follows.

The standard distribution for precipitation frequency analysis in Canada is the Gumbel (EV1) distribution, therefore it was used here in conjunction with the most extreme Representative Concentration Pathway (RCP) 8.5 emissions scenario.

Global climate models represent atmosphere dynamics in order to understand climate; When used to predict future climate they make use of RCPs. RCPs are time-dependent scenarios of greenhouse gas concentrations, aerosols, and chemically active gases in the atmosphere, as well as land-use / cover alterations (Schardong, Gaur, Siminovic, & Sandink, 2018). Four RCPs are commonly used, representing different potential emissions scenarios: RCP 2.6, 4.5, 6.5, and 8.5. The RCP 8.5 (high emissions) scenario used herein includes radiative forcing greater than 8.5 W m^2 by the year 2100 relative to 1750 (IPCC, 2013), and was used to understand how the most extreme case would impact geomorphology. Figure 9.1 illustrates the radiative forcing from the year 1750 to 2010, for reference. A combination of models were used for IDF generation, bias corrected and downscaled: CanESM2, CCSM4, CNRM-CM5, CSIRO-Mk3-6-0, GFDL-ESM2G, HadGEM2-ES, MIRCO5, MPI-ESM-LR, and MRI-CGCM3 (Simonovic et al., 2016).

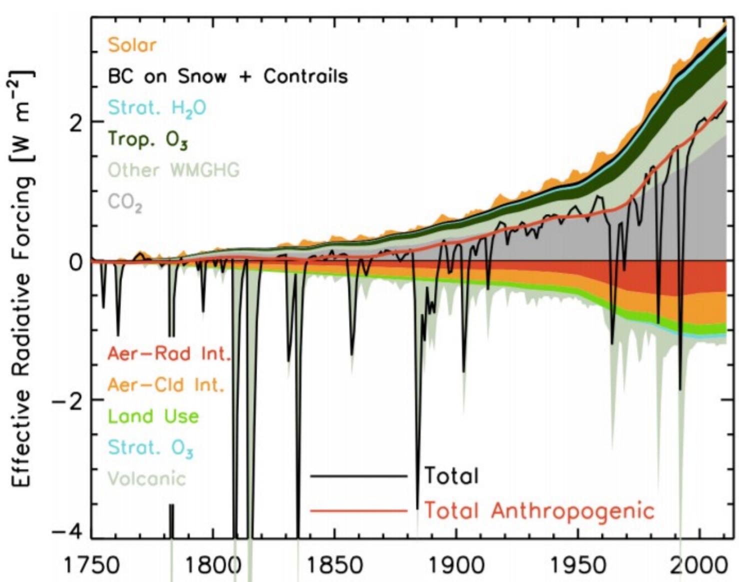

Figure 9.1 Radiative forcing relative to 1750 levels (IPCC, 2013).

Rainfall distributions are summarized up to the 100-year storm in Table 9.1. Historic rainfall distributions (Figure 8.8) were used for the first 20 years corresponding to the years 2000-2020. For climate change simulations, statistical storm events were inserted using the distributions in Figure 9.2-9.4, based on the year they occurred.

Table 9.1 Total statistical 24-hour storm depth in millimetres for the Ft. McMurray A climate station (ID: 3062693), retrieved using (Simonovic et al., 2016).

Annual storm event probability	Historic values	Projected RCP 8.5 values		
		2020-2045	2045-2075	2075-2100
1:100	93.53	124.11	127.37	128.92
1:50	84.57	104.57	107.23	110.95
1:25	75.56	89.76	90.14	96.27

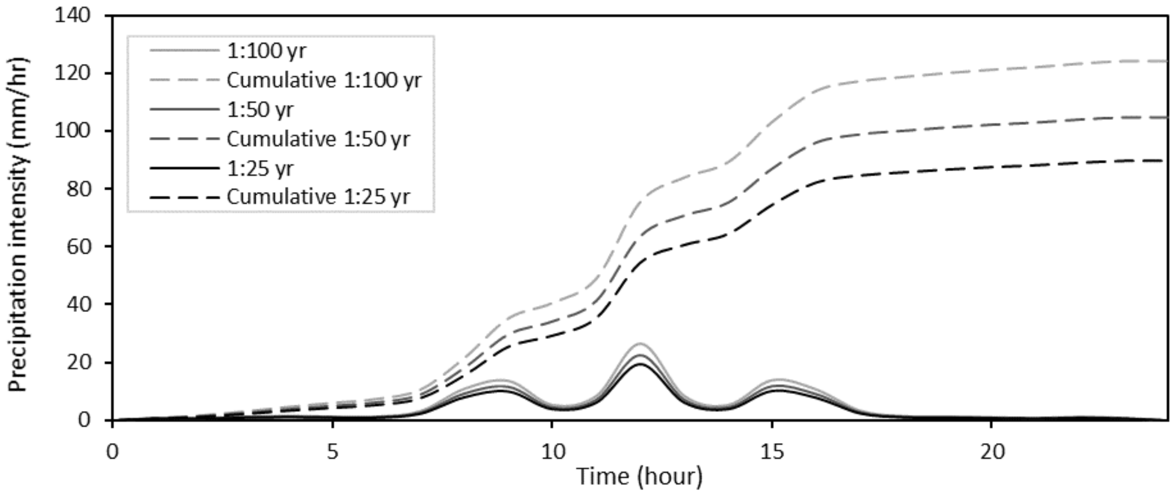

Figure 9.2 Hyetographs for projected 24-hr storms in Ft. McMurray, 2020-2045

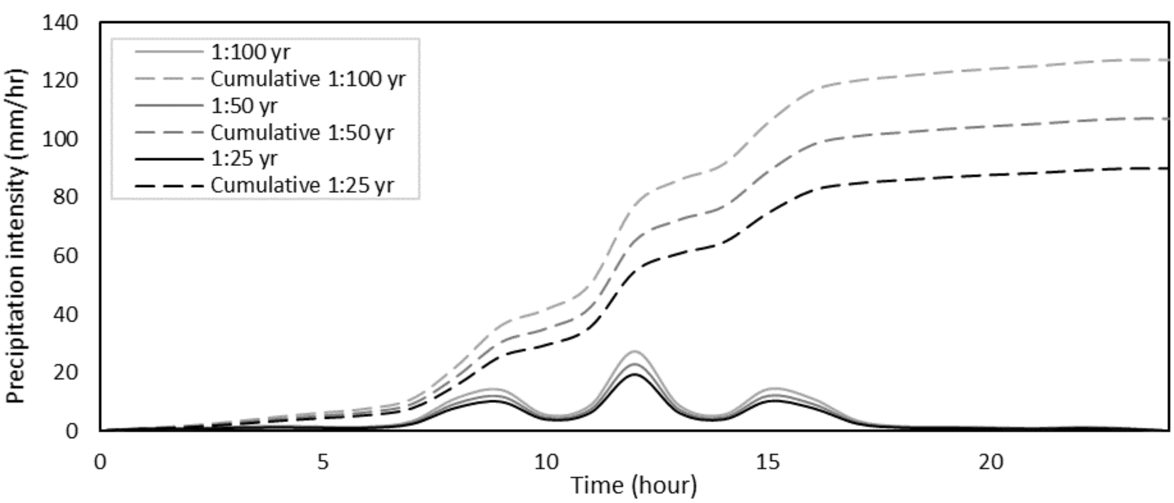

Figure 9.3 Hyetographs for projected 24-hr storms in Ft. McMurray, 2045-2075

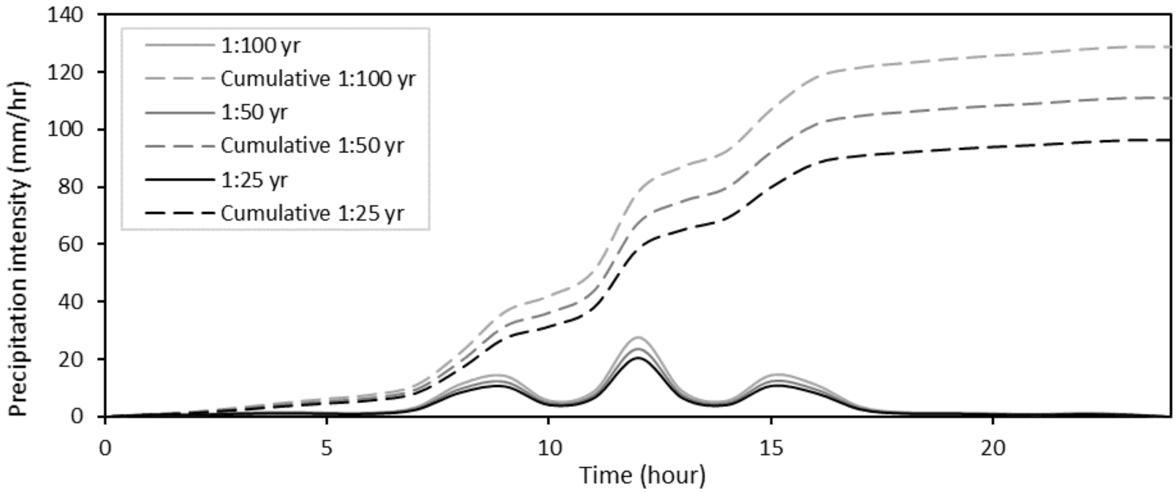

Figure 9.4 Hyetographs for projected 24-hr storms in Ft. McMurray, 2075-2100

With respect to the flow model, the only parameter altered is evapotranspiration. Climate change projections were available for calculated potential evapotranspiration and pond evaporation from a publicly available study for the region (Golder Associates Ltd., 2013). Pond evaporation was projected to increase by 38.7 mm / year, mostly concentrated in the spring, summer, and fall (Table 9.2). The evaporation for climate change scenarios was therefore set at 883 mm over the 234 days comprising these seasons, or 0.0036 m/day. Pond evaporation was used because CAESAR-Lisflood applies evaporation rates only to cells with a surface water depth, and this is a closer estimate to exposed water than PET.

Table 9.2 Climate change scenario A2 (most similar to RCP 8.5) projected increases in evapotranspiration and evaporation, from (Golder Associates Ltd., 2013)

Period	Change in Potential Evapotranspiration (mm)	Change in Pond Evaporation (mm)
Annual	64.0	38.7
Winter	1.0	0.1
Spring	18.7	8.0
Summer	36.6	26.0
Fall	7.7	4.6

The first climate change simulation only altered the precipitation file (statistical storms) and evaporation according to projections. The second climate change simulation made the same alterations, with the addition of adjusting the m-value within the hydrology section of the model set-up. This is detailed in the paper below.

9.1 Introduction

Tailings dams are common landforms on mine sites, constructed to hold the liquid waste (tailings) generated through mineral extraction and processing. Depending on the geology and processing methods used, tailings can have toxic levels of heavy metals, excess salt concentration, extreme pH values, and/or radioactive elements. Physical instability of containment dams can lead to unplanned release of tailings and environmental damage, as exemplified by recent high-profile dam collapses. The sensitivity of tailings dams to external forces and the extreme failure consequences make these structures of interest from a geomorphic perspective in long-term closure planning; This paper explores the prediction of dam morphology under various climate-induced forces.

The goal of current best practices in tailings dam closure is to create a sustainable landscape once mining has ceased; this requires that economic, environmental, and social conditions are not impeded by mining activities (ICOLD, 2013; World Bank & IFC, 2002). Physical stability is a fundamental requirement of full-spectrum sustainability, making it a priority area. Traditionally, short- and long-term stability objectives have been quantified in terms of factors of safety. Short-term geotechnical assessments encompass seepage, slope stability, deformation, and in some cases temperature effects. However, over long time frames, it is of interest whether cumulative erosion will also affect physical stability. Geomorphic changes can occur due to erosion from a single extreme precipitation event and/or cumulative exposure, and erosion is increasingly recognized for its influence on long-term dam stability and health of the downstream environment (Hancock & Willgoose, 2004; Lane, Tayefi, Reid, Yu, & Hardy, 2007).

Over the past several years, climate changes related to temperature and precipitation have been a growing global concern. Flooding, drought, and increasing storm severity are attributed to anthropogenic changes, predominantly greenhouse gas emissions (Crowley, 2000). These climate change concerns have not evaded geomorphologists, who are particularly interested in how altered climate patterns will be reflected on the earth's surface given the non-linear fluvial response (Coulthard & Van de Wiel, 2007; Lane et al., 2007). The cumulative effects of increasingly severe precipitation events and drought on tailings dam erosion is therefore essential to their design, especially where the sustainability of the final landscape is reliant on their retention of large volumes of waste and contaminants.

Global climate models (GCMs) are the predominant source of climate change projections at a regional scale (typically over a 300 km grid), that can be combined with local topography and climate patterns for finer-scale models (Kuo, Gan, & Hanrahan, 2014; Lane et al., 2007). GCMs provide information with respect to future changes to annual and seasonal precipitation, season length, air temperature, etc. using global emission scenarios generated by the Intergovernmental Panel for Climate Change (IPCC) (IPCC, 2001). Four representative concentration pathway (RCP) scenarios have been developed based on global greenhouse gas emission projections: stringent mitigation (RCP2.6), two intermediate scenarios (RCP 4.5 and 6.0), and a minimal emission mitigation scenario (RCP 8.5) (IPCC, 2014). Emissions scenarios can also be used to investigate the climate implications of various changes to technology, policies, and economic development (Moss, 2010). GCM results using any of the RCP scenarios can then be integrated into other models to determine secondary environmental changes. Precipitation intensity and frequency, air temperature, and vegetation coverage and type are key factors that are affected by climate change and influence soil erosion. It is therefore of interest to evaluate how these climate change factors may influence the geomorphology of tailings dams.

Geomorphic modelling has evolved over the last 20 years as three-dimensional models and computing power have developed. So et al. (2002) used the MINErosion model as a design tool for mine waste, and landscape evolution models (LEMs) such as SIBERIA and CAESAR-Lisflood have been used to predict the morphology and sediment loss from mining landforms using fictional and historic precipitation records (Hancock et al., 2000; Hancock & Willgoose, 2004; Hancock, Crawter, Fityus, Chandler, & Wells, 2008; Hancock, Lowry, & Coulthard, 2016; Lowry, Coulthard, & Hancock, 2013).

The effect of precipitation change on landform hydrology and geomorphology has been previously investigated within distinct climatic regions (Coulthard & Van de Wiel, 2007; Hancock, 2009; Lane et al., 2007). Lane (2007) found that in northern England floodplains were more frequently inundated under the extreme A2 Special Report on Emissions Scenarios (SRES) emissions scenario (similar to the RCP 8.5 scenario) than with historical data, and that this influenced sediment transport rates. Similarly, Hancock (2009) found that increased rainfall simulation quantity and intensity resulted in increased sediment transport as compared to historic figures, but similar morphology, at a small catchment in Northern Territory, Australia. Based on these findings, it is expected that increased precipitation and evaporation will more negatively impact the morphology of tailings dam slopes than historical values, which are typically used in LEMs.

The effects of climate change are seen in temperature, evaporation rates, vegetation, and soil moisture, in addition to precipitation; each of which can be represented through LEM parameterization. This study used a LEM to predict how the morphology of a tailings dam might vary when exposed to two climate scenarios represented through three different parameter sets: (1) historic climate, (2) climate change projections using RCP 8.5 represented via precipitation and evaporation, and (3) climate change projections using RCP 8.5 represented via precipitation and evaporation, and vegetation transition. The following questions guided this research:

1. Is CAESAR-Lisflood sensitive to changes in basic climate-related parameters?
2. How does climate change (as represented by increased precipitation intensity, increased evaporation, and changing soil moisture/vegetation regime) impact tailings dam erosion and physical stability relative to historic climate?
3. How does sediment transport and environmental loading differ using historic climate and climate change projections?
4. How might climate changes impact the present dam delicencing and mine site relinquishment strategy?

9.2 Regional and regulatory context

9.2.1 AOS climate, geology, and vegetation

The Athabasca oil sands mining region lies within the Boreal Plains ecozone, characterized by extensive wetlands, underlying glacial-origin mineral deposits, and an annual water deficit. Annual precipitation averages 420 mm with about half of this falling over the months of June, July, and August during convective, high-intensity storms (Carey, 2008; Government of Canada, 2018). Long winters allow for snow accumulation and the subsequent spring melt contributes to the erodibility of exposed surficial soils (Chanasyk & Woytowich, 1987). The average annual temperature for the AOS is approximately 1 °C, leading to an accumulation of organic material and peat formation where the hydrologic system is conducive (Government of Canada, 2018; Price, McLaren, & Rudolph, 2010). Upland areas are naturally less common than peatlands, and occur in conjunction with upland forest species such as trembling aspen (*Populus tremuloides*), balsam poplar (*Populus balsamifera*), jack pine (*Pinus banksiana*), and balsam fir (*Abies balsamea*) (Gillanders, Coops, Wulder, & Goodwin, 2008; Johnson & Miyanishi, 2008).

The present state of equilibrium between geology, hydrology, and vegetation is a result of complex interactions throughout the past 10,000 years. Climate change is likely to alter this equilibrium, particularly exchanges between peatlands and open ponds that are driven by precipitation and evapotranspiration (Thompson, Mendoza, & Devito, 2017). The RCP 8.5 scenario for Fort McMurray (based on the combined outputs of all models from the Pacific Climate Impacts Consortium (PCIC)) predicts a trend towards warming temperature, increased evapotranspiration, and increased precipitation intensity at least until the year 2100 when the extent of the current detailed predictive range is reached (Gray & Hamann, 2015; Kuo, Gan, & Gizaw, 2015; www.idf-cc-uwo.ca). Research has shown that these changes lead to a northern migration of ecosystems, whereby grasslands are likely to replace northern boreal zones (Schneider, Hamann, Farr, Wang, & Boutin, 2009). While increased evapotranspiration may balance the increased rainfall over days or weeks, it is unlikely to mitigate erosion resulting from increased rainfall intensity and runoff over a period of hours, particularly given projected vegetation changes on upland areas (Schindler & Donahue, 2006; Schneider et al., 2009).

Oil sands mining has generated additional upland landforms in the Athabasca region through mine waste. Tailings dams 40 - 100 m in height and overburden dumps greater than 100 m in height have been constructed across the mining region covering large areas. (Hein, 2000; Palmer, 2005) discuss the historical context of the oil sands in depth.

This study focuses on one of many sand tailings dams north of Fort McMurray, Alberta, Canada. AOS tailings dams are constructed primarily using coarse sand tailings in an upstream arrangement, as shown in Figure 9.5. The particular tailings dam investigated in this study is more than 20 km in length and approximately 60 m tall. In order to model with high resolution, a 1 km stretch of the dam was modelled.

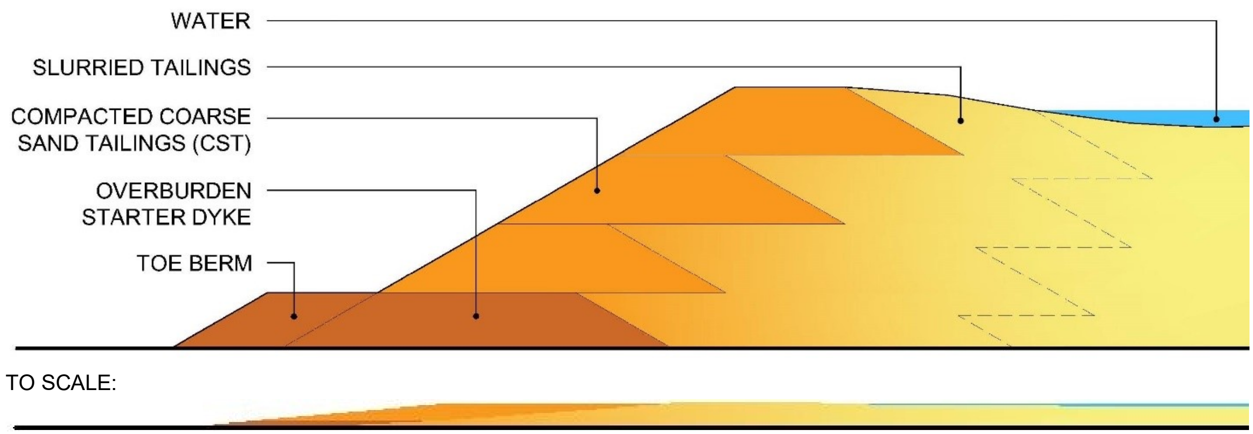

Figure 9.5 Hypothetical tailings dam cross section vertically exaggerated to illustrate the upstream construction method widely used in the AOS (top), and shown to scale below.

9.2.2 Regulatory process

Tailings dams are ideally delicensed and reclaimed following mining in Alberta, consistent with international best practices. This is a staged process that is considered to be complete when a dam owner has received a reclamation certificate from the regulator. The anticipated path to achieving reclamation certification is outlined by (Oil sands tailings dam committee (OSTDC), 2014) shown in Figure 9.6, and first involves converting the tailings dam into a solid structure by removing all liquefiable materials and water, re-grading the structure such that it cannot revert to a dam, and expanding drainage channels at the base of the dam to collect soil and water.

<table>
<tr><th></th><th colspan="2">PHASE</th><th>STRUCTURE TYPE</th></tr>
<tr><td rowspan="7">Time</td><td colspan="2">Mine phases: planning, design, construction, operation</td><td>Tailings dam</td></tr>
<tr><td colspan="2">End of mine life / Dam conversion</td><td rowspan="2">Non-operating dam</td></tr>
<tr><td>Active Care</td><td rowspan="2">Decommissioning / delicensing as a dam</td></tr>
<tr><td>Passive Care</td><td>Solid earthen structure</td></tr>
<tr><td colspan="2">Reclamation</td><td rowspan="2">Landform</td></tr>
<tr><td colspan="2">Certification as public land</td></tr>
</table>

Figure 9.6 Proposed delicensing and reclamation process for an oil sands tailings dam, in line with international best practices. Adapted from (Oil sands tailings dam committee (OSTDC), 2014 and Al-Mamun & Small, 2018).

After a period of active monitoring, and when the dam is observed to no longer require ongoing maintenance, the structure is delicensed as a dam. This means the structure is no longer a dam, but a "solid earthen structure" in the regulators view. At this point the structure enters a passive phase where monitoring takes place in order to identify when it is behaving similarly to natural landforms in the region. Once accomplished, the owner can apply for reclamation certification, and if granted the structure is considered a landform. This process from conversion to certification is expected to take decades, with most AOS mining companies allotting about 20 years in their closure plans, however no AOS dams have completed the process to date.

9.3 Landscape Evolution Models

9.3.1 Background

Geomorphic modelling has developed since the 1970's to include sediment deposition, channel and gully erosion, and location-specific information (Flanagan, Gilley, & Franti, 2007). The Water Erosion Prediction Project (WEPP) began in the mid-1980's to integrate these features as well as other physical processes such as infiltration and detachment mechanisms in a three-dimensional model (Flanagan et al., 2007). With increasing computing power in the 1980's and 1990's (and understanding of the damage that erosion and sedimentation cause), other numerical models were created to simulate fluvial and slope processes in greater detail (Coulthard, 2001). For example, TOPMODEL (Beven & Kirkby, 1979), ANSWERS (Beasley, Huggins, & Monke, 1980; Beven & Kirkby, 1979), SIBERIA (Willgoose, 2005; Willgoose, Bras, & Rodriguez-Iturbe, 1991 & 1994), GOLEM (Tucker & Slingerland, 1994), Cascade (Braun & Sambridge, 1997), CHILD (Tucker & Bras, 2000) and CAESAR (Coulthard, 2001). Each of these use variable spatial and temporal scales, and represent channel and slope geomorphic and hydrologic properties as they evolve. SIBERIA and CAESAR have perhaps been the most widely used landscape evolution models over the last 20 years, with their results being cross-referenced for evaluation.

LEMs are used to better understand how a natural system functions, and also to predict future system behaviour (Willgoose, 2018). This is particularly important in sensitive landscapes or environments. LEMs use fluvial processes as a primary mechanism for sediment movement and deposition, and can simulate timescales from less than one hour to more than 10,000 years. This involves a number of physical processes and non-linear features that vary over time and space such that outputs are not always a sum of component inputs (Coulthard & Van de Wiel, 2007; Willgoose, 2018).

9.3.2 CAESAR-Lisflood

The CAESAR-Lisflood LEM, previously described in detail in (Coulthard, et al., 2013; Lowry et al., 2013; Van de Wiel, Coulthard, Macklin, & Lewin, 2007), was used for this study due to its ability to capture peaks in precipitation intensity, to integrate and hydrodynamically model flow through features such as ephemeral ponds, and CAESAR-Lisflood's widespread testing and evaluation. This is a model that was generated from integrating the CAESAR LEM with the Lisflood-FP hydrologic flow model. CASEAR-Lisflood uses a regular, square grid digital elevation model (DEM) to represent the surface topography of a site, and another to represent bedrock topography, or the lower bounds of soil. For each cell, information is stored with respect to elevation, grain size distribution, water depth, soil moisture, vegetation growth, and water discharge. In catchment mode water enters the system uniformly over the DEM from the precipitation file, and is routed using the D4 algorithm. For each model iteration hydrologic routing, fluvial erosion and deposition, and slope processes are calculated then the cell information is adjusted accordingly (Hancock, 2009). The model adjusts these values in rapid succession: first water flow depth is calculated, then flow velocity is calculated using surface water slope, gravity and a h_{flow} parameter to determine erosion of deposition of the various grain sizes, followed by calculation of creep (dependant on slope) for the iteration and landslides in the event that the maximum slope angle has been exceeded between any two cells. Additionally, a vegetation component exists whereby parameters may be set, and have the effect of stabilizing soil with growth percentage.

The benefit of non-steady state flow in a combined geomorphology and hydrology model is that localized erosion and deposition is possible throughout the DEM, and more realistic sediment loads are acquired for water leaving the site. This is a particular benefit where contaminant transfer is possible or where streams are sensitive to elevated sediment loads. Where flow rates and particle size dictate, the smallest fraction of soil input to CAESAR-Lisflood can be flagged as suspended load and dropped out of suspension when flow rate decreases to the user-defined settling velocity.

9.4 Methods and LEM parameterization

In addition to parameterization of more than 30 variables, CAESAR-Lisflood requires data inputs in the form of: 1) a DEM representing surface topography, 2) a DEM representing bedrock topography, 3) soil particle size distribution lumped into nine grain sizes, and 4) optimally hourly precipitation data (mm/hr) for the length of the simulated time. Each of these inputs are discussed below.

9.4.1 Digital elevation models

Light detection and ranging data for the existing tailings dam were provided by the mine owner and converted into a DEM. The DEM was edited to expand ditches at the base of the dam to their full post-closure dimensions, as would be done on site during construction. A DEM representing the lower limit of CST erodibility was generated using AutoCAD and ArcGIS to roughly follow the pre-development topography. In order to achieve a high-resolution DEM and model outputs, the full 20 km length was truncated to a representative 1-km section with a cell/ grid size of 2.5 m by 2.5 m. Both the lower limit of erosion and surficial topography DEMs are shown in Figure 8.2.

9.4.2 Soil particle size

In the spring of 2017, two 500 g surficial soil samples were collected from 22 separate locations along the dam. One sample was taken from a depth of 1 - 150 mm below the surface, and another from a depth of 200 - 300 mm below surface. Particle size distributions were determined using the sieve method as per ASTM D6913 (American Society for Testing and Materials (ASTM) International, 2009), and the mean distribution was classified into nine ranges for use in CAESAR-Lisflood (Figure 8.3).

9.4.3 Precipitation data

Using CAESAR-Lisflood’s catchment mode, hydrologic inputs are restricted to precipitation. For this study, fifteen years of complete hourly precipitation data from January 2003 to December 2017 were attained predominantly from the Regional Aquatics Monitoring Program (RAMP) ‘Aurora C1’ monitoring station. The data was quality controlled and compare with other local sites to highlight inconsistent data, and gaps were replaced with data from Environment Canada’s Mildred Lake monitoring station based on congruence. Hourly precipitation data for September to December 2017 was attained from the Fort McMurray ‘A’ station as other data was not yet available.

CAESAR-Lisflood assumes all precipitation falls as rain, which has been the case for the majority of modelled sites to date. In order to recreate winter conditions in northern Alberta within the precipitation file it was necessary to adjust the precipitation record compiled. Welsh et al. (2009) previously used temperature and snow storage in order to create a precipitation record for the French Alps (Welsh, Dearing, Chiverrell, & Coulthard, 2009), and this method was applied to the site-specific conditions north of Fort McMurray. Temperature data was collected from the 'Aurora C1' climate station and used to adjust the precipitation file for winter conditions. In fall, once daily average temperature was consistently below 0 °C precipitation values were set to zero. In spring, once daily average temperatures were consistently greater than -1 °C precipitation values were once again read from the compiled data, with the addition of snow melt depths. Snow melt was calculated from the daily difference in measured snow depth readings at the 'Aurora C1' station and converted to water depth (mm). The daily melt depth in mm of water was then added to the precipitation file on the first hour of the day. Figure 8.4 provides an example diagram for how this was done. Note that precipitation and snow melt were not included during winter days where the temperature was above zero, because frozen ground conditions and snow depth would have existed, thereby impeding any resultant erosion.

The altered 15-year precipitation record was looped to create one 100-year record and used to create two distinct rainfall scenarios for input to CAESAR-Lisflood, as described below.

1. Historic statistical 24-hour storm events were added according to their return period (Table 9.3). 1-in-25 year precipitation events were added beginning at year 16, 1-in-50 year events were added beginning at year 50, and a 1-in-100 year event was added to year 80.

2. Statistical 24-hour storm events corresponding to those predicted by intensity-duration-frequency curves for RCP 8.5 were added according to their return period at the same years as in the first rainfall scenario (Table 9.3). More information is provided on the climate change scenario used in section 9.4.5.

Table 9.3 Precipitation event depths for major statistical storms added to the precipitation file for use in CAESAR-Lisflood. The historic 24-hour IDF was used for models without climate change considerations, while the RCP 8.5 24-hour IDF was used for models including climate change considerations.

Simulated Modelling Year	Return period (years)	24-hour event depth - Historic IDF (mm)	24-hour event depth - RCP 8.5 IDF (mm)
16	25	75.56	75.56
41	25	75.56	89.76
50	50	84.57	107.23
66	25	75.56	90.14
80	100	93.53	128.92
91	25	75.56	96.27
100	50	84.57	110.95

9.4.4 Vegetation and m-value

CAESAR-Lisflood simulates vegetation growth such that erosion is gradually reduced to a user-specified value when vegetation reaches full maturity. A user-defined vegetation critical shear must be achieved by flowing water, or mass wasting must occur, in order to remove vegetation from the model.

Land cover changes are represented in CAESAR-Lisflood by the m-value, which changes the flood hydrograph such that water transmissivity through soil is adjusted. A value of 0.005 equates to a hydrograph resembling that from a grassland landscape, whereas a value of 0.016 - 0.02 transmits water more slowly, as in a densely forested landscape (Coulthard & Van de Wiel, 2017; Welsh et al., 2009). The m-value was altered according to the simulation being modelled: for historic climate the m-value was set at 0.01, or about 70% forest cover. This value was determined by comparing density of reclaimed vegetation to natural undisturbed local forest (assumed value of 0.016 based on Welsh et al. (2009)).

Similar to paleoecological data from the last warm period in the Holocene when Alberta was 1-3°C warmer (Strong and Hills, 2003), drier areas of boreal forest are projected to convert to grassland over 50 years, while higher moisture boreal areas are expected to transition to parkland (Schneider et al. 2009). Due to their free-draining nature, CST-composed upland landforms are expected to be relatively dry compared to the low areas around them. For the climate change simulation, the transition from new forest to grassland (Schneider et al., 2009) was represented by gradually reducing the m-value over the 100 years modelled to a value corresponding to grassland (Table 9.4).

Other vegetation changes that are both expected due to climate change and have parameters in the model include: (1) time to full vegetation coverage, which would be shorter for grass than for trees, (2) proportion of erosion with full vegetation coverage, and (3) critical shear for vegetation removal. These parameters do not presently allow for variation over time, and the difference in values for trees and shrubs compared to grasses is expected to be high. As such, values for the historic climate were used in both simulations.

Table 9.4 Parameterization differences for models run with and without consideration of climate changes. [1] (May et al., 2011); [2] (Alberta Transportation, 2003b).

	Simulation 'A': Without Climate Change (historic values)	Simulation 'B': Temperature & Precipitation Climate Change effects only	Simulation 'C': Cumulative Climate Change
Time to full vegetation coverage	24 years[1]	24 years[1]	24 years[1]
Proportion of erosion with full vegetation coverage	0.15	0.15	0.15
Vegetation critical shear	177.23 Pa[2]	177.23 Pa[2]	177.23 Pa[2]
Statistical storms	Historic IDF	Projected IDF	Projected IDF
m-parameter	0.01	0.01	Year 0-20: 0.01 Year 20-40: 0.009 Year 40-60: 0.008 Year 60-80: 0.007 Year 80-100: 0.006
Evaporation	0.0034 m/day	0.0036 m/day	0.0036 m/day

9.4.5 Climate change representation in CAESAR-Lisflood

Detailed climate projections for the Fort McMurray region are available through to the year 2100 using the most recent GCM's, based on the baseline historical data set recommended by IPCC's Fifth Assessment Report from 1986 to 2005 (IPCC, 2014). Projections through to the year 2500 are available, however uncertainty increases dramatically. IDF (Intensity-duration-frequency) curves for 24 hour statistical storms at the Fort McMurray 'A' climate station were attained using the IDF_CC tool (Simonovic, Schardong, Sandink, & Srivastav, 2016) for the 100 year modelling timeframe. A Gumbel distribution (EV1) was used, as it is the standard for precipitation frequency analysis in Canada (Millington, Das, & Simonovic, 2011), and the most extreme RCP 8.5 was used. A combination of downscaled models was used, bias corrected and downscaled: CanESM2, CCSM4, CNRM-CM5, CSIRO-Mk3-6-0, GFDL-ESM2G, HadGEM2-ES, MIRCO5, MPI-ESM-LR, and MRI-CGCM3 (Simonovic et al., 2016).

Projected temperature increases of 0.3 to 4.8 °C by the year 2100 (IPCC, 2014) lead to an associated decrease in soil moisture and increase in evaporation (Gray & Hamann, 2015). Forecasted changes to potential evaporation previously documented for the region (Golder Associates Ltd., 2013) were averaged and applied to the CAESAR-Lisflood model such that evaporative losses were greater for models including climate change than for those without (Table 9.3). These values were similar to those found by (Keshta, Elshorbagy, & Carey, 2012) for the extreme scenario.

9.4.6 Modelling methods

The CAESAR-Lisflood model, version 1.9b (Coulthard, 2017), was used to evaluate the proposed post-mining tailings dams for long-term stability, erosion potential, and whether climate change projections (represented in the model) impact the structure over time, delicensing potential, or off-site environments. The current design life for post-mining tailings dams is ambiguously given as "long term" or "at least 1000 years" (ICOLD, 2013); however, cold regions cover systems guidelines (that are generally longer than in temperate climates) recommend a minimum 100-year design life (MEND, 2012). This 100-year period corresponds to the 100-year GCM detailed projection. As such, LEM simulations were conducted for a period of 100 years.

Three simulations were run, listed in Table 9.3. Simulation 'A' applied a widely-used approach to parameterization, whereby historic precipitation data and current climate figures are applied to the model. Simulation 'B' was identical to A with the exception of evapotranspiration, where an average projected value was used, and precipitation, where statistical storms reflective of the projected RCP 8.5 scenario were included. Simulation 'C' was identical to 'B', with the exception of the m-parameter that was reduced by 0.001 after every 20 years.

LEM's commonly over-predict sediment transport rates for the first 10-20 years modelled, as the digital elevation model is smoothed and the surficial grain size distribution is sorted due to precipitation and topographic inputs. For this reason, a "spin-up period" is often used on previously weathered terrain such that grain size distributions (GSDs) are more naturally variable across a site when the model starts. The tailings dam at the focal point of this research is relatively new and the GSD across the landform is uniform, such that use of a spin up period in this case would lead to GSD's and topography not representative of the study site characteristics. As such, no spin-up period is used in the models.

Model assessment is conducted via sediment discharge and erosion rates, as well as geomorphic descriptions over the modelling time. Due to the long modelling time at present, it is exceedingly time consuming to conduct Monte Carlo simulations to attain accuracy estimates or confidence limits on model outputs (Willgoose, 2018). Where reach mode is used, watercourse discharge from CAESAR-Lisflood may be compared to measured data for evaluation purposes; however, when using catchment mode for upland landforms, as is the case herein, the emphasis is placed more on correct parameterization up-front and long-term trends rather than specific outputs at particular points in time.

9.5 Results

CAESAR-Lisflood was found to be sensitive to alterations in precipitation, evaporation, and vegetation/ soil transmissivity, all of which are likely in northern Alberta over the next century. This is evident through both qualitative and quantitative geomorphology and the erosion rates and pattern produced, each of which is discussed further below. The model is sensitive to changes in the m-value, and therefore changes to vegetation and associate soil characteristics are most strongly represented in the simulation.

9.5.1 Qualitative and quantitative geomorphology

From visual examination of the DEMs following 100 years of simulation it is clear that the CAESAR-Lisflood LEM is sensitive to the input differences in the three sets used. Climate change parameters resulted in substantially more erosion than the historic parameters: while gullies are formed in similar locations, Simulation 'C' led to wider, branching gullies, compared to smaller, non-branching gullies formed in Simulation 'A' or 'B'. Cross-sectional analysis along the downstream slope of the dam at the base, and at 1/3, 1/2, and 2/3 of the total dyke height (Figure 9.7) was conducted to simultaneously assess the initial and final topography resulting from all parameter sets at multiple heights (Figure 9.8).

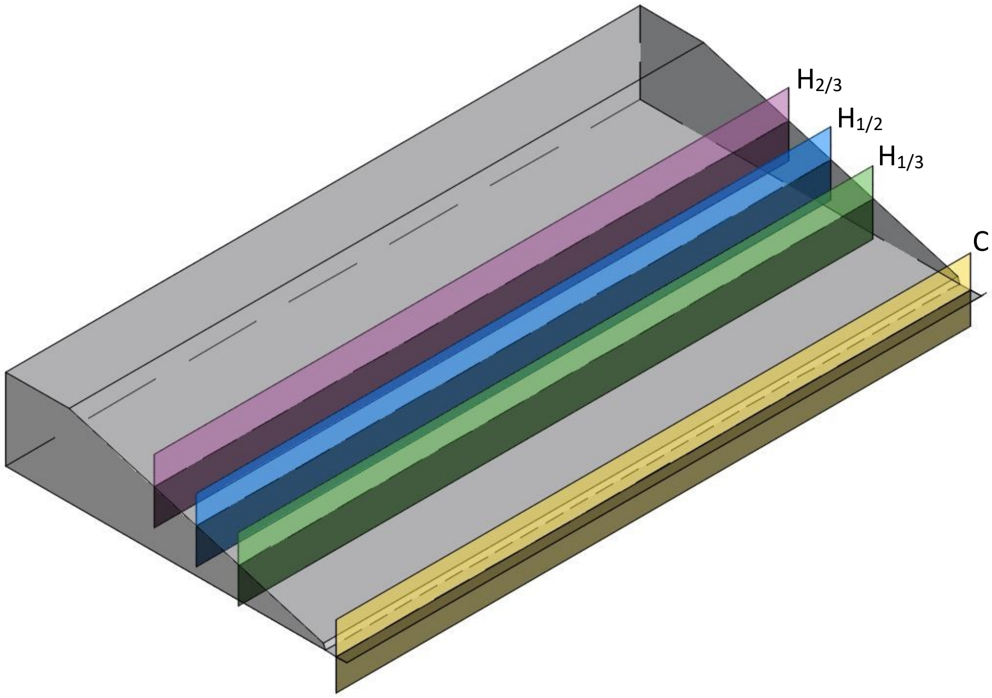

Figure 9.7 Locations of sections through the downstream face of a roughly 1 km section of the tailings dam, as illustrated in Figure 9.8.

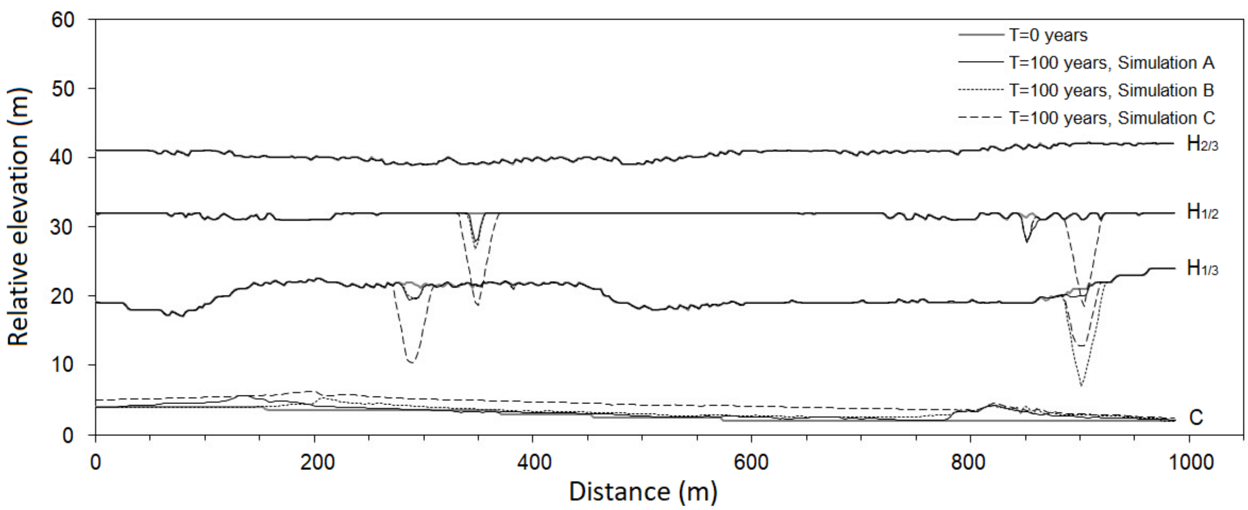

Figure 9.8 Sections through the downstream face of a roughly 1 km section of the dam prior to simulation (T=0, solid line), and following 100 years of Simulation 'A', 'B', and 'C'. Sections taken at the toe (in channel, C), at 1/3 height, 1/2 height, and 2/3 height.

Despite the qualitative geomorphic variability, quantitatively the dam slopes are not very different from each other. The mean elevation after 100 years is 0.21 m lower in Simulation 'C' than in Simulation 'A', but the hypsometric curves and integrals remain similar (Figure 9.9, Table 9.5). Quantitatively the descriptors for initial terrain (T = 0) and Simulation 'A' are quite close, demonstrating the relatively little change that has occurred. Notably, the hypsometric integral increases from T = 0 to T = 100 using historic parameters, primarily due to gully removal of soil at the base of the dam slope. The same change occurs in the climate change parameter simulation, but it occurs earlier in the simulation and is followed by advancement of the gully upwards and infilling of lower reaches with sediment, producing an overall lower hypsometric integral after 100 years. The hypsometric curve, while indicative of borderline mature topography is also indicative of a hillslope undergoing slow but continuous development. It is reasonably assumed that the curve will become more concave over time. Standard deviation across elevation values also shows greater variation resulting from Simulation 'B' and 'C' than from Simulation 'A', indicative of deeper erosional features.

Table 9.5 Geomorphic descriptors for dam section. HI's are all indicative of hillslope-dominated processes (Willgoose & Hancock 1998), as expected, and a mature but continuously developing slope. Units for mean elevation (of entire dam area) are in meters, and average denudation rate shown in brackets is in mm year^{-1}.

	T = 0 years	CAESAR-Lisflood, T = 100 years		
		Simulation 'A'	Simulation 'B'	Simulation 'C'
Hypsometric Integral (HI)	0.532	0.534	0.529	0.523
Mean Elevation	313.59	313.56 (0.31)	313.46 (1.27)	313.35(2.42)
Elevation Standard Deviation	14.82	14.83	14.92	14.99

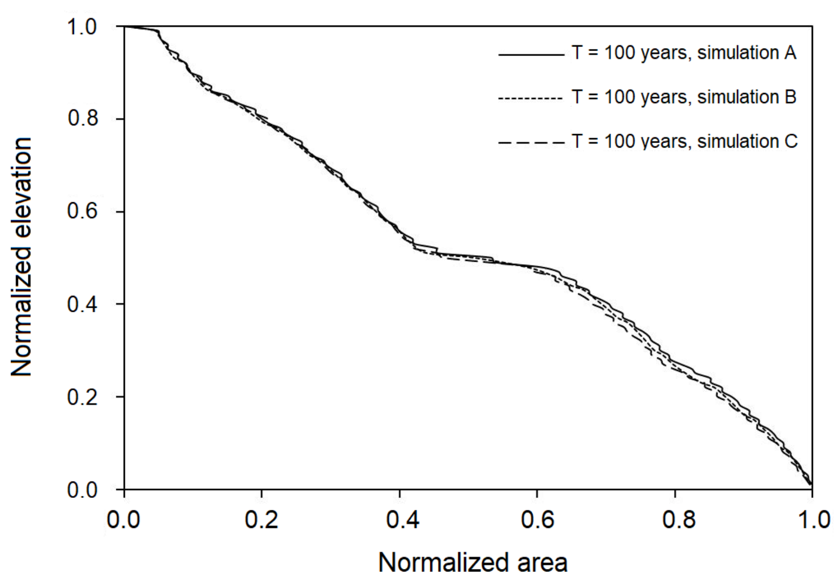

Figure 9.9 Hypsometric curves for the dam section for all simulations after 100 years

9.5.2 Erosion rates and patterns

As expected, climate change parameters led to more sediment discharge than historic parameters (Table 9.6). For all dam segment simulations there were years where no sediment was discharged from the channel at the base of the dam; however, over 100 years Simulation 'C' led to more than 20 times the sediment discharge of Simulation 'A'. Simulation 'B' generated higher maximum erosion values, but lower total soil loss over 100 years compared to Simulation 'C'. Variability in annual sediment discharge increased by an order of magnitude between Simulation 'A' and both climate change simulations.

Table 9.6 Annual sediment discharge statistics (in m^3/yr) for dam section over 100 years for the three simulations.

	Simulation 'A'	Simulation 'B'	Simulation 'C'
Minimum	0	0	0
Maximum	1503	7013	6765
Total (m^3)	2280	35079	51181
Mean	23	351	512
Std. Dev.	161	1097	1152

Analysis of annual sediment output from the drainage channel at the base of the dam indicates that climate change parameters impact the pattern of sediment discharge as well as the quantity. Annual sediment output starts high and decreases to values less than 100 m^3 / year by year 20 of Simulation 'A'. Sediment discharge from Simulation 'B' is significantly increased from Simulation 'A', decreasing to values less than 100 m^3 / year by year 60. Simulation 'C' generated sediment output that was both greater than Simulation 'A', and (in contrast to both 'A' and 'B') was sustained at high levels throughout the 100 years (Figure 9.10). High output peaks in the simulations correspond to the timing of large storms and resultant removal of simulated vegetation.

Erosion and deposition depths (Table 9.7) approach equilibrium before 50 years in Simulation 'A' and 'B', as noted by a comparison of mean depth of erosion and erosion depth variability (standard deviation) at year 50 and year 100. Between year 50 and year 100 gully bottoms are being raised slowly through deposition. In contrast, Simulation 'C' never reaches an equilibrium of erosion, as indicated by greater depth of erosion, mean erosion depth, and standard deviation after 100 years as compared to 50 years. These results illustrate the effects of the 'm-value', which represents the effect of vegetation on soil, and the associated hydrograph. As the hydrograph peakiness increases over 100 years, flow velocities increase, which in turn lead to sustained vegetation removal and erosion.

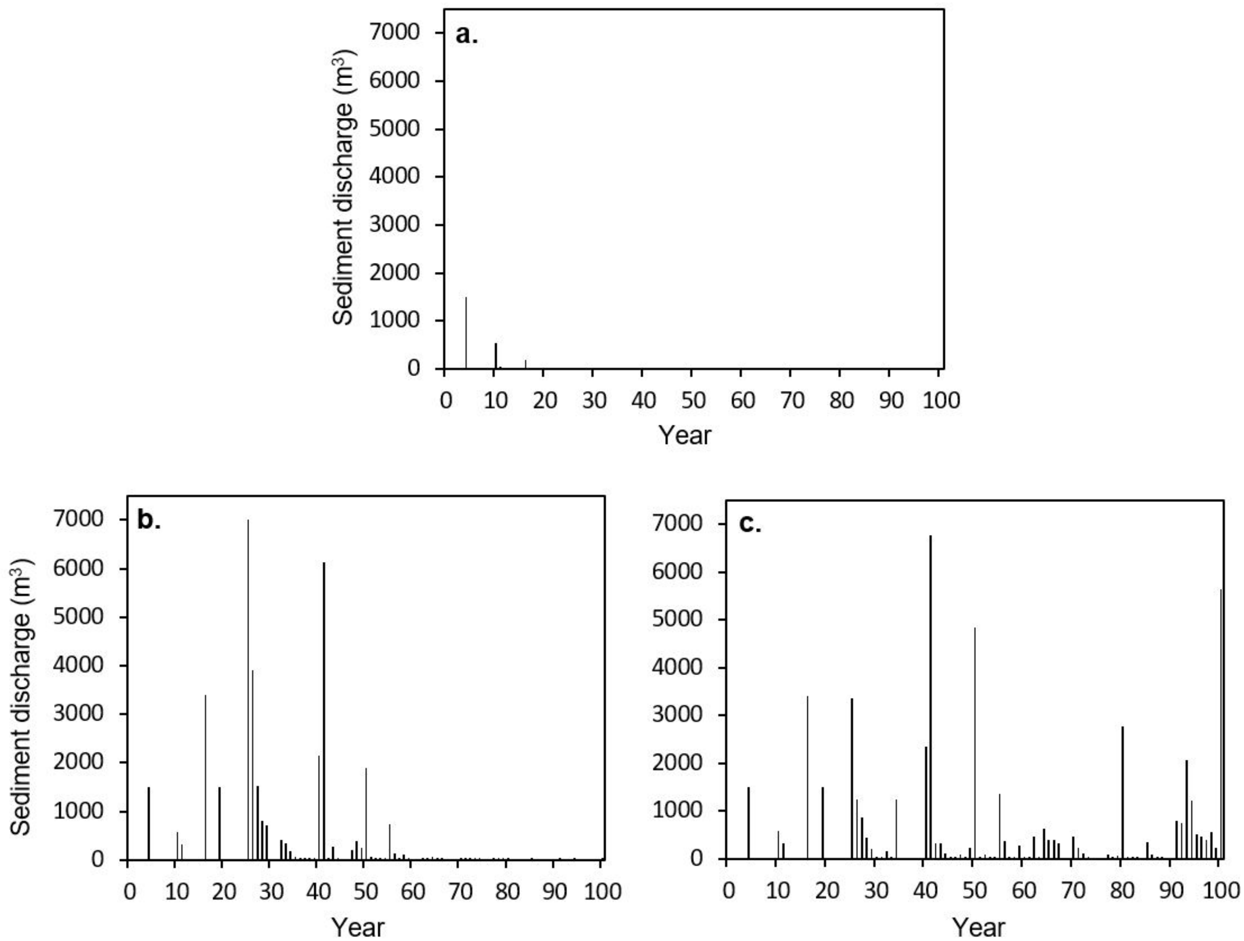

Figure 9.10 Sediment discharge throughout 100-year model: (a) Simulation 'A', (b) Simulation 'B', and (c) Simulation 'C'.

The maximum depth of erosion is along the centerline of the two gullies formed, while maximum deposition is at the base of the dam in the channel used to collect and transport water from the dam and eroded sediment (Figure 9.8).

While greater storm intensity and precipitation depth associated with climate change in Simulation 'B' does lead to increased erosion, continuous increased erosion rates are produced by the gradual decrease in the model's "m-value", which represents the effect of vegetation on soil, and the associated hydrograph. As the hydrograph peakiness increases over 100 years, flow velocities increase, which in turn lead to continued vegetation removal and erosion.

Table 9.7 Depth of erosion minimums, maximums, means, and standard deviations on dam section after 50 and 100 years (in meters). Negative values represent deposition.

	T = 0	T = 50 years			T = 100 years		
		Simulation 'A'	Simulation 'B'	Simulation 'C'	Simulation 'A'	Simulation 'B'	Simulation 'C'
Minimum	0	-3.69	-3.06	-3.06	-3.66	-3.05	-3.05
Maximum	0	6.56	15.92	12.23	6.43	16.14	15.71
Mean	0	0.03	0.12	0.11	0.03	0.12	0.14
Std. Dev.	0	0.37	0.98	0.84	0.37	1.00	1.45

Due to a lack of measured runoff data from the field, it was impossible to compare model discharge to actual discharge. However, equation (1) for average annual discharge can be used and compared to the model discharge.

$$Q = C_r RA \tag{9.1}$$

Note that C_r is a unitless runoff coefficient, R is the average annual rainfall in meters, and A is the catchment area. Sawatsky, Dick, Ekanayke, and Cooper (1996) ran field experiments on an AOS sand tailings dam by applying simulated rainfall events to new and reclaimed (up to 25 years old) reclamation plots while measuring discharge. The range of runoff coefficients calculated from measured data (0.01 - 0.33) (Sawatsky, et al., 1996) corresponds to the range listed in Alberta Transportation (2003a) for sandy pasture and cultivated rows (0.05 - 0.40) (Alberta Transportation, 2003a) which is most similar to the dam section conditions. Using equation (9.1), the overlapping C_r range of 0.05 - 0.33, mean annual rainfall for historic dataset and climate change dataset, and the catchment area, produced a discharge range for each parameter set that was compared to the model discharge outputs. Average annual discharge predicted by CAESAR-Lisflood for all simulations fell within the range given by equation (9.1) for the first 20 years of modelling, with Simulation 'A' generating higher rates than 'B' or 'C', likely due to increased evaporation in the latter two (Table 9.8). Over the complete 100-year simulation, the average annual discharge for Simulation 'A' exceeded the equation (9.1) maximum, but the increased evaporation in Simulation 'B' reduced discharge in comparison to within the equation (9.1) range. The steadily increasing soil transmissivity included in Simulation 'C' lead to very high discharge rates as compared to both of the other simulations.

Table 9.8 Water discharge predictions for a 1 km dam section using Equation (9.1) compared to those from CAESAR-Lisflood (C-L) for the three simulations over the first 20 and 100 years.

Time range	**Average annual discharge prediction (m^3 year^{-1})**					
	Simulation 'A'		Simulation 'B'		Simulation 'C'	
	Eq. (1)	C-L	Eq. (1)	C-L	Eq. (1)	C-L
0 – 20 years	28,746 to 189,724	57,673	28,852 to 190,370	40,781	28,852 to 190,370	40,781
0 – 100 years	28,746 to 189,724	208,818	28,852 to 190,370	163,738	28,852 to 190,370	275,370

9.6 Discussion

Climate change is a global issue, and the full effects of altered hydrologic cycles and temperature regimes on sensitive reclaimed landscapes is not yet fully understood. Current global best practices for reclamation of tailings dams include a design life in excess of 1000 years (ICOLD, 2013), which necessitates an understanding of how climate change may impact reclaimed tailings dams. Long-term landform design requirements associated with dam erosion include stability (retention of contents), sedimentation distance, and downstream water quality due to sediment loading; each of which are discussed herein.

9.6.1 Landform geomorphology

Landform and hillslope geomorphology is altered through precipitation intensity, air temperature, soil mineralogy and geochemistry, and vegetation. In this study, climate projections were used to generate a 100-year precipitation data set extending to the year 2100 for the mining region north of Fort McMurray, and in conjunction with projected vegetation composition, a 100-year m-value data set representative of vegetation and soil changes over the same timeframe. These three data sets, in addition to a projected average evaporation rate over the next 100 years, represent the parameters impacted by climate change within the CAESAR-Lisflood LEM. The climate change data sets were run alongside historic parameters in order to learn what impacts climate change effects might have on the design and reclamation of tailings dams.

The simulated landform and hillslope were evaluated with respect to their initial geomorphic features and those following 100 years of simulation. While qualitative assessment showed much larger gully formation using both types of climate change parameters compared to historic parameters, quantitatively there were only slight differences between the three after 100 years of simulation. Dam slope cross-sections following 100 years are therefore similar, though much exaggerated in the case of cumulative climate change parameters (Figure 9.8). Hypsometric curves of resultant dam slopes are similar: all indicate the dam slope is in transition after 100 years and additional geomorphic change can be expected although the slope exposed to cumulative climate change effects was slightly more mature (Figure 9.9, Table 9.4).

The soil, vegetation, and climate following 100 years of simulation is vastly different between the three parameter sets, which is reflected in the geomorphic changes noted. While all remain in transition, the climate change parameters led to a greater overall rate of geomorphic change over 100 years compared to the historic parameters, and these changes continued to occur throughout the entire simulation time (for Simulation 'C'), while historic parameters led to significant slowing of geomorphic change earlier in the simulation (Table 9.7, Figure 9.8). When Simulation 'B' and 'C' are compared it is clear that vegetation migration (as represented by the m-value) has a strong effect on long-term erosion. Simulating the cumulative effects of climate change produce different results than simulating temperature (evaporation rate) and precipitation changes only. This has repercussions for those seeking to make predictions about landscape change using landscape evolution models.

Maximum depths of erosion were found along the centerline of the gullies formed, initiated through development of concentrated flow along selected portions of the dam slope. This corresponds to field observation of gully causation. Maximum depth of deposition universally occurred in the channel at the base of the dam, where gullies deposited their sediment loads. The channel is roughly 40 m wide by 3 m deep and was blocked off with sediment at various times throughout all simulations (Figure 9.8), but more quickly with the climate change simulations. These channels collect and transport potentially contaminated seepage water and runoff to treatment facilities downstream, while creating and drainage divide between the dam and the natural environment. These findings suggest that the ongoing maintenance and clearing of these channels is likely to be required for a longer timeframe, and more frequently with climate change as modelled compared to those in the past.

In consideration of climate change, this study suggests that sand tailings dams in the oil sands are likely to continuously erode and become more geomorphically stable/mature for the timeframe of this study. Due to the confidence levels of present climate change projections, this study was conducted for a simulation time of 100 years, or roughly to the year 2100; however, running the simulation for longer timeframes (i.e. 1000 years) is likely to produce more defined long-term landform morphology. As the use of LEMs in mine closure design and planning grows, an understanding of climate inputs and cumulative effects contributing to geomorphology will be beneficial.

9.6.2 Erosion rates and patterns

Tailings dams are intended to impound contaminated and potentially toxic materials for a minimum of 1000 years (ICOLD, 2013). Design of erosion-resilient dams is one aspect of the planning process in order to achieve this target, and due diligence entails evaluation of how climate change might affect tailings dam erosion and sedimentation regimes.

Hancock et al (2009) and Coulthard and Van de Wiel (2007) demonstrated that increased rainfall and storm intensity did not affect the geomorphology or total sediment discharge of a catchment over 1000 years. It is less clear how the cumulative effects of increased rainfall and evaporation rates, as well as climate-induced alterations to vegetation and soil properties, will affect tailings dam geomorphology and sediment discharge. This is the first study to look at cumulative effects of climate change on geomorphology at a hillslope scale.

Sediment output from Simulation 'A' over 100 years leads to a decline in sediment discharge from high to a stabilized low (Figure 9.10), as is typical of most simulations, with highs generally (but not always) corresponding to heavy rainfall events. This variability is reflective of the non-linearity of several processes inherent in fluvial systems and captured by the CAESAR-Lisflood LEM (Lane et al., 2007). In contrast, Simulation 'C' produces no clear decline in sediment discharge over 100 years (Figure 9.10). Hancock (2009) and others found that increased magnitude and intensity of rainfall, as in Simulation 'B', increases sediment transport rates, as has been confirmed here. As compared to Simulation 'A', an increase in storm intensity increased sediment discharge and delayed the landform from reaching equilibrium, while the addition of a decreasing m-value increased sediment discharge and also inhibited the landform from ever reaching an equilibrium. Evaluation of cumulative soil loss from the dam slope (Figure 9.11) confirms no such stabilization tendency in Simulation 'C', while Simulations 'A' and 'B' both reach a stabilized form within the simulated timeframe. This is reflected in the total sediment discharge being more than 10 times greater for Simulation 'C' as compared to Simulation 'A'.

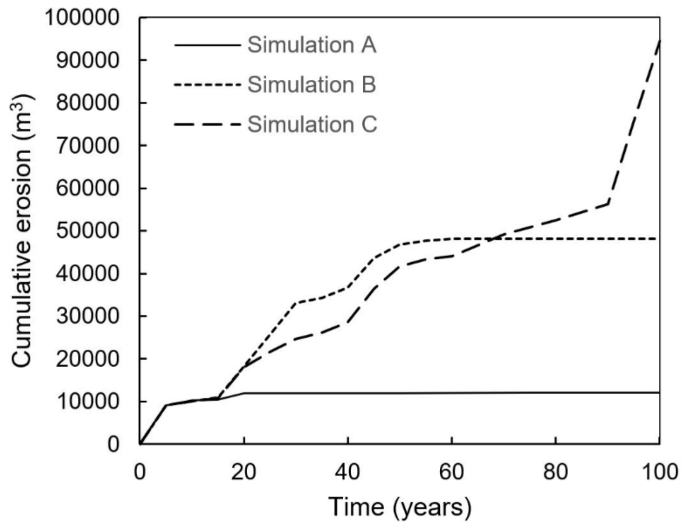

Figure 9.11 Cumulative soil loss (eroded volume) from dam slope over 100 years of simulation.

Average erosion rates predicted using the model are similar to those measured providing confidence in the model outputs. The model results show an average soil loss rate of 41 and 42 tonnes ha^{-1} year^{-1} for the first ten years of Simulations 'A', 'B', and 'C', respectively. These rates compare well to the rate of soil loss previously measured from the dam using LiDAR field data roughly 48.5 tonnes ha^{-1} year^{-1} (Slingerland, Sommerville, O'Leary, & Beier, 2018). After ten years Simulation 'A' reduces to less than 3 tonnes ha^{-1} year^{-1}; Simulation 'B' does so after 50 years, and Simulation 'C' continues to erode at a rate of 0.5 - 15 tonnes ha^{-1} year^{-1} over the full 100 years. Erosion of newly constructed landforms is generally higher than that of mature landforms, as climate sculpts the land towards an equilibrium. While climate itself is becoming more erosive and land is becoming more erodible over time, it follows that the land will continuously seek a balance. As such, predicted values compare well with measured rates, and the outputs for both dam section models over the long term are logical.

Off-site sediment loading can have detrimental effects on the downstream environment. While this was not the core goal of the study, sediment discharge rates from the bottom channel were predicted by the CAESAR-Lisflood model. Short-term predictions (i.e. 20 years) fit within the range of values calculated from Equation (9.1), but predictions made for longer timeframes (100 years) were well outside the range for two of three simulations (Table 9.8). This is possibly due to the runoff coefficients being calculated under past climate conditions and from short-term measurements. Aside from sediment load, water quality is not assessed in this study, nor is CAESAR-Lisflood presently capable of such predictions.

9.6.3 Implications with respect to the dam delicensing strategy

With respect to topographic change, this study found qualitative differences between predictions made with historic parameters and those made with climate change parameters, but little difference in terms of quantitative geomorphic indicators or metrics. In all scenarios the dam slope remains in transition after 100 years of simulated erosion. Evaluation of soil loss is perhaps a more meaningful comparison as this corresponds to future maintenance on the landform and ongoing water treatment monitoring such that downstream waterbodies are protected. When comparing the total quantity of soil eroded from the dam (Table 9.5) with the total quantity of sediment discharged out of the channel (Figure 9.9), it is determined that over 40,000 m^3, 13,000 m^3, and nearly 10,000 m^3 of soil is deposited in the channel (with Simulations 'C', 'B', and 'A', respectively. This is illustrated in Figure 9.8 and suggests that post-closure planning take into consideration (1) more maintenance in the short term and (2) an extended period of maintenance and monitoring in consideration of cumulative climate change effects on sand tailings dams. Life of Mine plans for each AOS mine were submitted in 2016, and the majority estimate a period of 20 years for active and passive care phases. This research predicts that given the cumulative effects of climate change on dam erosion, the time to reach equilibrium may be in excess of 100 years. In this sense, dam delicensing and reclamation certification may take much longer than anticipated, and an alternate approach to reclamation may be preferable. Progressive reclamation throughout the mine life could reduce the post-closure maintenance period.

In view of the elongated period of erosion with climate change parameters, mitigation methods such as creating a surface with a broader grain size distribution and early establishment of large shrub species may help to reduce ongoing erosion and are an opportunity for further research. Establishment of diverse forest vegetation with broad geographic zones may provide continued erosion mitigation benefits for a future climate, as compared to more narrowly-zoned local species. Additionally, considering the mine life is quite small relative to the time required to fully reclaim a dam to a (portion of a) landform, this provides support for the concept of designing a dam for closure prior to mining, and investigation into slopes shaped more in-line with stable landforms of similar materials in local context. Additional research is required in this area to fully understand the ramifications both during the active dam life and thereafter.

9.7 Conclusions

Climate change has caused more frequent and extreme precipitation events, flooding, and rising temperatures globally. Climate change models are updated periodically and emissions projections are translated into changes in the hydrologic cycle, future temperature regimes, and other secondary effects. Landscape evolution models have previously been used to model hydrologic changes from the past and for the future, but future predictions regularly use historic climate inputs. The CAESAR-Lisflood LEM is presently the most appropriate model for evaluating these effects due to the direct input of precipitation data at a sub-daily scale, capturing changes in intensity and therefore erosion, transport, and deposition trends.

This work looked at the impact of climate change representation in the assessment of soil loss, transport, and hillslope morphology. This type of study is particularly relevant to tailings dams as their sediments can be detrimental to downstream environments, and their ability to contain tailings is reliant on long-term geomorphic stability. CAESAR-Lisflood's ability to alter soil transmissivity/forest cover with time is an advantage in modelling future climate; however, its ability to do this type of work could be improved by integrating temporally variable evaporation rates, and the option for more than one soil type, as reclaimed environments are often designed with a reclamation soil layer quite different from their underlying substrate.

In particular, this study compared the effect of three different climate parameterizations on erosion rates over 100 years from a 1-km stretch of tailings dam: Simulation 'A' assumed precipitation patterns, vegetation coverage/soil transmissivity, and evaporation rates remained constant over time, Simulation 'B' altered temperature and evaporation in line with the IPCC's RCP 8.5 scenario, while Simulation 'C' included altered temperature and evaporation in line with 'B' while also decreasing forest coverage (as projected). Results showed that CAESAR-Lisflood was sensitive to changes in these parameters, particularly in the m-parameter representing forest coverage and corresponding to soil transmissivity. Simulation 'A' lead to an equilibrium point in dam stability following roughly 20 years, Simulation 'B' produced high erosion followed by stability within roughly 50 years, while Simulation 'C' lead to continued high erosion over 100 years. Qualitatively, all slopes are not yet at an "old age" of maturity and corresponding stability of form by the year 100, but the model showed slightly greater maturity was achieved by the Simulation 'C' than the others.

Vegetation plays a strong role in erosion mitigation and prevention, as confirmed through this study and Simulation 'C' in particular. While other studies have noted little impact on sediment transport and soil loss due to increased rainfall intensity, this study demonstrated marked increases. Caution should be taken in interpreting these results, as this is a baseline study and the full effects of future climate (increasing forest fire frequency, decreasing snow melt volume, etc.) have not been integrated into the model at this time.

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10.0 Dam erosion mitigation and stress testing

10.1 Introduction

In Chapter Eight and nine the external tailings storage facility (TSF), including geomorphic design for the former pond area, was run through the landscape evolution model CAESAR-Lisflood. The simulations were run for both the entire TSF at low resolution and a 1-km dam section at high resolution. It was observed that the geomorphic changes that occurred throughout 100 and 200 years of simulation were substantially more pronounced on the dam than on the landform-graded former pond area. This tells us that over long time frames, the relatively steep slopes of the dam itself are at a greater risk of erosion than the re-graded pond core. This dam evaluated in the previous chapters had gone through the "short term dam design process prior to construction, meeting all requirements. However, when the dam was subjected to landscape evolution modelling (long-term testing) using the proposed methodology in Chapter Seven (Figure 7.3) it, demonstrably, would not meet long-term requirements due to excessive erosion and deep gullies that potentially compromise dam stability. This dam does not meet long-term targets of sustainability as it has maintenance requirements in excess of natural local terrain well into the future.

Surficial design of dam slopes has changed over the years: Originally little thought was given to erosion and dams were shaped for stability and ease of construction. This was followed by a stage when engineers sought to capture and control the flow of water on a tailings dam. The most recent "geomorphic design" stage is in its infancy and stems from the observation that geomorphic processes have been more powerful than engineered mitigation methods to date, therefore a more naturally shaped dam should inherently be less susceptible to erosion, mass wasting, and require less maintenance (DePriest, Hopkinson, Quaranta, Michael, & Ziemkiewicz, 2015).

A single constant gradient along the entire downstream slope was (and continues to be) used; however, this method was found to produce excessive erosion and USLE-type methods of reduction became attractive. The platform-bank method is one such approach that has also been used for decades: the downstream dam slope is broken into a series of shorter slope lengths, interspersed with a bench (bank) sloping into the dam to catch water and prevent excess overland flow length (note there are many variations on this basic platform-bank model). This approach requires constant monitoring, maintenance, and has been found to fail when water reaches a low point or area of reduced compaction along a bank or overtops the bank. These two approaches are still used today despite their known weaknesses. The newest approach is to shape the dam surface into a 'catena' form, or an 'S' curve with a convex top and an elongated concave base. This mature landform shape is more consistent with what natural forces would generate in the untouched environment over long time frames. Today this last approach is rarely used, but is thought to provide a more stable result while also achieving some social closure goals.

Closure works for tailings ponds rarely include any changes to the downstream dam slopes. This is because (1) slope stability is a concern, (2) reshaping involves significant earth movement at high cost, traditionally nearing the end of mine life when revenue generation is low, and (3) oil sands tailings ponds are often located adjacent to site boundaries or mining pits such that the land area is not available for re-shaping their dam, reducing slopes, etc. Where the design methods outlined in Chapter seven, Figure 7.3 are used, the dam would be designed and constructed from the beginning with the final stable topography, eliminating point (2) above.

The modelling and site measurements conducted thus far have found no minimum slope for which a CST dam becomes erosion-free, and in many instances elongating the downstream dam to reduce the slope is not possible; it is therefore of interest whether a different shape would be beneficial. The results from Chapters eight and nine suggest that erosion mitigation methods and alternate designs are worthy of reconsideration for long-term stability. This chapter seeks to assess the geomorphic performance of several different historic and hypothetical dam designs using CAESAR-Lisflood (Coulthard, 2017).

10.2 Methods

The methods used in this section are similar to those used in preparing and running the simulations discussed in Chapter five. The goal of simulation in this case was to determine how each fictional dam design would respond to extreme precipitation events, and which was most stable over time. As such, the models were fitted with parameters for the Athabasca oil sands as completed previously, but the precipitation inputs were very extreme over a 50-year time period. This length of simulation was determined based on the time it took for TSF and dam simulations (with the exception of simulations using climate change projections) to reach a steady erosion rate.

Results were assessed qualitatively and quantitatively with respect to geomorphology. Other results generated by CAESAR-Lisflood including water and suspended sediment discharge were considered extraneous with respect to the objectives.

10.2.1 Digital elevation models

Five different dam designs were simulated, requiring five surficial topography DEMs and five DEMs representative of the limit of erosion, or “bedrock DEMs”. Designs were drawn and converted into .dem files using AutoCAD Civil3D version R21.0.52.0.0 (Autodesk Inc., 2016), then trimmed, re-sampled to a 500 x 500 m grid of 1 m cells, and converted to ACSII (.txt) format using ArcGIS ArcMap (version 10.4.1). Cross-sections for the dam designs are shown in Figure 10.1 and DEMs are shown in Figure 10.2.

The five dam designs created all have a channel running along the base of the dam and are 60 m tall from channel base to crest height. The channels are 5 m deep and 44 m wide at the base with 25% side slopes. The designs include:

1. Constant slope
2. Platform-bank
3. Catena
4. Horizontal wave with directed flow over a catena-shaped swale
5. Horizontal wave with directed flow over an armoured catena-shaped swale

The ‘constant slope’ base case was constructed with a 7H:1V slope across the entire 500 m width, giving a constant cross-section. The ‘platform-bank’ design has the same overall slope as the base case, but is broken up via several 6 m deep benches tilted back into the dam; this design also has a universal cross-section across the entire 500 m width. The ‘catena’ design has more geomorphically mature shape relative to the first two designs. ‘Catena’ has an elongate ‘s-curve’ cross-section where the upper portion in rather abrupt while the bottom are is elongated to extend the area of deposition prior to the basal channel. This option is likely more difficult to construct, but present day technologies including GPS guidance for heavy equipment, rounded landforms like the 'catena' shape are becoming more practical. This option has a constant cross-section across the full width as the first two option do.

'Directed flow' and 'armoured directed flow' surface topography was created by merging the 'constant slope' contour signature on the edges with the 'catena' contour signature at the center in a smooth and continuous manner. This created a dispersive flow path on the outside of the curve and a concentrated flow path on the inside.

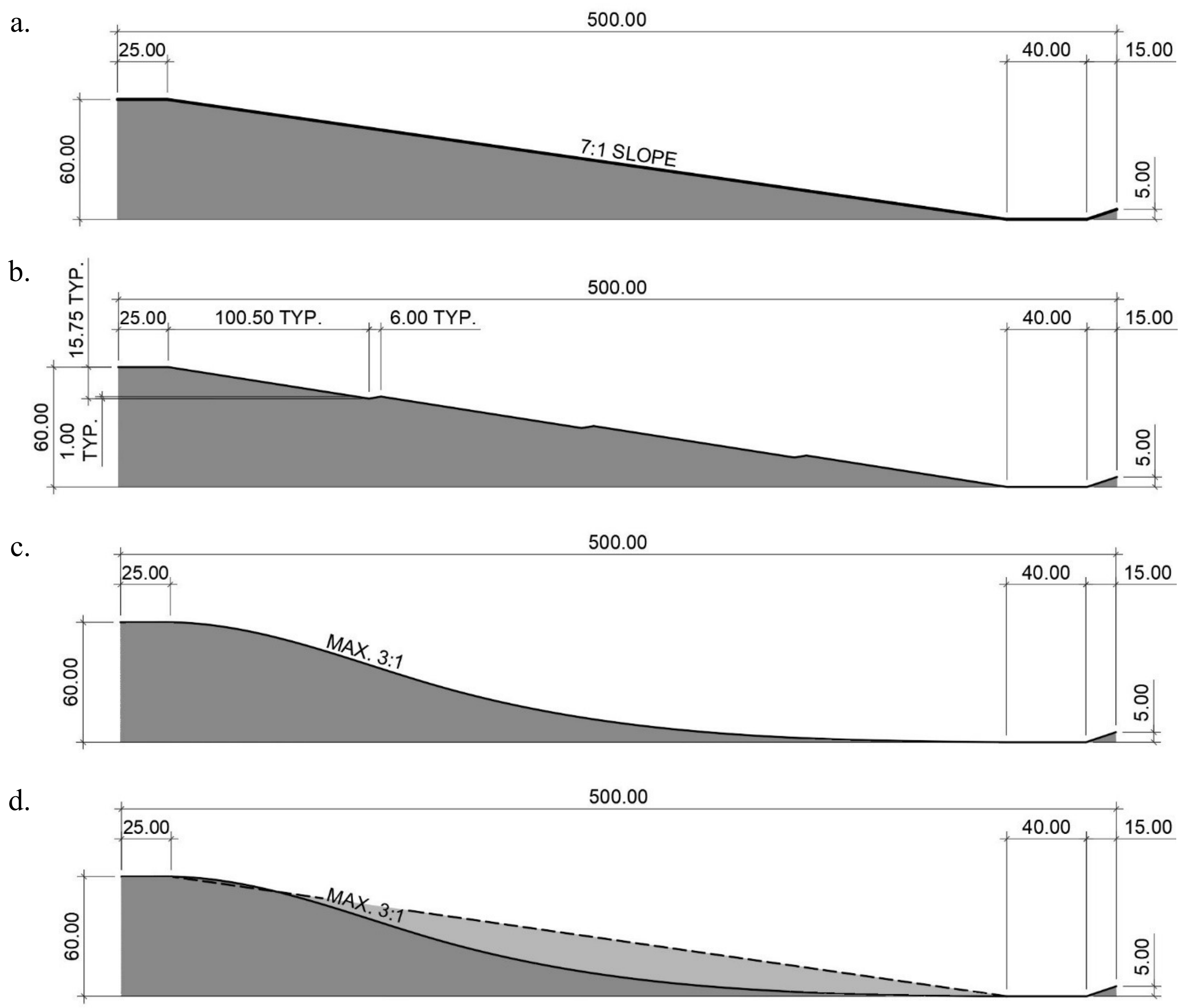

Figure 10.1 Cross-sections through centreline of dam designs: (a) constant slope, (b) platform-bank, (c) catena, (d) directed flow and armoured directed flow (with dashed line showing cross section at edges). All dimensions in meters, slopes H:V.

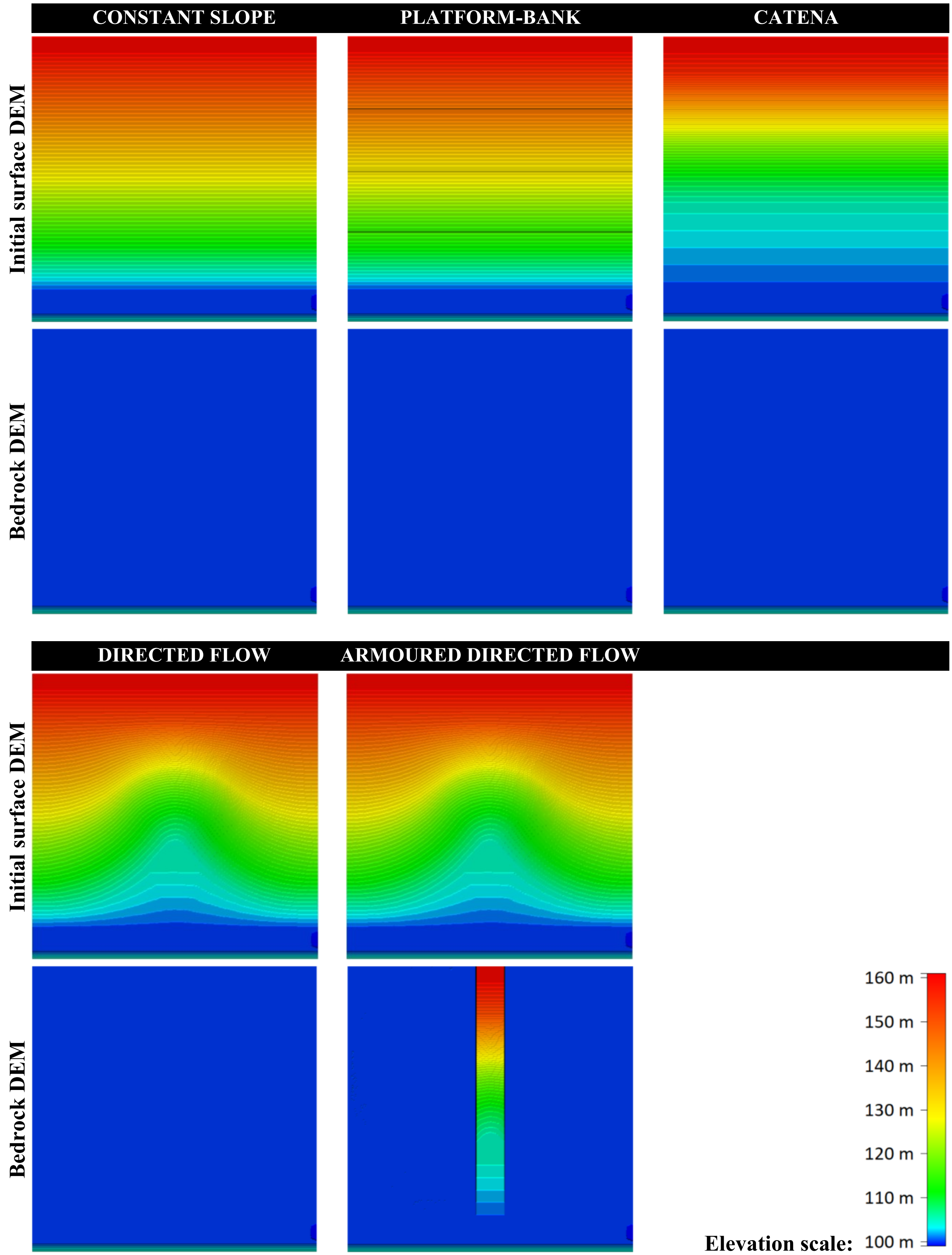

Figure 10.2 Surficial topography DEMs and bedrock DEMs (500 x 500 m each) for the five dam designs simulated.

Dam designs one through four each included a “bedrock DEM” that maintained the elevation of the channel base beneath the dam, such that the maximum extent of erosion was to the channel elevation. Dam design five used the “bedrock DEM” to simulate armouring since only one grain size distribution is permitted in CAESAR-Lisflood. In reality, rip rap (medium-sized rock) would be placed in this area. By raising the “bedrock DEM” to the surface elevation for a 50 m wide stretch along the central swale, no erosion was permitted down the center of the swale.

10.2.2 Grain size distribution

The same grain size distribution as described in section 8.2.2 was used in these simulations.

10.2.3 Precipitation record

Catchment mode was used for these simulations, and the same 100-year hourly precipitation file (adjusted for winter conditions, snow melt, statistical storms inserted) as described in section 8.2.3 was used here. The second half of the 100-year record was removed to make a 50-year record. Next the 24-hour probable maximum precipitation (PMP) event for the Fort McMurray ‘A’ climate station (ID: 3062693) was applied using a triple-peak distribution (Dick & Ghavasieh, 2015) as shown in Figure 10.3. PMP events (24-hour) were added every five years immediately following spring snow melt, beginning in year one. PMP events were therefore applied to the DEM in years 1, 6, 11, 16, 21, 26, 31, 36, 41, and 46. This method was not meant to simulate probable conditions, but to bombard the dam sections and monitor simulated response.

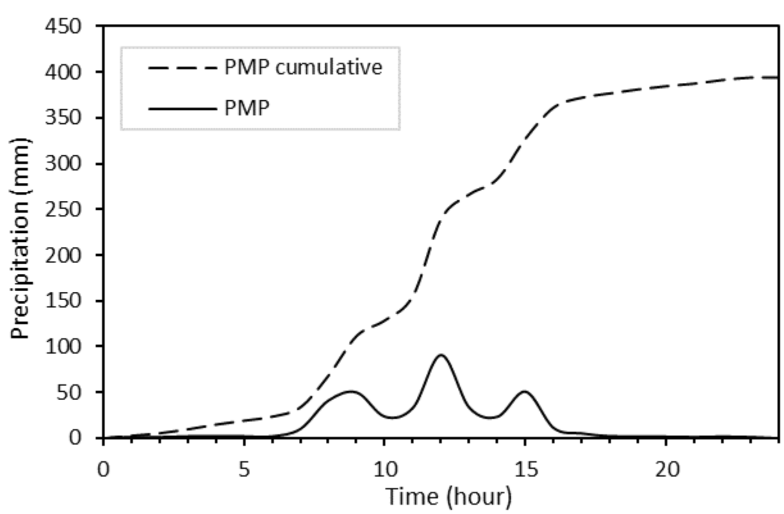

Figure 10.3 Hyetograph for historic 24-hour PMP at Fort McMurray ‘A’ climate station (ID: 3062693)

10.2.4 Parameterization

As discussed in Chapters Seven, Eight, and Nine, a number of parameters are required such that model calculations are refined. These parameters are discussed and listed below.

10.2.4.1 Sediment

The sediment parameters used are outlined in Table 10.1.

Table 10.1 Sediment tab parameters

Parameter		Recommended Value (if any)	Value used	Notes / justification
	Bedrock erosion threshold	-	0 Pa	N/A
	Bedrock erosion rate		0 m/Pa/yr	N/A
	Suspended sediment? (y/n)		yes	
v_f	Fall velocity for suspended sediment	-	0.004398 m/s	Calculated for finest fraction (average particle size of 75 microns) using Stokes' Law
	Maximum velocity used to calculate Tau on steep slopes	Default: 5 m/s	5 m/s	N/A
ΔZ_{max}	Maximum erode limit	0.02 m. DEMs with cells < 10 m should be set at 0.01 m. Increase with cell size.	0.01 m	
L_h	Active layer thickness	0.1 to 0.2 m. At least 4 times the maximum erode limit.	0.1 m	Lower depth suitable for DEM sizes used
λ	In-channel lateral erosion rate	Typical values are 10 - 20 for most river types (larger for wide, lower for narrow).	20	Due to the physical, non-cohesive nature of CST, the highest typical value was used.
	Lateral erosion (L.E.) included? y/n	-	no	This parameter is most applicable to reach mode: waterways with constant flow.
Λ	If L.E.=Yes. Lateral erosion rate	Braided rivers: 0.01 - 0.001 (typ.) Meandering channels or channels with little lateral erosion: 0.0001	undefined	N/A
N_{smooth}	If L.E.=Yes, Number of passes for edge smoothing filter	-	undefined	N/A
N_{shift}	If L.E.=Yes, Number of cells to shift lateral erosion downstream	-	undefined	N/A

ΔV_{max}	If L.E.=Yes, Max. difference allowed in cross channel smoothing	-	Undefined	N/A

10.2.4.2 Hydrology

The hydrology parameters are listed in Table 10.2.

Table 10.2 Hydrology parameters

Parameter		Recommended Value (if any)	Value used	Notes / justification
	Rainfall data file time step	60 minutes	60 minutes	
m	m-value	0.005 to 0.02. May be calibrated using storm hydrograph. Values have been chosen from relative forest cover across value range.	0.01	As discussed in Section 5.2.4.2, a value of 0.01 is estimated based on reclamation vegetation coverage.

10.2.4.3 Vegetation

Vegetation parameters (vegetation critical shear, years to grass maturity, and proportion of erosion that can occur when vegetation is fully grown) are consistent with those outlined in Table 8.5.

10.2.4.4 Slope processes

Slope processes remain consistent with those used in the 100 and 1000-year simulations in Chapter Eight and Nine; they are listed in Table 10.3 for clarity.

Table 10.3 Slope processes parameters

Parameters		Recommended Value (if any)	Value used	Notes / justification
C_{rate}	Creep rate	Typical value is 0.0025	0.0025 m/yr	Not measured due to time requirements and constant site activity. Minimal impact from creep is expected over the relatively short timeframes modelled.
	Slope failure threshold		40°	Slopes viewed in tailings sand on site were measured both steeper and shallower than this median angle.
	Dynamic slope fail angle, varying according to soil saturation? y/n		yes	

E_r	Soil erosion rate		-	This parameter has not yet been tested or calibrated.
	Soil erosion varies according to soil saturation? y/n		yes	

10.2.4.5 Flow model

Parameters used for the flow model tab are outlined in Table 10.4. Due to the high resolution of the DEM, many of the parameters that would normally require calibration were best set at the lowest possible value. The input/output difference was adjusted down based on the expected low flow values in consideration of the drainage area.

Table 10.4 Flow model parameters

Parameters		**Recommended Value (if any)**	**Value used**	**Notes / justification**
Q_{diff}	Input / output difference allowed	Close to the watershed low flow value. Standard value: 1 m^3/s.	0.05 m^3/s	Scaled to drainage area
Q_{min}	Min Q for depth calculation	Historically 0.1 for 10 m cell size, 0.5 for 50 m cell size. This is currently under review and it is presently recommended that Q_{min} remain constant regardless of cell size for the same area.	0.01	
Q_{max}	Max Q for depth calculation	-	1000 m^3/s	Used in reach mode
d_{min}	Water depth threshold over which erosion will happen	Typically 0.01 m. Larger values can be used on cells > 50m, smaller values for higher resolution DEMs.	0.005 m	
S_{edge}	Slope for edge cells	-	0.005	
	Evaporation rate	-	0.0034 m/day	See section 5.3.5 text.

α	Courant number	0.3 to 0.7. Low resolution DEMs (50 m cells) may use larger numbers, high resolution DEMs may use smaller numbers. (Typ. 0.4 for cells 10 m or less)	0.3	
h_{flow}	h_{flow} threshold	Default value is 0.00001 m.	0.00001 m	
Fr	Froude's # flow limit	Default value is 0.8. Values up to 1 may work. Lower values can be used when modelling deep flows (lakes) at fine cell size.	0.8	
n	Manning's n, coefficient of roughness and sinuosity.	None. Calculate or look up values from tables.	0.0345	Uniformity coefficient, C_u, for CST is 1.6, or very well sorted. For uniform sediment, C_u <3: $n = \frac{{d_{50}}^{1/6}}{21.2}$

10.3 Results and discussion

The initial and final surface DEMs are shown graphically in Figure 10.4. Geomorphic changes were assessed both qualitatively and quantitatively over the 50-year simulation period. Since the precipitation applied was meant as a stress-test, the timing is purely relative across the five dams (I.e. dam 'X' reached a near-equilibrium erosion rate sooner than dam 'Y'). Note that these simulations are comparable to a situation where the dams are abandoned.

Model evaluation in Sections 8.5 and 9.5 demonstrated congruence between predicted and measured sediment loss, the size of predicted and measured gullies, and the water discharge predicted versus calculated. As a result, model outputs are considered as a good evidence-based estimation of geomorphology and erosion. The dams simulated in this Chapter are subjected to non-realistic precipitation conditions and therefore the results put forth are not subject to traditional "validation" or "evaluation" by comparison.

10.3.1 Qualitative geomorphology

By visually examining the resultant DEMs, it is observed that all of the dam designs were negatively impacted by the stress test. The ‘platform-bank’ and ‘directed flow’ designs generated a single gully feature that concentrated deposition at a single location in the channel, while the others produced multiple gullies dispersed across the dam slope and correspondingly disbursed soil deposition in the channel. Very deep, isolated gullies can be difficult to repair due to size, but the work is targeted at one location. In contrast, the occurrence of many smaller gullies may be easier to repair but the larger affected area can be more time consuming to repair. While both of these scenarios have unique maintenance challenges, potentially blocking the basal channel via deposition at one point is an added undesirable complication of isolated, deep gullies.

The ‘platform-bank’ design generated deeper gullies than all others, and to a greater elevation than all others other designs, visible in Figure 10.4 and 10.5. The ‘catena’ shape allowed for deposition of eroded sediment on low-lying ground up-slope of the channel, such that the channel did not fill as rapidly but a risk of burying new or young vegetation exists as a result. Gullies are dangerous for a number of reasons on tailings dams, but with respect to geomorphology the greatest threats are due to (1) erosion of the cap/cover such that atmospheric exposure of tailings occurs and (2) erosion to an extent that the geotechnical stability of the dam itself is compromised. The former can occur as a result of any gully that extends deeper than the cap thickness, while the latter is more likely when a single large gully is generated. Proposed covers for tailings dams in the AOS range between 0.3 and 0.5 m of reclamation material or cover soil / sub soil combination.

The ‘directed flow’ and the ‘armoured directed flow’ designs were nearly identical in appearance initially, but the final results are visually quite different: the false armouring had the intended effect of inhibiting a large central gully from forming, as developed in the ‘directed flow’ design, but gullies formed over the rest of the structure and along the side of the false armouring. It is likely that this method of simulating armouring is deficient as it has the knock-on effect of also raising the water table to the surface; however, it is of interest that similar instances have been found in the field whereby surface water simply runs along side the armour, eroding an adjacent path. This highlights the dominant role that initial landform topographic / grading design holds, and secondarily the importance of proper sizing of the rock armour / rip rap used.

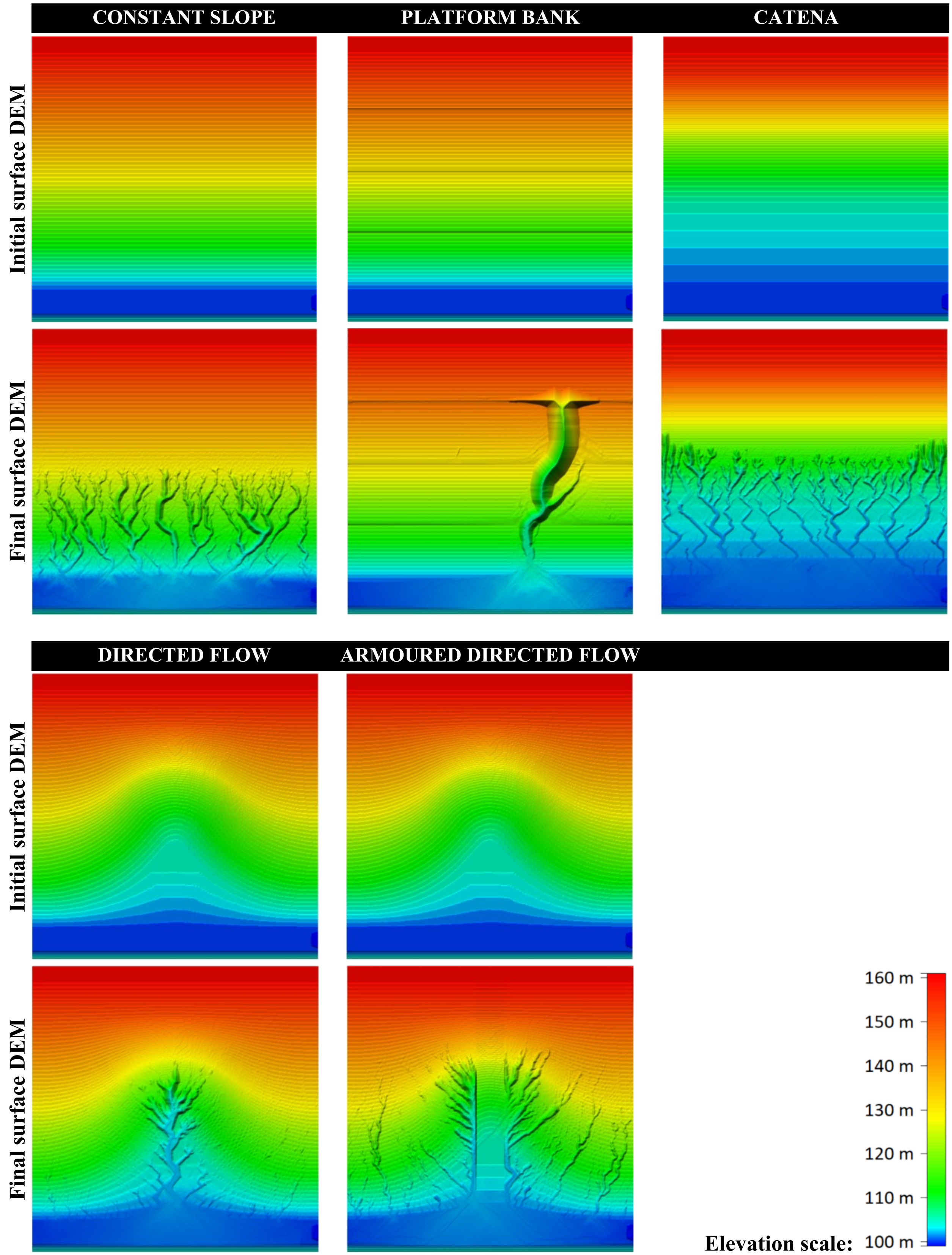

Figure 10.4 Initial and final DEMs illustrating the five dam surface designs. Each DEM has dimensions of 500 x 500 m.

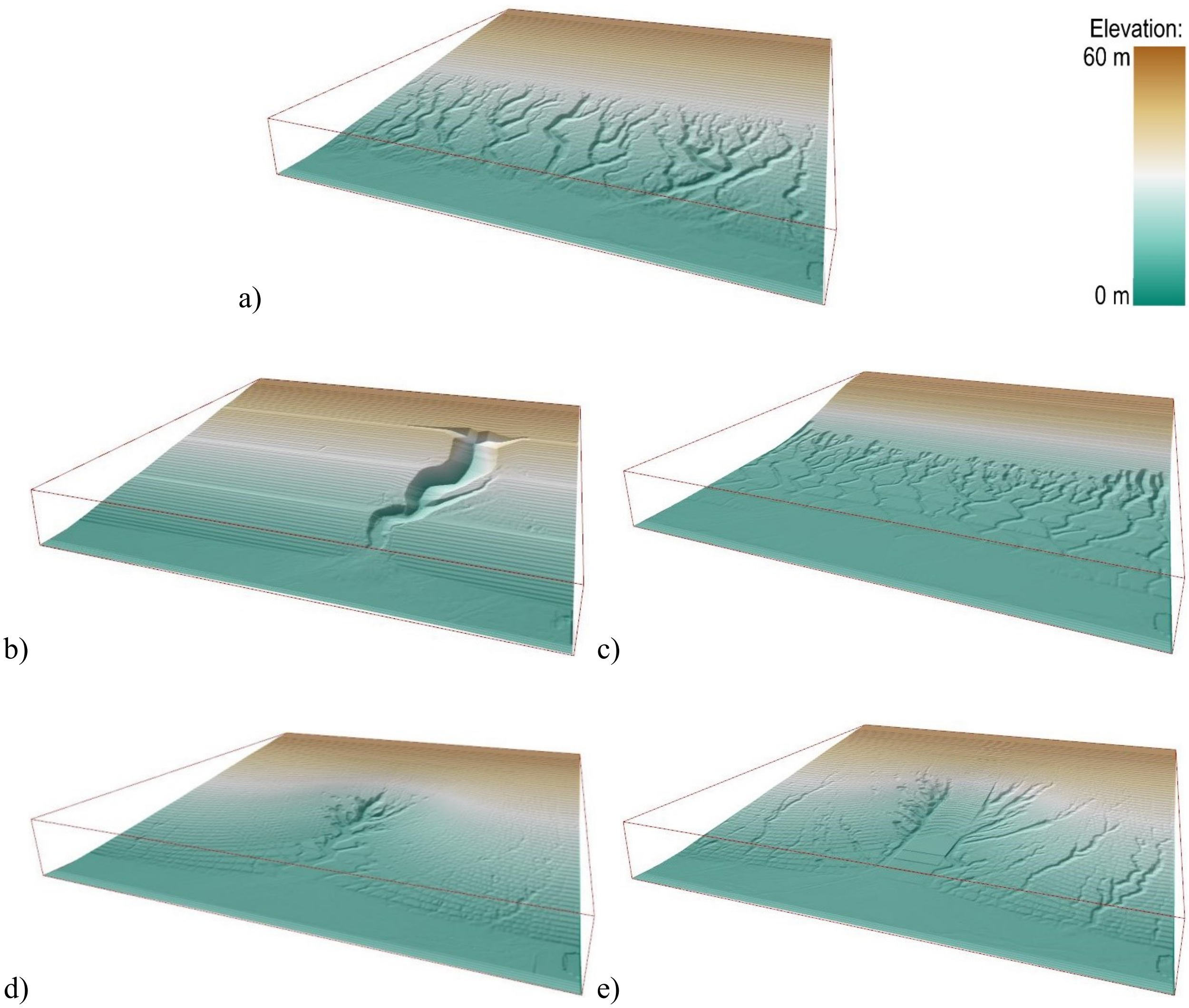

Figure 10.5 Dam designs following stress testing. Shown in three-dimensions (with colour ramp representing elevation): a) constant slope, b) platform-bank, c) catena, d) directed flow, and e) armoured directed flow.

10.3.2 Quantitative geomorphology

Geomorphic descriptors were used to quantify the relative maturity of each dam slope and the amount of change that took place during the stress testing. The hypsometric integral is used as a measure of maturity, with lower values corresponding to more mature landforms than higher values (Table 10.5). Mean elevation is used as a more general descriptor of change. The most mature landform was the ‘catena’ dam, since the majority of the slope is at a low elevation relative to the total height difference. The ‘directed flow’ dam, while more youthful according to the hypsometric integral (HI), underwent the least change in terms of HI and mean elevation over the course of the simulation, suggesting it is more stable than the others. The ‘‘platform-bank’’ dam underwent the greatest change in HI and mean elevation, suggesting that this form is the least stable.

Table 10.5 Geomorphic descriptors for trial dam section. Units for mean elevation are in meters.

	Constant slope		Platform-bank		Catena		Geomorphic		Armoured geomorphic	
T=	0 y	50 y	0 y	50 y	0 y	50 y	0 y	50 y	0 y	50 y
Hypsometric Integral (HI)	0.475	0.472	0.474	0.464	0.346	0.343	0.421	0.420	0.421	0.419
Mean Elevation	128.5	128.3	128.4	128.0	120.4	120.3	125.1	125.1	125.1	125.0

Elevation change was evaluated for the designs such that the dam and the bottom channel were separated for individual analysis (Table 10.6). With respect to the dams, the 'platform-bank' design generated the greatest gully depth; however, this feature acted as a drain for the rest of the dam producing little erosion elsewhere and leading to a focussed hazard area. This deep and largely localized erosion is evident in the comparatively large standard deviation of elevation changes and mean elevation change for the dam. As might be expected, this erosional feature produced a large deposition fan at its base and within the channel, as illustrated in Figure 10.4 and quantified in Table 10.6.

Despite use of the 'platform-bank' design to prevent erosion previously observed on 'constant slope' type dams, the 'constant slope' design generated a shallower maximum depth of erosion and only about half the sediment loss in comparison. The 'constant slope' dam had the second largest standard deviation of elevation changes made, and a mean elevation change of 0.17 m, which is consistent with the widespread gullying seen in Figure 10.4. This widespread gullying resulted in the second largest 'maximum depth of deposition' and 'mean elevation change' in the channel.

Erosion patterns were visually similar between the 'constant slope' and the 'catena' designs. While the gully heads reached a higher elevation on the 'constant slope' design, the gully depth was deeper in the 'catena' dam. Less soil (volume) was removed from the 'catena' dam compared to the 'constant slope' dam. Much of the eroded soil was stabilized at lower elevations before reaching the channel, therefore while the statistics for the two dams are similar (Table 10.6), the channel statistics for the 'catena' design show less overall (mean) loading and a maximum depth of deposition less than half that of the ‘constant slope’ design. As previously mentioned, this may have ramifications for the low-elevation vegetation in terms of burial and success rates, but it also means that channel maintenance for this option is likely lower than for that of the ‘constant slope’ dam.

Table 10.6 Summary of elevation changes (erosion and deposition) on the dam slopes and in the channels at the bottom of the dams. Units are in meters unless otherwise indicated.

	Constant slope	Platform-bank	Catena	Geomorphic	Armoured geomorphic
Dam slope					
Maximum depth of erosion	7.45	23.78	7.64	9.88	9.55
Total soil loss (m^3)	71,840	132,030	57,830	29,990	48,078
Mean elevation change	-0.17	-0.37	-0.15	-0.05	-0.10
Standard deviation of elevation changes	0.98	2.65	0.79	0.68	0.81
Bottom channel					
Maximum depth of deposition	2.43	3.79	1.13	1.55	1.85
Total soil added (m^3)	28,830	39,110	19,350	16,380	23,640
Mean elevation change	+0.68	+0.92	+0.46	+0.39	+0.56
Standard deviation of elevation changes	0.77	0.95	0.39	0.46	0.59

The ‘geomorphic’ and ‘armoured geomorphic’ designs performed quantitatively quite differently from one another. The ‘geomorphic’ design resulted in a single, branching gully nearly 10 m in depth, but very low mean elevation change elsewhere and low total soil loss. In contrast, the ‘armoured geomorphic’ design generated deep gullies at the edge of armour and relatively shallow gullies placed ubiquitously throughout the bottom half of the dam except for where the false armour was located; this created much greater total soil loss and more than double the mean elevation change. In terms of maintenance, it is likely easier to repair shallow gullies compared to deep ones, but the disturbed area associated with the shallow gullies is so great that one deep gully is likely preferable. With respect to channel maintenance the two are similar, with the ‘armoured geomorphic’ design producing more total soil to be cleared out than that of its’ unarmoured counterpart. When we observe the rate of soil erosion over time it is evident that of the designs tested the 'geomorphic' design reaches a lower steady state sooner than the others (Figure 10.6), and that the cumulative soil loss is substantially lower than the other four designs.

While the ''platform-bank'' design may have created a single, albeit large, gully, the rest of the dam remained mostly intact throughout the stress test. The challenge with this option is evident in Figure 10.5: the rate of soil loss is quite rapid once a gully is initiated. In the likely scenario that minimal on-site staff remain after extraction and reclamation construction is complete, these features may be difficult to identify and stabilize in a timely manner. This design may be a reasonable option for a small, low consequence dam with regular, ongoing monitoring and maintenance. Given the much higher initial and sustained rates of erosion, and the heights of oil sands tailings dams now in excess of 100 m at some locations, the 'platform-bank' design is not recommended for the AOS.

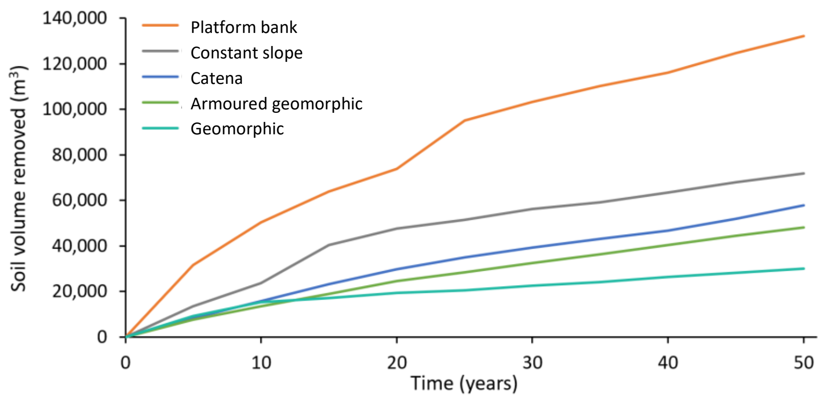

Figure 10.6 Cumulative soil loss from dam designs throughout the stress test

With respect to erosion rate over time and cumulative soil loss, the 'armoured geomorphic', 'catena', and 'constant slope' are clustered in the middle. Constant slope initially has a higher rate of soil loss compared to the other two designs, but the three eventually reach a similar steady state.

Overall, the 'geomorphic' design performed best throughout the stress test in that it had the lowest cumulative soil loss, mean elevation change, and lowest change in HI. While the 'geomorphic' design generated a deeper gully than three of the other designs, a predictable location for erosion monitoring and relative ease of a single repair compared to a large area of repairs is considered advantageous. In its present state, CAESAR-Lisflood is incapable of vegetation variation across a site, but this is likely to be a mitigating feature for the 'geomorphic' design: in areas of concentrated moisture, larger and more dense vegetation typically grows, in turn providing additional shallow and deep-rooted erosion resistance. This is also a natural phenomenon that would not be possible to its full extent were the central drainage path to be armoured.

Due to the inexplicable erosion patterns that developed on the 'armoured geomorphic' dam, it is not possible to conclude from these tests whether armouring is beneficial or not; however, the gullying adjacent to the false armour is consistent with personal observations and reports from other researchers in the field. The addition of a second grain size distribution and DEM allocating the location of that second soil / aggregate layer would improve the ability of modelling rip rap or rock armour in the future. Design of armouring using rip-rap is plagued by three challenges according to Walters (1982): precipitation event estimation and corresponding flood magnitude particularly in consideration of climate change, estimation of scour forces, and rock durability over long time frames (Toy & Hadley, 1987). In assessments of hydraulic variables on riprap performance at two closed tailings dams, probable maximum floods generated such large shear forces and flow velocities that "abnormally large-sized rocks" would be required for stabilization (Toy & Hadley, 1987; Walters & Skaggs, 1984). This topic requires further investigation related to the oil sands region, particularly due to the quantities required (in light of the scale of disturbance) and the distance from which armouring rock must be transported: at present, the vast majority of rip rap comes from a quarry in Exshaw, AB approximately 900 km from Fort MacKay at roughly the center of the AOS mineable region.

10.4 Conclusions

Over the years, the surficial form of tailings dam designs has evolved from an efficient approach, to a heavily controlled approach, and more recently the trend is towards designing in-line with natural forms, as illustrated with the 'catena' and 'geomorphic' designs. The 'design with nature' concept is in rebuttal to years of standard practices in opposition to natural forces: at its essence, the concept seeks to treat nature as an ally rather than something to be conquered (McHarg, 1969). Upon reflection of the design life for these tailings structures, between 1000 years and "forever", this is a logical concept to work with. The five stress-test simulations have illustrated that natural designs (catena, geomorphic, and armoured geomorphic) performed substantially better than the more rigid designs (constant slope and platform-bank). Of the five, the 'geomorphic' design produced the least soil loss and soil loss was concentrated such that site disturbance and maintenance activities were theoretically localized.

While Chapter Eight and Nine demonstrated that CAESAR-Lisflood can give important feedback on the lifespan and maintenance periods for a landform, the simulations run here demonstrate the ability of an LEM to be used for comparison of multiple end designs, such that the resilience of a structure and early failure indicators can be determined. Designing for the long-term thus far has largely gone un-tested; however, this approach provides an evidence-based method for designing and assessing performance and design-life over extended periods. Several improvements have previously been recommended for the software moving forward. With respect to the stress-testing, it was recognized that the ability to simulate more than one vegetation profile (other than through the m-value) with different critical shear values and more than one grain size would make modelling of diverse topographic landforms and armoured areas more realistic.

In terms of constructability, the natural-shaped designs are certainly more difficult than the rigid designs, and likely require skilled and engaged heavy equipment operators. The construction costs are also likely to be much higher up-front for these designs, but it is hoped that over the long term reduced maintenance costs, earlier de-licensing and reclamation certification would act as an offset.

11.0 Conclusions

The overriding goal of this work, as outlined in Chapter One, sought to investigate the long-term geomorphic stability of oil sands tailings storage facilities in the AOS, and to identify what a stable slope might be for CST landforms. This research was predominantly conducted on an active oil sands tailings storage facility in northern Alberta, Canada, that is several square kilometers in area. Through remote methods, no stable slope was found to exist, and that downstream dam slopes at a gradient of less than 6% were being reduced to less than 1%: this material continued to erode until it was nearly flat. Through landscape evolution modelling, dam slopes were shown to be likely to erode for an extended period of time, possibly several hundred years, and that even after 1000 years of simulation no minimum slope threshold was identified. Cumulative climate change effects have been demonstrated herein to increase the erosion of sand dams in the AOS, potentially such that an equilibrium erosion rate is not achieved for over 100 years. Given these findings, various dam design topographies were stress-tested to determine if an optimal shape rather than an optimal uniform slope gradient existed to impede erosion. While all five dam designs produced large amounts of soil loss, the unarmoured geomorphic design performed the best. This shape is similar to the landforms typical of Saskatchewan's Qu'Appelle Valley plateau transition or the undulating banks of the Athabasca River north of Fort McMurray. These landforms may be useful as natural analogues for future TSF closure designs in the AOS.

Individual objectives were outlined in Chapter One, have been addressed throughout the previous chapters, and are discussed in greater detail below:

To identify considerations in tailings dam design and for the design of post-mining above-ground mine waste (tailings) landforms.

Current tailings dam design practices were discussed in Chapter Two. Fundamental considerations for dam design include physical and chemical stability, and dam designs regularly include slope stability and seepage analysis, deformation analysis, and thermal analysis where applicable. The design life of a tailings dam is globally moving towards an excess of 1000 years, and while geomorphic design is widely considered as the path to achieving this, very few designs internationally are assessed with regard to their geomorphic rigor. The closure design for a TSF was conducted using current best practices and documented in Chapter Three. The design process allowed for a more thorough understanding of implications relating to this existing design process. The multiple accounts analysis of tailings dam design for closure was dominated by waste holding capacity of the landform, ease and cost effectiveness of construction, and proportion of drainage area captured and routed through the main outlet.

Through the design and analysis process, identify design considerations for ease of closure and long-term stability of both existing and new (proposed) aboveground tailings landforms.

A design for the closure topography of two conjoined TSFs was completed in Chapter Three. The design process yielded several considerations that, had they been realized earlier, would have made closure construction more efficient and provided a more beneficial outcome. Chapter Four includes an extended explanation of these considerations for ease of closure. The first set of considerations occurs in planning stages with location, ensuring sufficient space exists for construction of outlets that drain the dam surface, and extension of slopes where necessary. The second set of considerations pertains to tailings placement, such that undesirable tailings are located furthest from drainage outlets, and end of pipe location is such that a natural slope is generated towards the outlet reducing the landform grading necessary at a later date.

To quantify, using semi-empirical analysis, the potential soil loss from tailings dam slopes as they are presently designed.

In Chapter Five, the revised universal soil loss equation for application in Canada (RUSLEFAC) was used to quantify potential average annual soil loss from a downstream dam slope. While this number will vary based on the design of each dam section, a typical dam at the study site was expected to have an average annual soil loss of just over 100 Mg ha^{-1}. This excludes soil loss from gullying or mass wasting and is restricted to losses from rill and interill erosion.

To inventory, classify, and describe geomorphic processes acting on AOS tailings dams and identify corresponding causes.

In Chapter Six existing erosional features were identified via on-site inventory and using remote methods including LiDAR and digital stereo aerial photography. As discussed, both wind and water erosion were identified, but only large fluvial features were quantifiable remotely in terms of sediment loss. 190 gullies were identified on the tailings dams, many initiated by seepage, while others were initiated through pooling of water or concentrated flow. Gullies were initiated on slopes of less than 6% and resulted in slopes less than 1%. CST dam slopes of 4% have been heavily eroded at other sites. This suggests that if left exposed this material will continue on a trajectory towards nearly flat slopes. It also suggests that gullying could be a failure mechanism if abandonment were to occur. Stabilizing vegetation is important, but gullies were noted even on reclaimed areas of the dams and therefore a combined approach including vegetation and designed dam slopes is considered better protection long-term.

The methods used to remotely identify, characterize, and quantify erosion on the dams were individually lacking, but in conjunction provided a wealth of information. In addition to erosion monitoring, the ability to locate areas of high moisture either through photo tone or density and height of vegetation would be beneficial to recognize seepage, and for identifying exact locations for water quality samples, vegetation assays, or wildlife assessment.

To evaluate the susceptibility of TSFs to erosion resulting from current and projected climates, and identify geotechnical and environmental implications, if any, using landform evolution models.

Chapters Seven, Eight, and Nine explore and document the use of a modern landscape evolution model in the AOS for the first time. Chapter Seven provides an introduction to LEMs, and an overview of how the CAESAR-Lisflood LEM operates. Chapter Eight discusses preliminary models run for 1000 years and 200 years, respectively. It was found that the TSF and SEA are susceptible to erosion over these timeframes, and that without ongoing maintenance it may be possible for gullies to penetrate tailings pond cores, block perimeter channels, and lead to adverse environmental impacts including sediment loading of adjacent land and waterways. Additionally, the central pond plateau (that was designed in Chapter Three using a natural analogues approach) produced substantially less erosion than dam slopes, and erosion on the designed plateau was concentrated in the base of the drainage channel, suggesting it may be mitigated through rockfill check dams, armouring, or most preferably by adding an alternate outlet to the structure to reduce volume of flow. The inability and failure to adjust dam slopes for closure may contribute to a longer period of monitoring and maintenance due to their geomorphic instability. Long-term maintenance is therefore a central aspect of a functional dam drainage system and of protecting the surrounding environment. Models without maintenance reached a steady state soil loss around 50 years into the simulation. Note it is not possible to determine the sensitivity of this number, but the number is important due to the substantial difference relative to expected delicensing timelines.

Models run using a historic climate scenario tended to reach a steady state of soil loss over several decades, while models run using cumulative climate change projections (Chapter Nine) failed to achieve a steady state of soil loss over 100 years. This has implications for the delicensing of tailings storage facilities as the timeframe for monitoring and maintenance may be longer than previously anticipated, should climate change projections be met.

Landscape evolution models are not able to precisely predict the future – this is not possible by any means – but they provide a best guess as to longer term geomorphology, areas of concern, and rates of change. The predicted soil loss on dam slopes corresponded well to measured soil loss over short time frames (10 years), and water discharge was within the range calculated over short to medium time frames (1-25 years) using measurements from a different AOS tailings dam. This provides a degree of confidence in longer term predictions provided herein.

Given the goal of this research to investigate long term geomorphically stable slopes, a series of dam designs were developed and stress tested using repeated PMP events and historic precipitation events to provide ambient moisture levels. A regular slope, platform-bank, catena, and two geomorphic designs (with and without armouring down the central flow-line) were tested. The most stable slope, producing the least erosion overall, was the un-armoured geomorphic design, whereby an exaggerated s-curve profile swale is cut into the dam. This design corresponds most closely with what might be found in nature (for example, the Qu'Appelle Valley transition to plateau), and indorses the concept that long-term stability of these landforms is best achieved by designing with nature rather than against it.

11.1 Contributions

- Description of the international state of practice with respect to tailings dam closure and closure design

- Guidance on modern closure planning with respect to slope erosion and explanation of the need for a closure landscape that evolves, yet still meets performance standards agreed to by the industry, regulator, and local communities
- Documentation of a step-by-step process for geomorphic design of tailings storage facilities for closure
- Demonstration of a 'landform design options analysis' for the closure of an above grade oil sands tailings storage facility
- Identification of several early considerations to improve the ease and effectiveness of tailings dam closure. Documentation of these lessons learned from experience is particularly important as little is published publicly on such topics in mining and in the AOS.
- Quantification of average annual erosion due to rills and interrill processes using RUSLEFAC on a typical downstream dam slope, exceeding Alberta Transportation's "very high" hazard class.
- Demonstration that tailings dams, not the surface plateau, are the greatest cause of long-term geomorphic instability on a TSF
- Measurement and quantification of actual soil loss on an oil sands tailings dam due to gully erosion, also exceeding Alberta Transportation's "very high" hazard class.
- Identification and characterization of erosion in the form of wind-blown sediment, deflation, fluvial rills and gullies.
- Causes of fluvial erosion were identified to include seepage, ponding, and concentrated flow in conjunction with soil saturation.
- Development of a method to integrate long-term assessment to present short-term dam design assessment methods
- Parameterization and assessment of the applicability of CAESAR-Lisflood to the AOS mining region

- Documentation of a simplified method to account for winter conditions in the precipitation record for use in CAESAR-Lisflood v. 1.9b, on CST materials
- Confirmation that the CAESAR-Lisflood LEM (v. 1.9b) is capable of providing estimates of soil loss and geomorphology on an oil sands tailings storage facility.
- Estimated timelines for steady state erosion to be achieved on the AOS tailings dam studied, assuming no climate change effects. This timeline encourages progressive reclamation in the AOS where mine life is long, such that a point of steady state erosion is reached on TSFs without needing to extend the post-closure maintenance period.
- Identification of topographic features that lead to increased erosion
- Description and simulation of dominant erosional processes on an AOS TSF
- Assessment of large- and small-scale geomorphic changes, soil loss, and sediment transport on an AOS CST-constructed tailings dam
- Identification of potential challenges with respect to CST-constructed landform geomorphology and closure/reclamation targets
- Demonstration that, in-line with the 1000-year design life, LEM simulation for about 1000 years is optimal to understand short and long-term processes and dam behaviour. More than this can restrictively time consuming given present computational ability (and fast-paced design environments), and less fails to capture the long-term fate of the structure
- Initial assessment of the cumulative effects of climate change on CST landforms in the AOS, and clear demonstration that climate change (and in particular cumulative climate change effects) has the potential to worsen the impact of erosional processes on CST landforms
- Demonstration of how a LEM can be used to aid in tailings dam design for closure and evaluation of design with respect to target closure design criteria
- Evaluation of five potential sand dam designs with respect to erosion and geomorphology

11.2 Future work and research

The recognition that tailings dams pose the greatest risk to long term (geomorphic) stability of TSFs has led to preliminary stress-testing of a few dam designs. There is a gap in the current body of knowledge with respect to long-term failure modes for tailings dams in addition to erosion. Additional site measurements with respect to water and sediment discharge would allow for further calibration of the model.

No natural analogue exists for sand landforms of the height produced in the AOS, making closure design to a stable form a challenge. Further development of dam design alternatives, short-term stability modelling of the alternatives, additional LEM stress-testing for design refinement, and ultimately field-scale trials of various dam designs would be a beneficial next step in evaluation of optimal dam shapes.

This study assumed that acceptable erosion rates outlined by Alberta Transportation and Agri-Food Canada were applicable to closed tailings storage facilities. As no other local erosion thresholds are presently available, this was considered to be a valid first approach; however, it is of interest what the actual permissible erosion rates for AOS mine waste structures might be, based on their subgrade / construction material and downstream environments. Such specific and quantifiable reclamation targets would be beneficial to regulators and to industry.

Included in this work was an evaluation of the erosion occurring on tailings dam slopes in the AOS at one point in time. This would be enhanced by repeated annual evaluations such that gully characteristics and erosion mechanisms could be tracked over time. Additionally, erosion due to wind has not been fully evaluated here beyond the recognition and documentation of its occurrence. The CAESAR-Lisflood LEM is capable of simulating wind and water erosion in conjunction. This type of dual-erosion analysis is of interest due to the visible signs of wind erosion at present, and the gradual change in soil moisture expected with climate change.

The CAESAR-Lisflood and SIBERIA LEMs are predominantly scientific tools for hydrologists and geomorphologists in their present state. Since the former was used for this research, recommendations are made below with respect to this software, although it is suspected that similar considerations would be beneficial to SIBERIA users as well.

1) In order to make the software more applicable to the challenges inherent to oil sands tailings dams, it would be beneficial to integrate a land differential settlement tab, whereby a portion of the DEM surface settles over time with tailings consolidation.
2) With respect to mining landforms in general, multiple particle-size gradations would assist in mimicking the variable surficial distribution of granular materials (i.e. an armouring layer for localized placement), and at least one additional soil layer/DEM would be helpful to simulate erosion over the multi-layered caps that are often used.
3) Seepage effects erosion lower in the slope, and this would be a beneficial integration, similar to that described in CLiDE (Barkwith et al., 2015).
4) Where gullies have developed in reclaimed areas of tailings sand (CST), vegetation typically does not regrow, however in CAESAR-Lisflood vegetation growth is re-initiated as soon as overland flow rates are below the critical shear for vegetation. It would be beneficial in this instance to have variable vegetation re-establishment built in to the LEM.
5) Most regions have seasonal differences in their hydrologic patterns. In northern Alberta, evaporation rates vary considerable through the four seasons. Integration of seasonal evaporation would better represent site conditions.
6) Integration of a temperature file and code to automatically read precipitation as snow or rain, and generation of snow melt by hourly temperature would save significant time and effort in data quality control and processing.

This research represents a first-attempt to use CAESAR-Lisflood in TSF closure design evaluation, particularly with respect to the integration of climate change projections. Further work is required in order to fine-tune the integration of climate change, for example time variable evaporation inputs, time variable vegetation critical shear, etc.

Lastly, it is of interest to compare the results herein with those from the SIBERIA LEM. A minimum of one-year of field measurements from the area of interest are required to calibrate the model. The ideal site for measurements would consist of a dam slope including at least one gully and one inter-rill area, and will have been exposed to natural conditions for a number of years without maintenance. This would provide additional insight as to the long-term predictions made herein, as well as the relative ease of use and applicability of each model.

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Appendix A: Vegetated waterway calculations

A.1 Design calculations

The following pages outline the calculations performed to arrive at the three design options.

Table A.1 Basis for TSF design calculations: Drumlin field design option A.

Drainage Basin No.	Drainage Basin Area (Ha)	Recommended Maximum Slope (%)	Designed Slope (%)	(Channel Bottom Width) / (%Slope)	Required Channel Bottom Width (m)	Vegetated (V) or Alluvial (A)
Drumlin Field Option A						
1 (outlet)	500	0.5	0.5	68	34	A
2	107	3.5	0.5	6.5	3.25	V
3	25 +45.7 +48.1 118.8	2.0	0.5	8	4	V
4	57.4 +152.5 +62.5 =272.5	1.0	0.5	24	12	A
5 (feeds 4)	28 +14.6 +14.8 =57.4	7.0	0.5	2.5	1.25	V
6 (feeds 4)	69.5 +36 +47 =152.5	1.5	0.5	13	7.5	A
7 (feeds 6)	16 +19 =36	12.0	0.5	1.2	0.6	V
8 (feeds 6)	69.5	6.5	0.5	3.0	1.5	V
9 (feeds 3)	45.7	8.5	0.5	1.75	0.875	V
10 (feeds 3)	25	>20	0.5	0.5	0.25	V
11 (feeds 5)	14.6	>20	0.5	0.5	0.25	V
12 (feeds 5)	16 +12 =28	20.0	0.5	1.0	0.5	V
13 (feeds 7,12)	16	>20	0.5	0.5	0.25	V

Table A.2 Basis for TSF design calculations: Options B (hummocky ridge and swale) and C (dome).

Drainage Basin No.	Drainage Basin Area (Ha)	Recommended Maximum Slope (%)	Designed Slope (%)	(Channel Bottom Width) /(%Slope)	Required Channel Bottom Width (m)	Vegetated or Alluvial
Ridge & Swale Option B						
1 (outlet)	480	0.5	0.5	68	34	A
2	61	7	0.5	2.5	1.25	V
3	87.4	3.5	0.5	4.5	2.25	V
4	33.8	11.5	0.5	1.25	0.625	V
4a	4.7	>20	1	0.25	0.25	V
4b	17	>20	0.5	0.5	0.25	V
5	98.5	3.0	0.5	6.5	3.25	V
6	50.7	8.5	0.5	2.5	1.25	V
6a	8	>20	0.5	0.25	0.125	V
6b	15.4	>20	0.5	0.5	0.25	V
7	63	6%	0.75	3.5	2.625	V
7a	15.25	>20	0.5	0.5	0.25	V
7b	12.25	>20	0.5	0.5	0.25	V
Dome Option C						
1 (outlet)	315 +295 +20 =630	0.5	0.5	90	45	A
1a	315	0.5	0.5	35	17.5	A
1b	295	0.5	0.5	46	23	A
	(As Designed)	(From Golder (2004))	(As designed)	(From Golder (2004))	(Calculated from previous column)	(From Golder (2004))

Note that drainage basin area includes all feeder sub-watersheds. For example, drainage basin 3 is fed by #9 and #10 so its total area is the area of basin 3 + 9 + 10 (48.1 + 45.7 + 25 = 118.8) as outlined in grey and on the drainage basin map in Figure A.3. Also note that 100% of sub-drainage basin 13 is estimated to enter both 7 and 12, in case one of these routes should become blocked. A lesser slope than the recommended maximum slope from Golder (2004) was sometimes used in order to slow water and reduce the grade increase around TSF edges, which would in turn increase the amount of area flowing to the SEA as opposed to out the TSF north outlet.

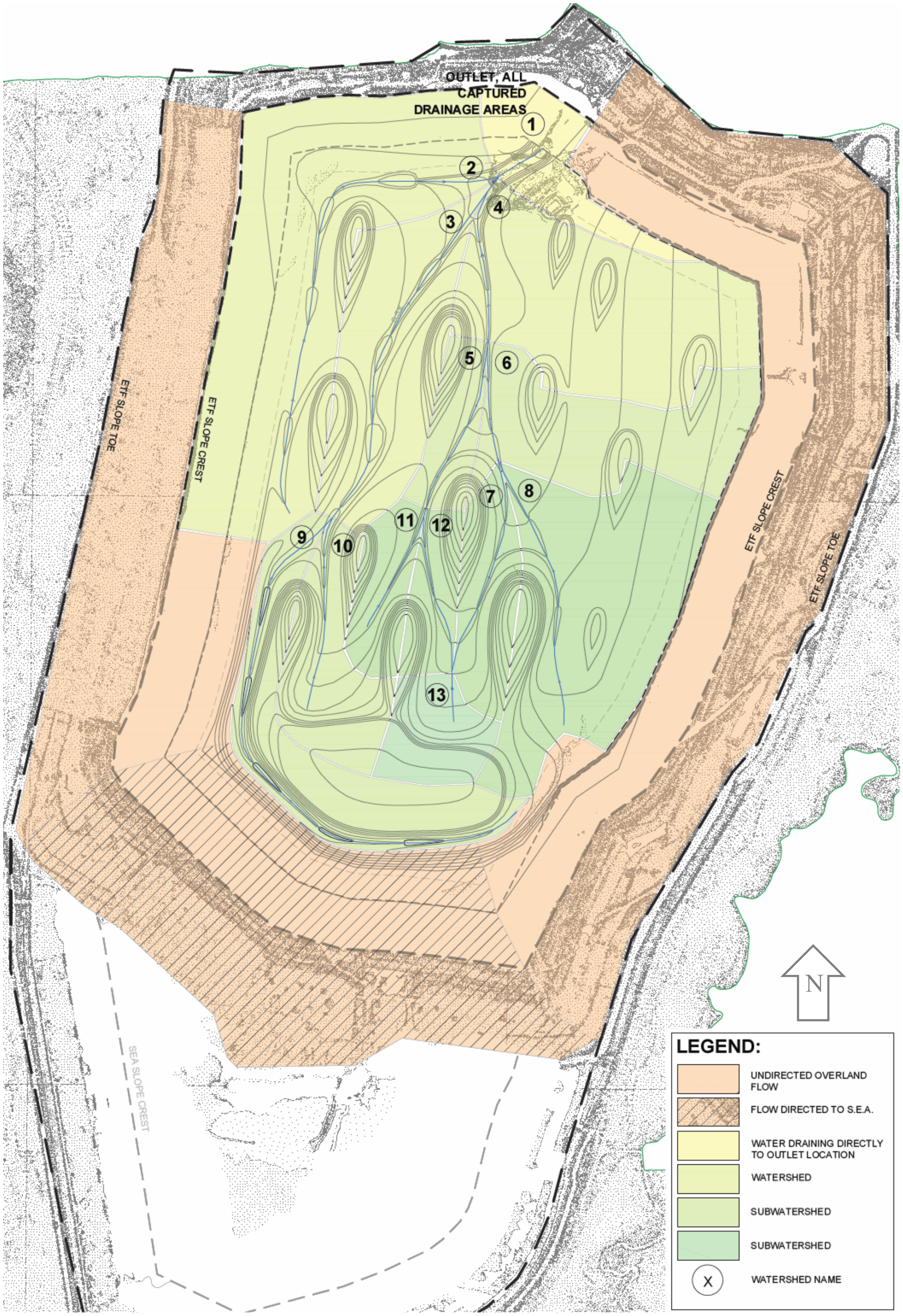

Figure A.1 Drainage Basins designed for the TSF Closure Topographic Design Option 'A' - "Drumlins".

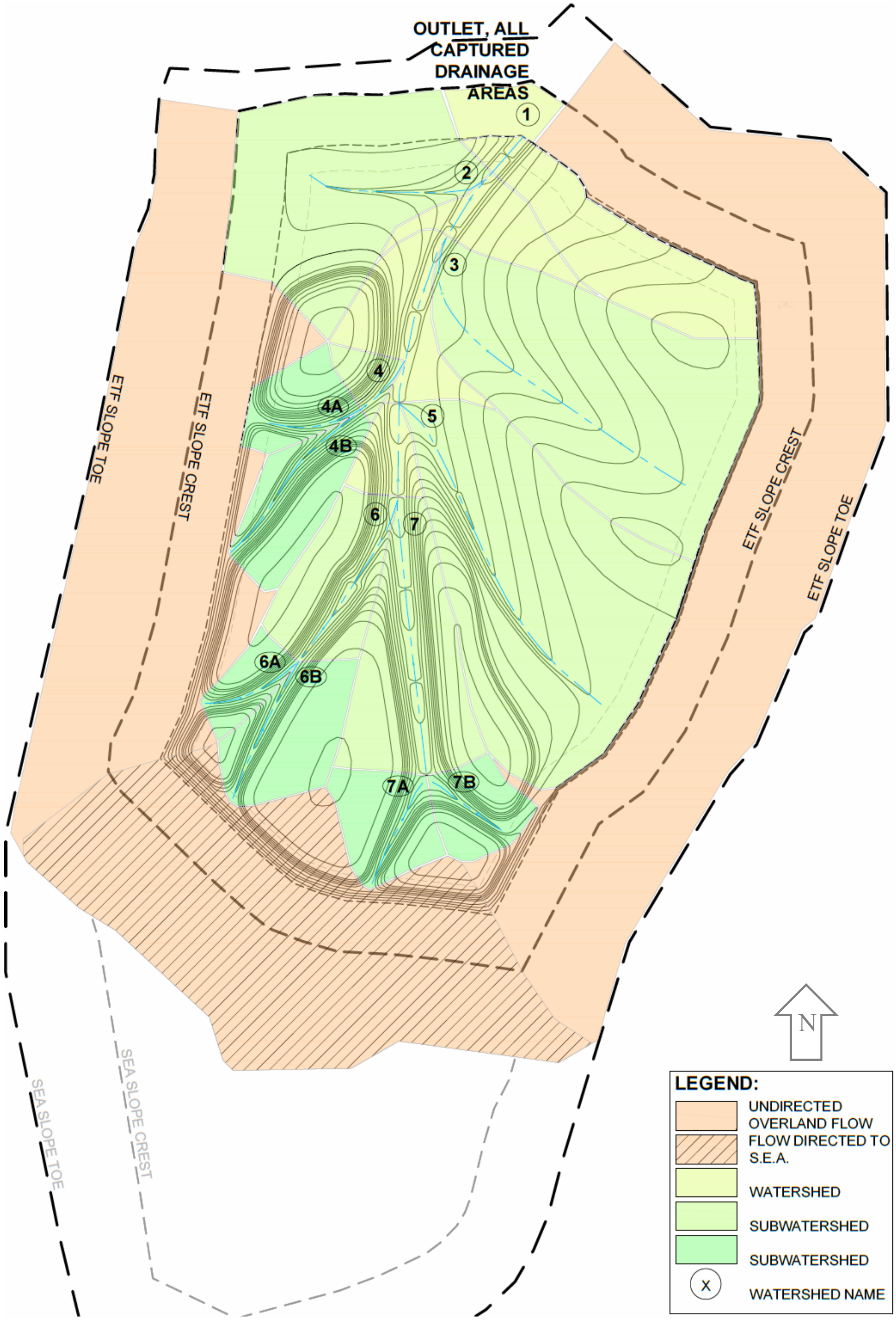

Figure A.2 Drainage Basins designed for the TSF Closure Topographic Design Option 'B' - "Ridge and Swale".

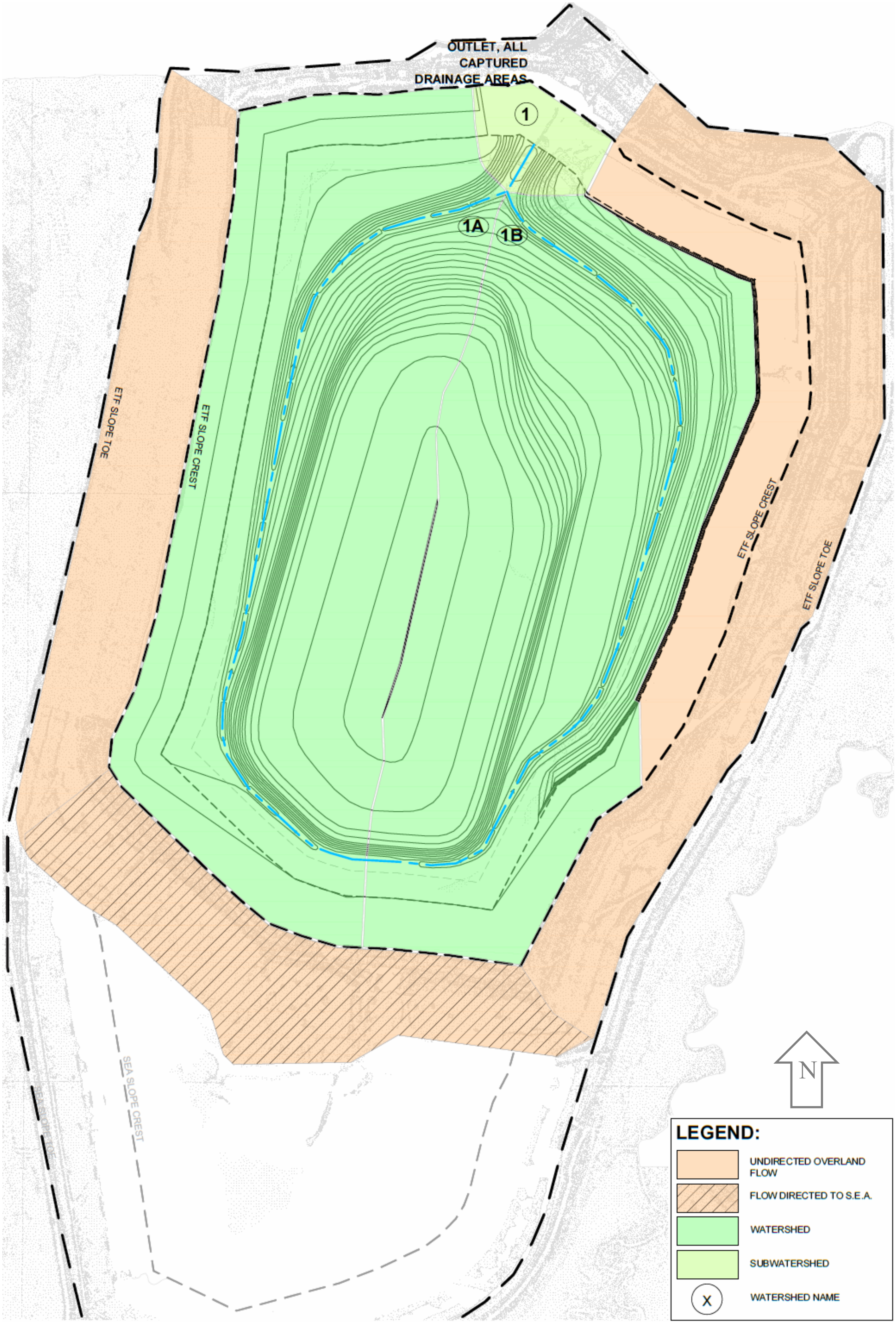

Figure A.3   Drainage Basins designed for the TSF Closure Topographic Design Option 'C' - "Dome".

Table A.3 Basis for SEA design calculations. Note drainage basin area includes all feeder sub-watersheds. Total drainage area directed to end deposition area is 409 ha, including potential runoff region from the TSF and SEA dyke slopes. Areas captured by the drainage channels designed in each option are listed below.

Drainage Basin	Drainage Basin Area (Ha)	Recommended Maximum Slope (%)	Designed Maximum Slope (%)	(Channel Bottom Width)/ (%Slope)	Required Channel Bottom Width (m)	Vegetated (V) or Alluvial (A)
Radial with multiple outlets directed to north east (SEA Option One)						
West, W	18.5 +28.5 +70.5 98	3.0%	3.0%	6.5	19.5	V
West, W(n)	18.5	>20%	10%	0.5	5	V
West, W(s)	28.5	15%	10%	1.0	10	V
South West, SW	61	6.5%	6.5%	2.5	16.25	V
South East, SE	52	8.5%	8.5%	1.75	14.88	V
East, E	67	5.5%	6.1%	3.0	16.5	A
Radial with multiple outlets directed to the south (SEA Option Two)						
West, W	28.5 +18.5 +48.5 95.5	3%	3%	6.5	19.5	V
West, W(n)	18.5	>20%	10%	0.5	5	V
West, W(s)	28.5	15%	10%	1	10	V
South West, SW	45.5	9%	9%	1.5	13.5	V
South East, SE	51	8.5%	8.5%	1.75	14.88	V
East, E	89	3.5%	3.5%	4	14	V
Single outlet to the north east (SEA Option Three)						
Central, C	137.8	1.5%	0.5%	12	6	V
(All remaining areas flow overland to perimeter ditches)						

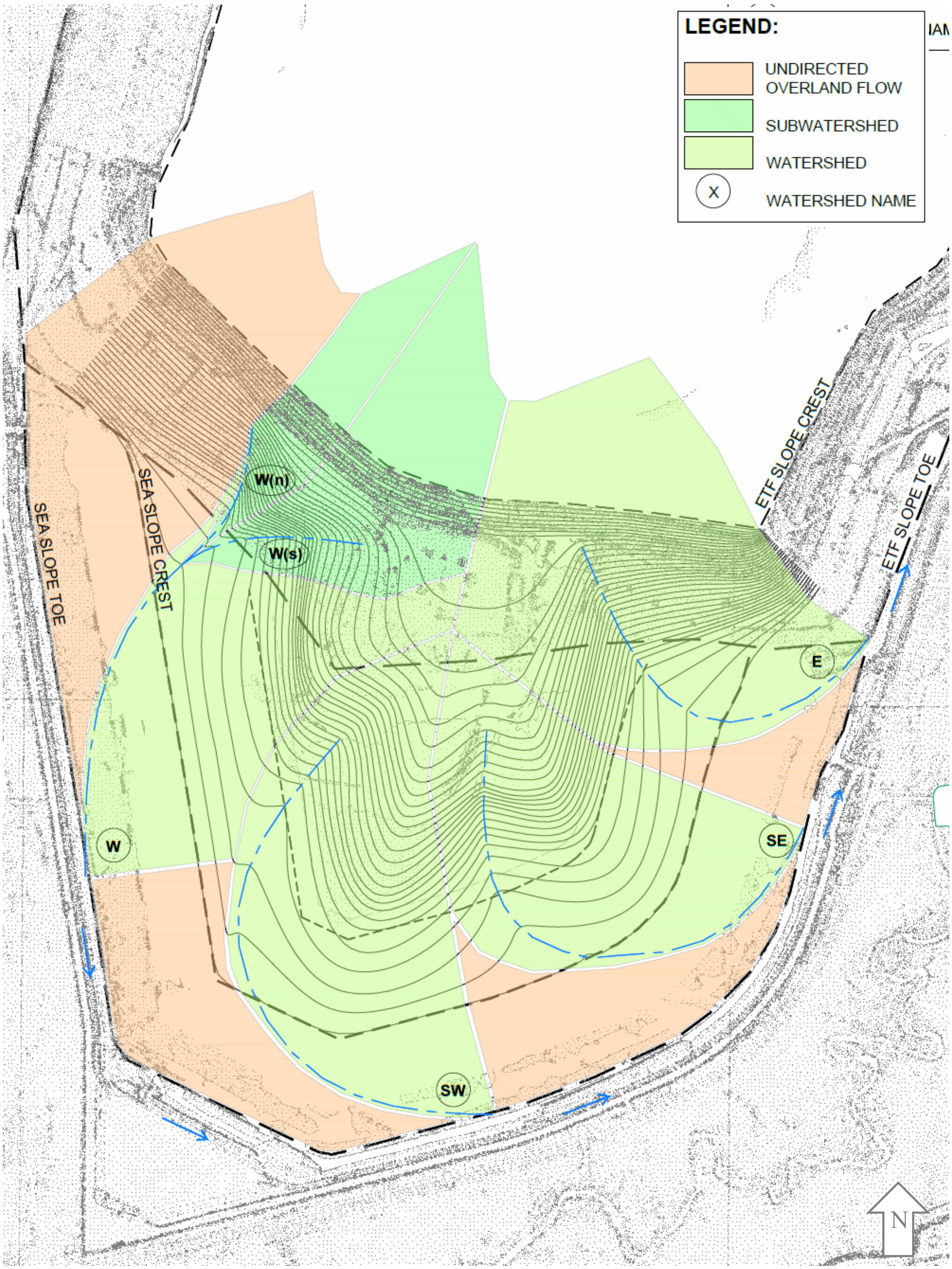

Figure A.4 Drainage Basins designed for the SEA Closure Topographic Design Option 'One'.

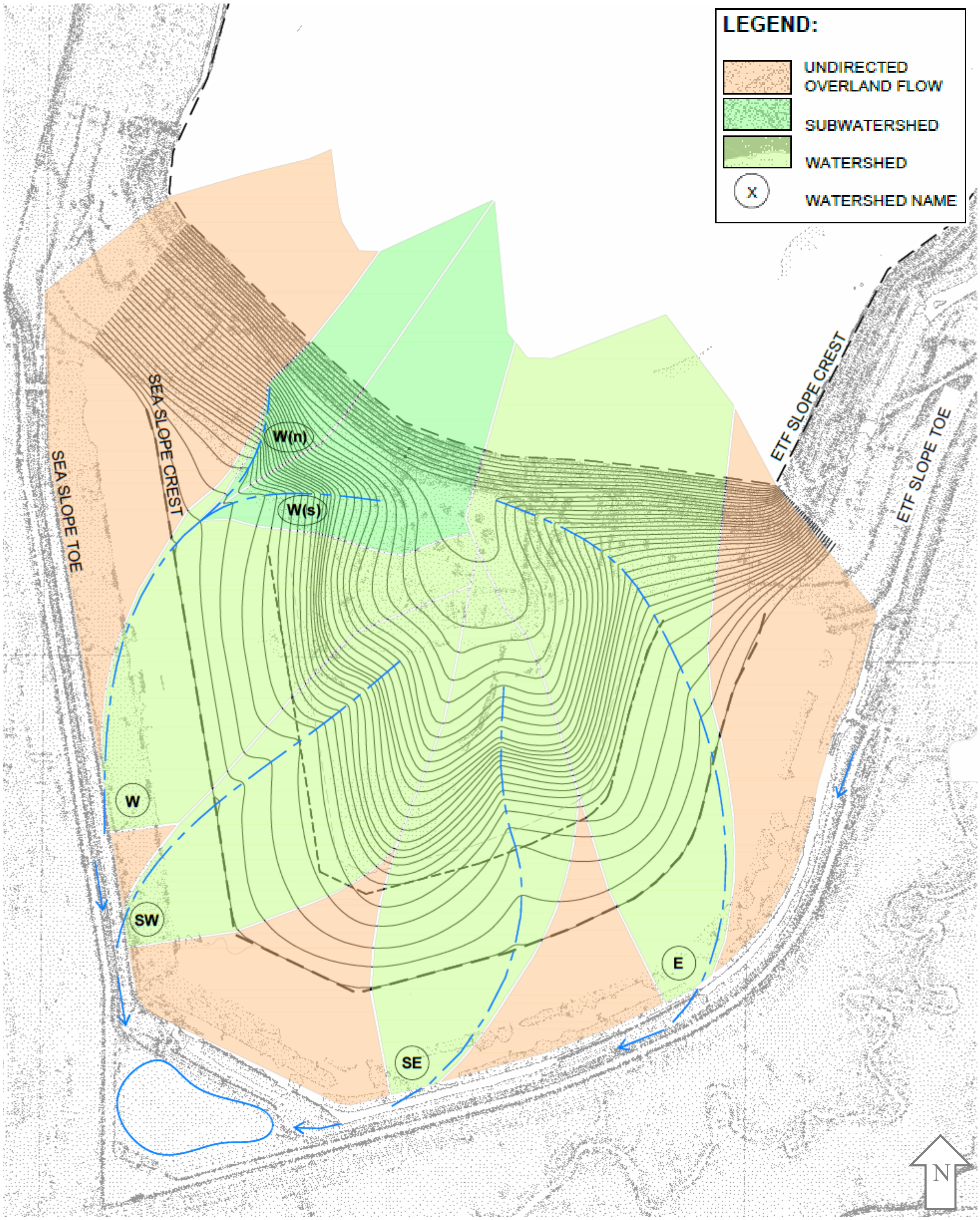

Figure A.5 Drainage Basins designed for the SEA Closure Topographic Design Option 'Two'.

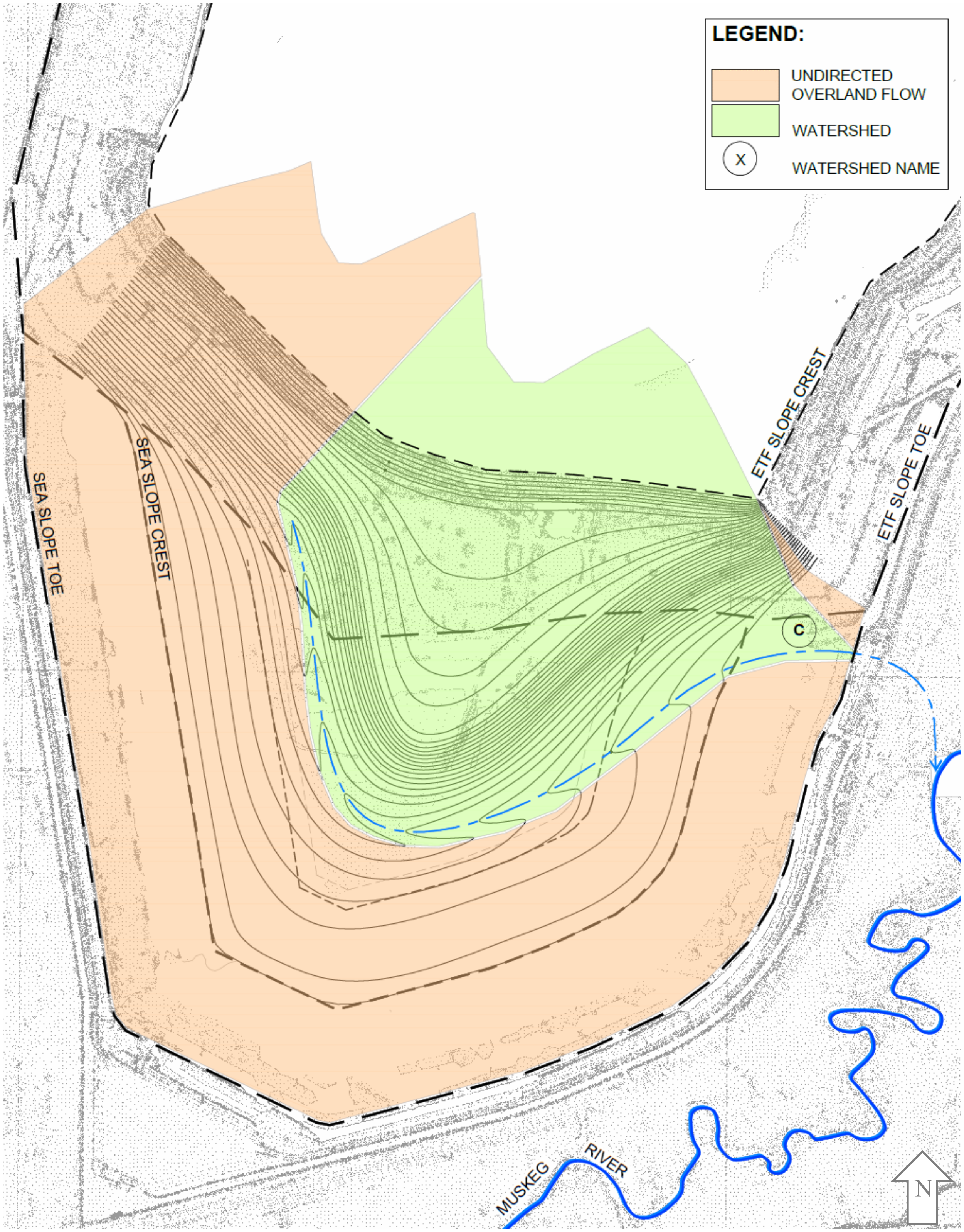

Figure A.6 Drainage Basins designed for the SEA Closure Topographic Design Option 'Three'.

Appendix B: CEMA Landscape Design Checklist

B.1 Evaluation summary for TSF / SEA

LANDSCAPE DESIGN CHECKLIST SUMMARY - From CEMA, 2006

Design Items	Items applicable to this project:	Completed?
PLANNING		
1. Regulations, agreements, and corporate objectives	1.1 Prepare a list of all specific applicable regulations and agreements that are being considered in design.	Y
	1.2 Prepare a list of all specific corporate objectives	Partial
	1.3 Design landscape to clearly meet these objectives	Y
2. Technology selection	None - determined at project start-up	
3. Footprint – size/location	None - determined at initial construction	
4. Mass balances	4.1 Design to accommodate material balances.	Y
	4.2 Plans and schedules shall meet operational and longterm goals and include the transition (and retrofitting) from an operational landform to a reclamation landform.	OPS
5. Preservation of byproduct resources	5.2 Design and manage byproduct landforms to reduce potential for combustion triggered by internal (spontaneous combustion) or external sources (lightning, wildfire).	OPS
6. Design for operations	6.1 Choose suites of technologies that support the ongoing operation (e.g. acceptable recycle water quality).	OPS
	6.2 Design and schedule reclamation and closure activities to allow continuing oil sands operations.	OPS
	6.3 Avoid compromising operational safety to satisfy closure goals.	Y
	6.4 Design to promote timely and progressive reclamation.	Y
7. Design for closure	7.1 Design landforms to be consistent with approved closure plan including surrounding lands	Y
	7.2 Plan all phases of construction and reclamation to achieve closure landform.	OPS
	7.3 Plan and schedule decommissioning of facilities, inventories of process affected water, byproducts and wastes.	OPS
	7.4 Integrate any long-term infrastructure with reclamation plans and landscape designs.	Y
8. Closure Management, (Pre-certification)	8.1 Design to avoid or minimize the need for post operational maintenance, design for stable, selfsustaining landforms and to prevent re-disturbance of previously reclaimed lands.	Y
	8.2 Identify areas requiring or at risk of needing post operational monitoring and mitigation.	Y
	8.3 Develop a monitoring and mitigation program for the period during and after construction and reclamation and until the landform is considered stable and suitable for reclamation certification.	OPS
	8.4 Give explicit consideration to monitoring and mitigation requirements, where there may be a potential for extreme events and impacts of targeted end land use.	OPS
	8.5 Develop conceptual plan for potential mitigation activities.	OPS
9. Post Certification	9.1 Design recognizing that no post certification maintenance is envisioned under the EPEA Act and Public Lands Act.	Y

LANDSCAPE DESIGN CHECKLIST SUMMARY - From CEMA, 2006

Design Items	Items applicable to this project:	Completed?
DESIRED CHARACTERISTICS / GOALS		
10. End Land Use	10.1 Design with human and wildlife health and safety as the highest priority.	Y
	10.2 Design landscape to meet goals for targetted land uses including access and meeting equivalent capability targets on the whole lease.	OPS
11. Soils	11.1 Design and construct landform morphology and substrate to support replaced soil quality and to protect soils from loss and degradation.	Y
	11.2 Design reclamation material layers to achieve target soil capability.	OPS
12. Vegetation	12.1 Design topographic features, soils, and substrate to support vegetation to achieve end land uses.	Y
	12.2 Create a vegetation plan that meets intended land uses on a lease- wide basis.	OPS
	12.3 Create a vegetation plan that meets intended land uses for landform.	OPS
	12.4 Design vegetation plan to aid landform stability (erosion, water table, moisture).	OPS
13. Wildlife	13.1 Incorporate wildlife habitat and movement into design of landform and landscape scales .	OPS
	13.2 Provide spatial attributes appropriate for wildlife and aquatic habitat goals.	Y
14. Aquatics	14.1 Design drainage patterns, watercourses and waterbodies to be an appropriate combination of biological zones.	OPS
	14.2 Avoid pond / lake evapoconcentration that leads to unproductive water bodies.	Y
15. Geotechnical slope stability	15.1 Design to protect slopes from instability.	Y
	15.2 Design to protect downstream areas from effects of catastrophic release of mobile materials.	Y
	15.3 Design to allow only acceptable consequences of potential flowslides	Y
16. Trafficability / bearing capacity	16.1 Plan construction techniques to enhance trafficability for reclamation.	Y
	16.2 Design trafficability and bearing capacity to be compatible with end land use.	OPS
17. Natural appearance	17.1 Design topography to resemble natural landforms in the region.	Y
18. Seepage and groundwater (quality and quantity)	18.1 Design to protect groundwater from impacts that affect offsite and/or on-site end land use.	Y
	18.2 Evaluate reclamation water balance at all critical scales.	OPS
	18.3 Avoid reliance on seepage controls that require longterm maintenance.	Y
	18.4 Evaluate landscape performance (geotechnical, soils, etc) for long-term seepage conditions.	OPS
19. Surface water hydrology (quantity and quality)	19.1 Design an integrated landform, landscape and regional drainage system.	OPS
	19.2 Design watercourses and waterbodies to have physical capacity to accommodate all ranges of hydrologic processes at acceptable rates of erosion.	Y
	19.3 Integrate operational and closure water balances to reduce inventory of process affected water at closure.	OPS

LANDSCAPE DESIGN CHECKLIST SUMMARY - From CEMA, 2006

Design Items	Items applicable to this project:	Completed?
PROCESSES		
20. Natural hazards and disturbing forces	20.1 Design landscapes to be acceptably stable under target end land uses.	Y
	20.2 Design landscapes to be acceptably stable under a variety of natural hazards and extreme events including fire, floods, drought, extreme precipitation, blight and disease, wind, earthquakes, animal effects.	Y
21. Erosion, transport, and sedimentation	21.1 Design operational wind and water erosion control measures where needed.	Y
	21.2 Design to accommodate all forms of erosion of (or depositing onto) landforms including lakes and major drainages at acceptable rates.	Y
22. Settlement of fills	22.1 Design long-term properties and topography to accommodate settlement and control any undesirable ponding.	Y
	22.2 Design surface water drainage system to accommodate settlement, including long-term saturation settlements and settlement of soft tailings.	Y

B.2 Guidance documents for Landscape Design Checklist

The following is the Landscape Design Checklist (Revised RSDS Government Regulator Version) completed by the Cumulative Environmental Management Association's (CEMA) Reclamation Working Group (RWG) Landscape Design Subgroup in 2005. This provides additional detail with respect to available guidance documents available for use with respect to each action item.

Design items	Action	Examples of available guidance/ comments
Planning		
1. Regulations, agreements, and corporate objectives	1.1 Prepare a list of all specific applicable regulations and agreements that are being considered in design. 1.2 Prepare a list of all specific corporate objectives 1.3 Design landscape to clearly meet these objectives	Proposed Landscape Design Manual (Goals and regulations chapter) AENV, EUB and SRD Approvals Guidelines and Standards (ELU, IRP) Corporate closure plan
2. Technology selection	2.1 Select technologies that produce materials that can be reclaimed to desired end land use. 2.2 All competing technologies must be evaluated using formal screening processes that consider life-cycle economics and environmental impacts.	Proposed Landscape Design Manual (Mine and closure planning chapter)
3. Footprint – size/location	3.1 Design footprint considering all relevant issues. 3.2 Resolve and document lease boundary issues with adjacent users. 3.3 Resolve and document issues about mining up to or through rivers, lakes, wetland, and other natural features. 3.4 Integrate footprint with closure landscape commitments and plans.	Proposed Landscape Design Manual (Mine and closure planning chapter) *Footprint considerations include items such as resource recovery, economics, social values, natural appearance, environmental impacts, historic sites, adjacent land uses and infrastructure*
4. Mass balances	4.1 Design to accommodate material balances. 4.2 Plans and schedules shall meet operational and long-term goals and include the transition (and retrofitting) from an operational landform to a reclamation landform.	Proposed Landscape Design Manual (Mine and closure planning chapter) *Material balances would include overburden, granular resources, tailings, water, and reclamation coversoils*
5. Preservation of byproduct resources	5.1 Store any byproduct that is considered a potential future resource, in such a way that it can be recovered in a manner acceptable to the EUB, AENV, SRD, and post-recovery landscape has the capability to meet environmental and end land use goals. 5.2 Design and manage byproduct landforms to reduce potential for combustion triggered by internal (spontaneous combustion) or external sources (lightning, wildfire).	Proposed Landscape Design Manual (Mine and closure planning chapter)

Landscape Design Checklist

The landscape designer (or evaluator) shall address the following design issues so that landscape performance will sustain proposed end land uses and equivalent capability.

Design items	Action	Examples of available guidance/ comments
6. Design for operations	6.1 Choose suites of technologies that support the ongoing operation (e.g. acceptable recycle water quality). 6.2 Design and schedule reclamation and closure activities to allow continuing oil sands operations. 6.3 Avoid compromising operational safety to satisfy closure goals. 6.4 Design to promote timely and progressive reclamation.	Proposed Landscape Design Manual (Mine and closure planning chapter)
7. Design for closure	7.1 Design landforms to be consistent with approved closure plan including surrounding lands 7.2 Plan all phases of construction and reclamation to achieve closure landform. 7.3 Plan and schedule decommissioning of facilities, inventories of process affected water, byproducts and wastes. 7.4 Integrate any long-term infrastructure with reclamation plans and landscape designs. 7.5 Design infrastructure with a consideration of its future decommissioning and reclamation.	Proposed Landscape Design Manual (Mine and closure planning chapter) Legislation Guidelines (IRP, ELU, etc) Approvals EUB/AENV/SRD
8. Closure Management, (Pre-certification)	8.1 Design to avoid or minimize the need for post operational maintenance, design for stable, self-sustaining landforms and to prevent re-disturbance of previously reclaimed lands. 8.2 Identify areas requiring or at risk of needing post-operational monitoring and mitigation. 8.3 Develop a monitoring and mitigation program for the period during and after construction and reclamation and until the landform is considered stable and suitable for reclamation certification. 8.4 Give explicit consideration to monitoring and mitigation requirements, where there may be a potential for extreme events and impacts of targeted end land use. 8.5 Develop conceptual plan for potential mitigation activities.	Proposed Landscape Design Manual (Environmental risk management chapter)
9 Post Certification	9.1 Design recognizing that no post certification maintenance is envisioned under the EPEA Act and Public Lands Act.	Proposed Landscape Design Manual (Environmental risk management chapter)
Desired Characteristics / Goals		
10. End Land Use	10.1 Design with human and wildlife health and safety as the highest priority. 10.2 10.2 Design landscape to meet goals for targetted land uses including access and meeting equivalent capability targets on the whole lease.	Integrated Resource Plan Proposed Landscape Design Manual (Mine and closure planning chapter)

	Landscape Design Checklist The landscape designer (or evaluator) shall address the following design issues so that landscape performance will sustain proposed end land uses and equivalent capability.	
Design items	**Action**	**Examples of available guidance/ comments**
11. Soils	11.1 Design and construct landform morphology and substrate to support replaced soil quality and to protect soils from loss and degradation. 11.2 Design reclamation material layers to achieve target soil capability.	Land Capability Classification System Manual, proposed Landscape Design Manual (Soils chapter)
12. Vegetation	12.1 Design topographic features, soils and substrate to support vegetation to achieve end land uses. 12.2 Create a vegetation plan that meets intended land uses on a lease- wide basis. 12.3 Create a vegetation plan that meets intended land uses for landform. 12. Design vegetation plan to aid landform stability (erosion, water table, moisture).	The Veg Manual, proposed Landscape Design Manual (Vegetation chapter)
13. Wildlife	13.1 Incorporate wildlife habitat and movement into design of landform and landscape scales . 13.2 Provide spatial attributes appropriate for wildlife and aquatic habitat goals.	The Veg Manual, Landscape Design Manual (Wildlife habitat chapter) Guidelines (IRP) SEE Design guide for details
14. Aquatics	14.1 Design drainage patterns, watercourses and waterbodies to be an appropriate combination of biological zones. 14.2 Avoid pond / lake evapoconcentration that leads to unproductive water bodies. 14.3 Indicate any water treatment wetlands that may be exempt from some aquatic ecology and influent water quality considerations.	The Wetland Manual, Landscape Design Manual (wetlands, lakes, and aquatics chapter), Alberta Water Quality Guidelines See Design Guide for details
15 Geotechnical slope stability	15.1 Design to protect slopes from instability. 15.2 Design to protect downstream areas from effects of catastrophic release of mobile materials. 15.3 Design to allow only acceptable consequences of potential flowslides.	Proposed Landscape Design Manual (Geotechnique chapter) *It will include failure mechanisms such as liquefaction, piping, material mobility, earthquakes, overtopping, rising water table, slope instability, retrogressive erosion or slumping, toe erosion*

Landscape Design Checklist

The landscape designer (or evaluator) shall address the following design issues so that landscape performance will sustain proposed end land uses and equivalent capability.

Design items	Action	Examples of available guidance/ comments
16 Trafficability / bearing capacity	16.1 Plan construction techniques to enhance trafficability for reclamation. 16.2 Design trafficability and bearing capacity to be compatible with end land use.	Proposed Landscape Design Manual (Geotechnique chapter)
17. Natural appearance	17.1 Design topography to resemble natural landforms in the region.	Proposed Landscape Design Manual (Mine and closure planning chapter)
18 Seepage and groundwater (quality and quantity)	18.1 Design to protect groundwater from impacts that affect offsite and/or on-site end land use. 18.2 Evaluate reclamation water balance at all critical scales. 18.3 Avoid reliance on seepage controls that require long-term maintenance. 18.4 Evaluate landscape performance (geotechnical, soils, etc) for long-term seepage conditions.	Proposed Landscape Design Manual (Seepage and groundwater chapter)
19 Surface water hydrology (quantity and quality)	19.1 Design an integrated landform, landscape and regional drainage system. 19.2 Design watercourses and waterbodies to have physical capacity to accommodate all ranges of hydrologic processes at acceptable rates of erosion. 19.3 Integrate operational and closure water balances to reduce inventory of process affected water at closure.	Proposed Landscape Design Manual (Surface water hydrology chapter)
Processes		
20 Natural hazards and disturbing forces	20.1 Design landscapes to be acceptably stable under target end land uses. 20.2 Design landscapes to be acceptably stable under a variety of natural hazards and extreme events including fire, floods, drought, extreme precipitation, blight and disease, wind, earthquakes, animal effects.	Proposed Landscape Design Manual (Environmental risk management chapter)
21 Erosion, transport, and sedimentation	21.1 Design operational wind and water erosion control measures where needed. 21.2 Design to accommodate all forms of erosion of (or depositing onto) landforms including lakes and major drainages at acceptable rates.	Proposed Landscape Design Manual LCCS manual
22 Settlement of fills	22.1 Design long-term properties and topography to accommodate settlement and control any undesirable ponding. 22.2 Design surface water drainage system to accommodate settlement, including long-term saturation settlements and settlement of soft tailings.	Proposed Landscape Design Manual (Geotechnique chapter)