Long-term Evolution of the Phreatic Surface in a Tailings Dam following Closure

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Abstract

Following mine closure, tailings dams remain on the site, eventually becoming part of the landscape. Historically, it was common practice to design these structures with consideration of failure modes that could occur during the mine's active life. This is problematic as the life of the tailings dam is expected to far exceed the life of the mine. Further, the importance of reclamation and decommissioning through the processes of sustainable mining practice is a relatively recent development in the mining industry. Despite this, there is limited information regarding how a tailings dam ages in perpetuity.

The evolution of the phreatic surface in a tailings dam is a potential area of uncertainty associated with the closure phase of a tailings dam. Changes in the phreatic surface can act as a trigger for failure of different elements in a tailings dam following closure. Consequently, understanding the long-term evolution of the phreatic surface in a tailings dam is essential to the process of reclamation and closure and is an integral component of the long-term risk management of tailings dams. This paper aims to evaluate this commonly made assumption through the analysis of the evolution of the phreatic surface of an oil sands tailings dam case study in Alberta, Canada in response to different scenarios, including: drain failure, formation of ponds on the reclamation surface, and climate change.

The seepage modelling demonstrated under certain scenarios, drains failing and ponds forming on the reclamation surface had the potential to cause a rise in the phreatic surface in the case study dam. Long-term seepage modelling can also be used to help guide monitoring and maintenance plans for closure works, which can be anchored back to the observational method or an adaptive management framework.

Introduction

Following mine closure, tailings dams remain on the site, eventually becoming part of the landscape. Historically, it was common practice to design these structures with consideration of failure modes that could occur during the mine's active life. This is problematic as the life of the tailings dam is expected to far exceed the life of the mine. Further, the importance of reclamation and decommissioning through the processes of sustainable mining practice is a relatively recent development in the mining industry. Despite this, there is limited information regarding how a tailings dam ages in perpetuity. This knowledge gap poses an unprecedented environmental, public, and financial risk, especially when combined with the serious consequences associated with the failure of tailings dams. These consequences are clearly shown by a number of different tailings dam failures that have occurred under different closure scenarios.

For example: following closure of the mine site at the Matachewan Consolidated Mine in Ontario, Canada (Baker et al., 1996); when the mine was in a period of care and maintenance at the Obed Mountain Mine in Alberta, Canada (Provincial Court of AB, 2017); and when the mine was operating but the tailings dam was no longer receiving tailings (but had not yet been reclaimed) at the Córrego do Feijão Iron Ore Mine in Brazil (WISE, 2020). Closing a tailings dam requires the structure to transition to a solid landform that is "physically, chemically, ecologically, and socially stable" (ICOLD, 2013). Combined with the serious consequences associated with failure, closure of a tailings dam requires a comprehensive understanding of the long-term behaviour, such that physical stability issues can be understood.

As noted by Schafer et al. (2019, 2020), the evolution of the phreatic surface in a tailings dam is a significant area of uncertainty associated with the closure phase of a tailings dam. It is commonly assumed that the phreatic surface will decrease in the long term, despite there being limited literature resources to support this and a number of conditions that may result in a rise in the phreatic surface (i.e., clogging of drains or the aging of sands) (Schafer et al., 2019). Schafer et al. (2021) showed that the changes in the phreatic surface can act as a trigger for failure of different elements in a tailings dam. Consequently, understanding the long-term evolution of the phreatic surface in a tailings dam is essential to the process of reclamation and closure and is an integral component of the long-term risk management of tailings dams. This paper aims to evaluate this commonly made assumption through the analysis of the evolution of the phreatic surface of a case study tailings dam in response to different scenarios, including: drain failure, formation of ponds on the reclamation surface, and climate change. An oil sands tailings dam in Alberta, Canada, was used as a case study to conduct two-dimensional numerical seepage modelling using SEEP/W in the GeoStudio 2019 R2 software package (GEO-SLOPE, 2020).

Case study facility

The case study external tailings facility (ETF) is an oil sands tailings dam in Alberta, Canada. The ETF, described in detail in Schafer at al. (2022), is a sand dam with a starter dyke constructed using overburden. The cross-section analysed in this research was constructed using upstream method with hydraulic fill deposition and cell construction. In cell construction, tailings are discharged to a cell where the solids settle, and the water and fines flow to the end of the cell and through a weir structure to the beach. The sand remaining in the cell is spread and compacted through vibration using dozers.

The tailings dam consists of coarse sand tailings (CST) and beach deposits (i.e. beach above water (BAW) and beach below water (BBW)) and contains fluid fine tailings (FFT). The dam also has a toe berm with benched slopes at the downstream toe constructed of lean oil sands (fines and a modest amount of bitumen). The tailings dam has two levels of drains (level 1 drains and level 2 drains) that consist of 200 mm diameter perforated collector pipes surrounded by a woven geotextile sock drain that run parallel to the dam centreline. Water is discharged to the perimeter ditch via smaller outtake pipes that connect to the collector pipes at approximately 150 m intervals.

During reclamation, the facility will be infilled with CST, using methods similar to cell construction, to partially displace the FFT. It is expected that this process will result in a zone of mixed CST and FFT. The compacted CST will be capped with mine waste. The cross-section used for the transient modelling is provided in Figure 1. The case study ETF used for the seepage analysis corresponds to a real cross-section and material properties. The operator has requested anonymity.

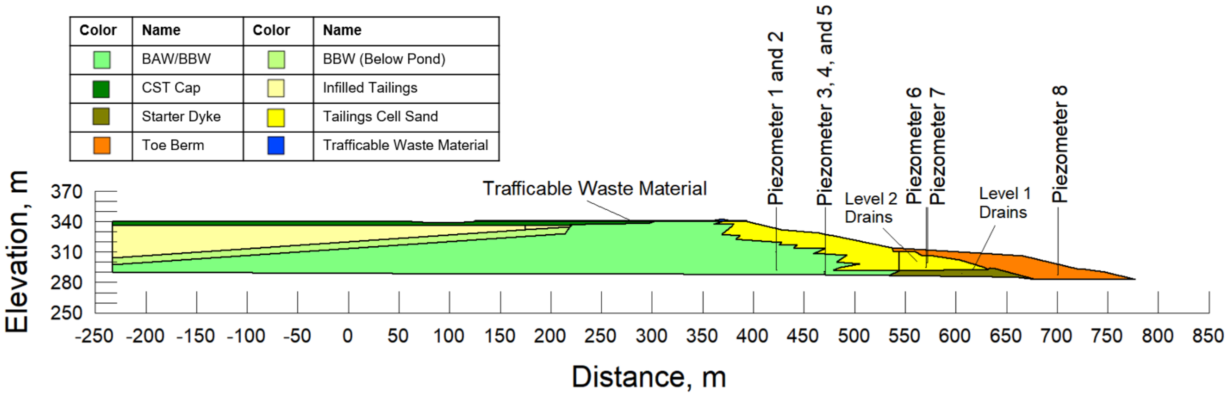

Figure 1: Transient model geometry (Piezometer tip elevations: 1–292.6 m, 2–310.6 m, 3–290.7 m, 4–290.1 m, 5–288.7 m, 6–295.0 m, 7–299.9 m, 8–287.8 m)

Numerical model

Modelling may enhance engineering judgement, help to understand processes and train our thinking with regard to assessing the long-term phreatic surface of a tailings dam. The objective was to evaluate how long-term changes may impact the phreatic surface of a closed tailings dam. The modelling occurred in two phases, including steady state and transient modelling. The steady state modelling was used to calibrate the hydraulic conductivity functions, evaluate the sensitivity of the model to different model changes (i.e. boundary conditions, material properties), and determine the initial conditions for the transient model. The transient modelling was used to determine the soil water characteristic curves (SWCCs) and evaluate the response of the phreatic surface to different scenario changes. Convergence was evaluated with consideration of the relative water balance error, pressure head convergence, material property functions, and engineering judgement. The transient scenarios analysed were designed to understand the uncertainty associated with the evolution of the phreatic surface.

The meshing in SEEP/W is fully automatic (GEO-SLOPE, 2015) however, modellers may change the element size or pattern. A mesh pattern of quadrilateral and triangular elements with a global element size of 4 m; however, localized areas used a smaller element size. The base boundary conditions used in the transient seepage analysis are provided in Table 1.

Table 1: Transient seepage analysis boundary conditions

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

The pond was extended upstream substantially so that a no flow boundary condition could be employed under the assumption that the pond extends past the hydraulic divide. Muskeg was not stripped prior to construction of the facility therefore were constrained to the assumption that the hydraulic properties of the muskeg were sufficient to create a hydraulic barrier or a no flow boundary condition. The drains were modelled as circular floating regions using a potential seepage face and a rate of 0 m^3/s.

A significant challenge with conducting the transient analysis on the dam is determining the net infiltration over long periods of time. GeoStudio uses a land-climate interaction (LCI) boundary condition to do this where climate data is input and given that climate data, the solver determines the net infiltration over time (GEO-SLOPE, 2020). The LCI boundary condition was used for this work with the Penman-Wilson evapotranspiration method. Climate data were collected from the Alberta Climate Information Service using their historical weather station data for the Mildred Lake weather station from February 2009 to February 2019 (10 years). Full details on the climate data set can be found in Schafer (2022).

Material properties

The steady state modelling was used to calibrate the transmissivity (hydraulic conductivity functions) of the materials. The calibration was conducted in accordance with ASTM D5981/D5981M–18 using data provided by the oil sands operator, including pore pressures from piezometers and drain outflows. For the steady state modelling, the dam geometry reflected the conditions prior to closure works. Due to limited space, the calibration will not be discussed further in this paper but are provided in Schafer (2022). The water storage function (or SWCC) cannot be calibrated using steady state methods. For the case study, the tailings dam has not yet been closed and there are no data to calibrate to at the current time. To mitigate these issues, a scenario analysis was conducted to determine the material properties that should be used for the remainder of the analysis by assessing the impact of different water storage functions on the overall conclusions of the model. Two different SWCCs were assigned to the materials: tailings sand and lean oil sand. The BAW/BBW, tailings cell sand, CST cap, and infilled material were assigned the tailings sand SWCC, and the starter dyke/berm and mine waste material were assigned the lean oil sand SWCC. Due to limited space, the SWCC scenario analysis will not be discussed but are provided in Schafer (2022). The calibrated hydraulic conductivity material properties (saturated hydraulic conductivity and anisotropy) are provided in Table 2, the hydraulic conductivity and SWCC functions are provided Figure 2.

Table 2: Saturated hydraulic conductivity and anisotropy

Material	Saturated hydraulic conductivity (Kx) (m/s)	Ky/Kx
Fine tailings	1x10-7	0.1
BBW	2x10-6	0.005
BBW/BAW	2x10-5	0.0333
Cell sand	9x10-6	0.1
Starter dyke	1x10-8	0.2
Berm	1x10-8	0.2

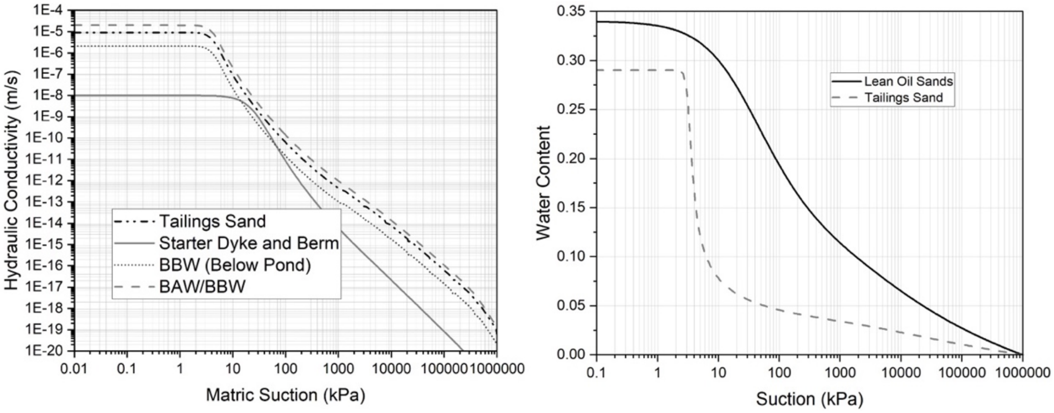

Figure 2: Hydraulic conductivity (Left) and SWCC (Right) functions

Transient model scenario results

Drain failure

The drains in this tailings dam can fail through a number of different mechanisms, including breakage of the pipe, clogging, blockage, clogging of the surround, or a breakage of the connection between the drain and the outlet pipe. Drains can have a critical impact on performance of a tailings dam in closure; however, it is becoming common practice to assume that drains fail in closure. The question becomes, does the facility require the drains to function for a certain amount of time prior to them failing, and if so, how critical is this to the stability of the facility? Different scenarios of drain failure were modelled for the case study facility, as outlined in Table 3. The drain scenarios were modelled by altering the boundary condition at the drain as a discrete event changing from functioning or non-functioning (failed). The level 2 drain failure was focused on the first 10 years as the phreatic surface drops below the level 2 drains before 10 years. Failure of the level 1 drains was spread out over the 100-year time scale (5, 25, 50, 75 years).

Table 3: Drain failure or pond formation scenarios

Scenario ID	Level 1 drains	Level 2 drains	Pond formation
1	Functioning	Failed at 5 years	1 m deep pond forms at 10 years
2	Functioning	Failed at 10 years	1 m deep pond forms at 50 years
3	Failed at 5 years	Functioning	1 m deep pond forms at 75 years
4	Failed at 25 years	Functioning	1 m deep pond forms at 10 years and remains for 1 year
5	Failed at 50 years	Functioning	1 m deep pond forms at 10 years and remains for 10 years
6	Failed at 75 years	Functioning	0.5 m deep pond forms at 10 years
7	Failed at 5 years	Failed at 5 years	Not applicable

The different modelling scenarios were assessed based on the piezometer total heads over time (Figure 3), drain outflows over time (not shown, see Schafer 2022). Scenarios 3, 4, and 7 all had a maximum total head difference with no failure base case that exceeded 5 m for many of the piezometer locations. The maximum total head difference was between 1 m to 5 m for most of the piezometer locations (except Piezometer 2) for Scenario 5. The maximum total head difference was less than 1 m for most of the piezometers for Scenario 1, 2, and 6. The most substantial impact on the total heads is seen in Scenario 7 where the level 1 and level 2 drains fail at 5 years. The phreatic surface in the facility rises quickly in response to the drain failure and then establishes a stable high phreatic surface with fluctuation at the location of Piezometer 8 in response to climatic data. The maximum total head difference established between the no failure base case and the scenario is greater than 7 m for all piezometer locations. Further, the total head difference does increase rapidly. For example, the total head difference for Piezometer 7 is 7.5 m at 1 year after failure, 12.1 m at 5 years after failure, and 13.8 m at 10 years after failure.

Ponds forming on reclamation surface

Ponds may form on the reclamation surface via different mechanisms with the most predominate being

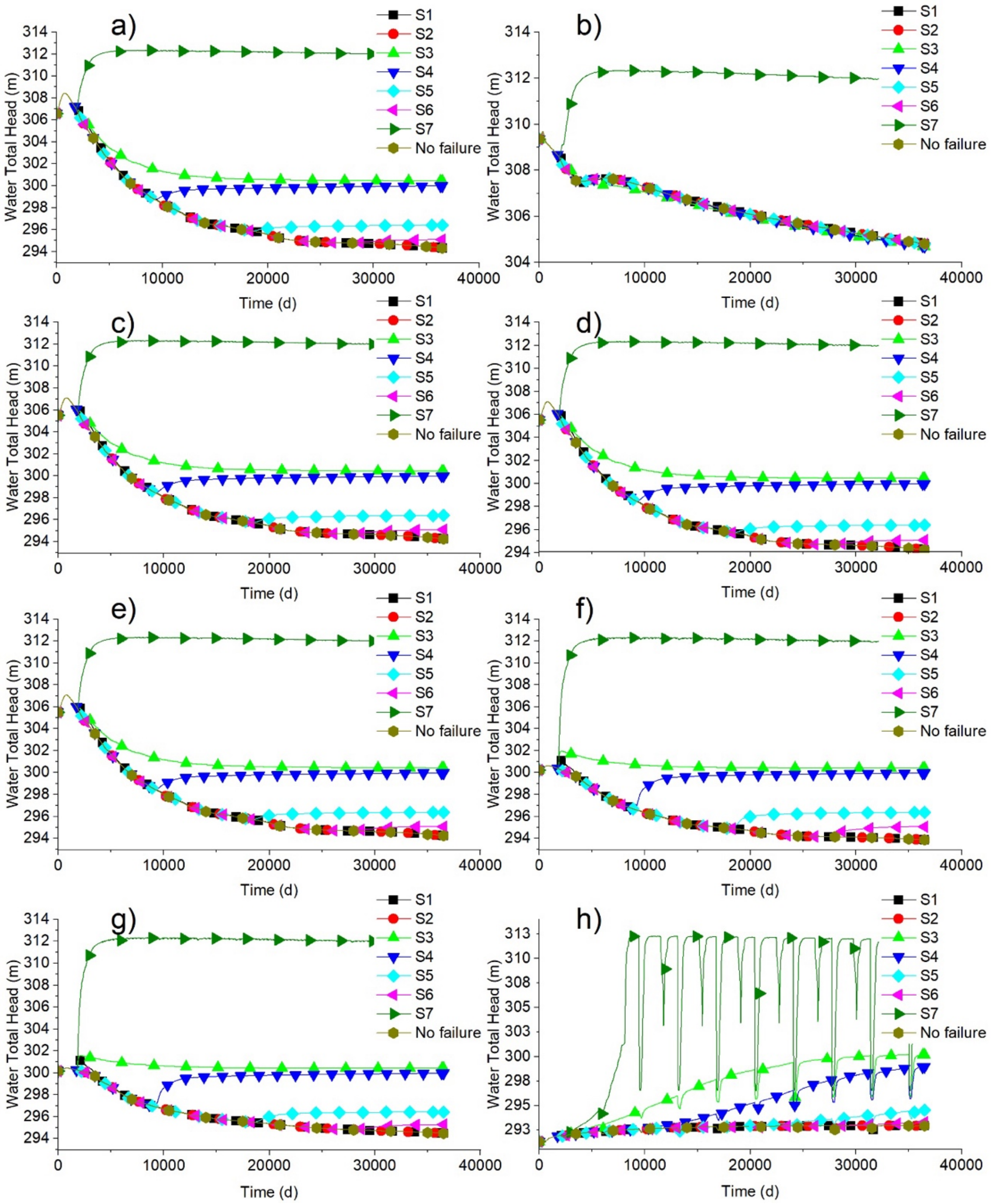

Figure 3: Total head over time for drain scenarios for a) Piezometer 1 b) Piezometer 2 c) Piezometer 3 d) Piezometer 4 e) Piezometer 5 f) Piezometer 6 g) Piezometer 7 h) Piezometer 8

consolidation and settlement of the landform cap or the infilled material. The different pond formation scenarios that were modelled are outlined in Table 3. The pond formation scenarios were modelled using a total head boundary condition in a 1 m depression in the upstream area of the facility (approximately 270 m from the dam crest) and fully functioning drains. The impact of the location of the pond in the upstream area was not assessed. The pond formation scenarios evaluated the impacts of a pond forming as a discrete event at different points in time and assessed the duration of that pond existence.

Figure 4 shows that the formation of a pond on the reclamation surface has the potential to have a substantial impact on the phreatic surface as total heads at the piezometer locations and drain outflows rise above initial levels for some of the scenarios. The total head difference 1 year after the scenario change was negligible for all scenarios. Scenarios 1, 2, 3, and 6 resulted in maximum total head differences with the no pond condition that exceeded 5 m for all piezometer locations (except Piezometer 8). These scenarios evaluated a pond forming at different points of time with different depths. Similar to the total heads, the drain outflows for Scenarios 1, 2, 3, and 6 rise to a similar water rate at the respective times (Schafer 2022). These scenarios show that a pond forming on the reclamation surface has the potential to impact the phreatic surface regardless of what point in time it forms or how deep the pond is.

Scenarios 4 and 5 investigated the impact of how long the pond remained on the reclamation surface. Scenario 4 considered the pond forming at year 10 and remaining for 1 year. For this scenario, the total heads for Piezometers 1 to 7 begin to rise initially and then decrease back down to the no pond condition following removal. The maximum total head difference exceed 5 m for all piezometers nor rise above the initial condition. The level 2 drain outflow is not impacted while The level 1 drains show an increase in the drain outflow initially that decreases following pond removal.

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

Climate change

It is common practice to use historic climate information when conducting long-term analysis (Ferguson et al., 2009). However, this is changing as regulations move towards expecting operators to account for long term failure modes that may not be present during operations and develop risk profiles that account for the uncertainties in predicting the future, including climate change. Due to the potential impact on the phreatic surface, climate change scenarios were investigated to determine if the results were significant enough to warrant using climate projections (especially at a preliminary design level).

To account for climate change, global climate models (GCMs) can be used to provide information regarding long-term changes to annual and seasonal precipitation, season length, air temperature, etc. (IPCC 2014). Three scenarios (two with GCMs (CSIRO-Mk2-6-0 and IPSL-CM5A-LR) and one Representative

Concentration Pathway, RCP 8.5) were conducted and compared to a base case that used historic climate information. The scenarios evaluated the impact of climate change to the year 2100, which represents the time period that climate change projections are available in the greatest detail (IPCC, 2014).

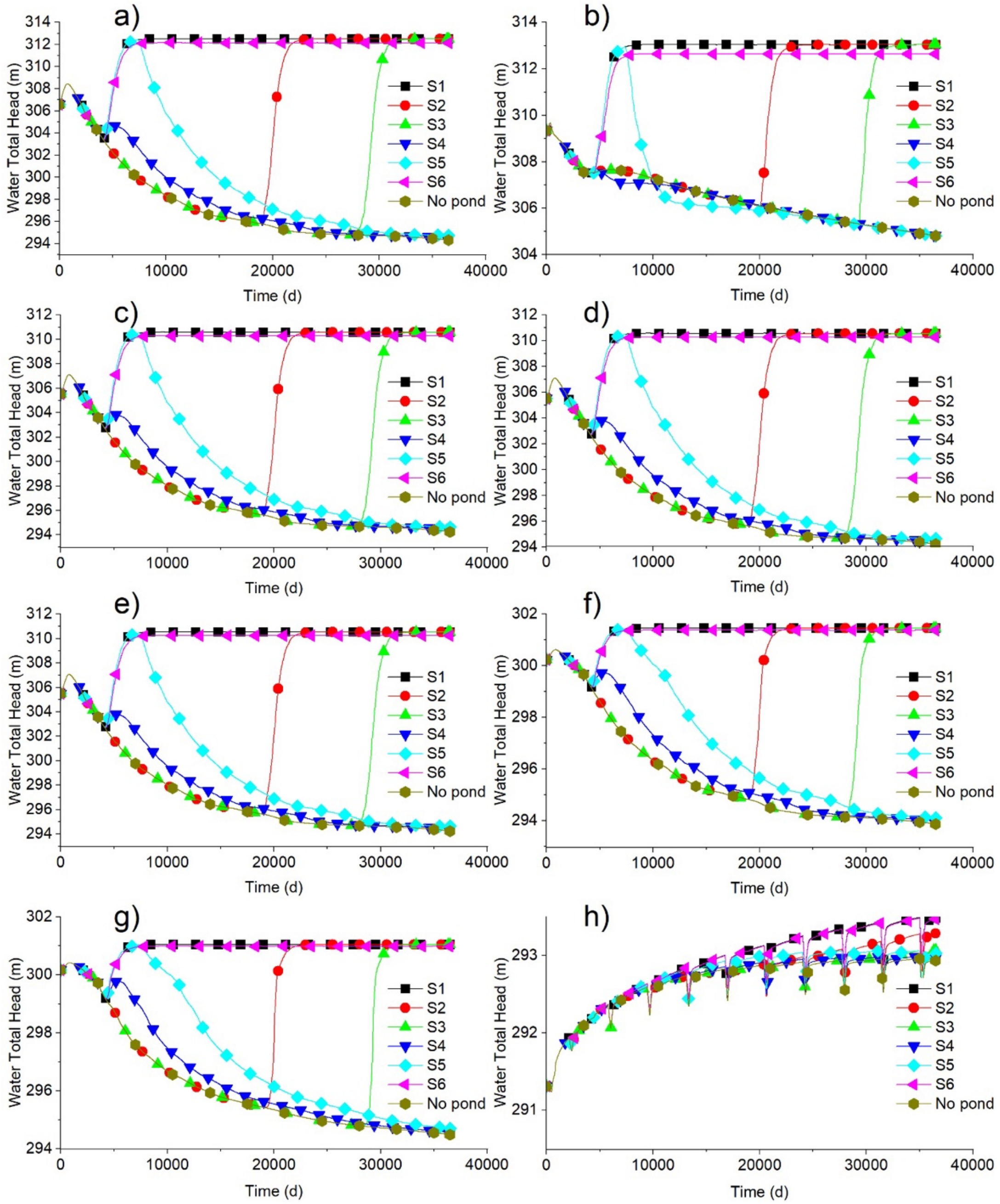

Figure 4: Total head over time for pond formation scenarios for a) Piezometer 1 b) Piezometer 2 c) Piezometer 3 d) Piezometer 4 e) Piezometer 5 f) Piezometer 6 g) Piezometer 7 h) Piezometer 8

RCP 8.5 was selected to evaluate an extreme emissions scenario on the phreatic surface. Data were attained for the GCMs from ClimateData.ca from the CMIP5 climate model datasets (Climeatedata, 2022;

McKenney et al., 2011). Full details of the climate data are provided in Schafer (2022). The results of the modelling show a minimal impact on the phreatic surface in response to the integration of climate change from each scenario into the LCI boundary condition.

Discussion

The impact of different potential changes to the phreatic surface of a case study dam were investigated using transient seepage modelling to inform and guide risk management decisions, including monitoring and maintenance schedules, where applicable. It is commonly assumed that the phreatic surface of a reclaimed tailings dam will decrease over time; however, these assumptions need to be supported by literature from other sites, field performance, and modelling projections due to the importance of the phreatic surface on the stability of the facility.

Evaluating the change in the total head difference between the scenarios and the no failure base case at different points in times is a useful tool when it comes to establishing monitoring and maintenance schedules. The phreatic surface increased with drain failure when the phreatic surface was above the drain before failure. This has important implications for guiding maintenance plans during periods when drain performance is critical to controlling the phreatic surface. For example, the results showed that the level 2 drain failure does not impact the phreatic surface following 10 years as the phreatic surface is sufficiently low (Scenario 2 in Figure 3). Consequently, maintenance of the level 2 drains may be more important in the first 10 years, especially when there is the potential for the level 1 and level 2 drains to fail together (Scenario 7 in Figure 3).

A pond forming on the reclamation surface was modelled at different points in time, remaining for different points of time, and with different depths. All scenarios showed a substantial impact on the phreatic surface in response to the pond formation. The general trend showed that there needs to be a careful evaluation of the impact of a pond forming on the reclamation surface, especially for closure plans that are designed to have wetlands incorporated into the reclamation surface. The scenarios did not assess the impact of the location of the pond on the phreatic surface and should be assessed for site specific considerations. The implementation of climate change resulted in minor changes in the phreatic surface. Consequently, it may be appropriate to use historical data sets for the LCI boundary condition in the early planning stages.

Long-term seepage modelling can be used to help guide monitoring and maintenance plans, which can be anchored back to the observational method or an adaptive management framework. As an example, pond formation resulted in a substantial increase in the phreatic surface, regardless of the point in time that it happened at. Scenario 4 investigated the impact of a 1.0 m pond forming at year 10 and remaining for only 1 year. In this scenario, the phreatic surface increased rapidly, but did not rise above the initial condition (Figure 4). In contrast, the pond remained for 10 years in Scenario 5 and the phreatic surface rose substantially above the initial condition before lowering following the removal of the pond (Figure 4). This may suggest that a 1-year maintenance schedule (combined with regular monitoring) is required to respond to the formation of any ponds on the reclamation surface to prevent the phreatic surface from rising above the initial condition. The schedule could be amended as more is learned about the dam's behaviour in closure and compared to the seepage modelling predictions. As with anything in closure, this requires a realistic evaluation of the custodial transfer scenario.

Conclusions

Seepage modelling was conducted on a case study oil sands tailings dam to investigate how the phreatic surface of a tailings dam may evolve over time in response to various factors. The seepage modelling showed that the phreatic surface has the potential to rise in response to different events, including the formation of ponds on the reclamation surface and drain failure. The predicted rise should be compared to historical piezometer levels as a way of assessing how critical the change in the phreatic surface may be to the potential for a failure mode to develop.

Long-term seepage modelling requires data to be collected during design, operations, and closure/reclamation, including climate data, material properties, and piezometer and drain outflows. Seepage modelling represents one tool that can be used to reduce uncertainty in long-term risk management of tailings facilities and can be accompanied by other methods, such as LEM to understand the geomorphology. The process of using long-term seepage modelling to guide monitoring and maintenance plans is all a part of the process of continuously learning and creating a "story" to build a comprehensive understanding of the tailings dam. These tools allow practitioners to forecast complex processes and employ engineering judgement in risk management decisions. The confidence in these tools may be increased over time through the comparison of model predictions to field data.

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