

Assessing the effect of snowmelt on mine covers in cold climates using numerical modelling and laboratory columns

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Abstract

Multilayer cover systems are commonly used for reclamation of waste rock and tailings facilities to prevent the diffusion of oxygen to underlying mine waste. The construction of this type of cover needs large amounts of soil material. The material needs specific hydraulic properties, e.g. the sealing layer properties that are difficult to reach, such as low hydraulic conductivity and high water-retention capacity. To enable the use of locally available soils that do not meet those requirements, a proposed solution is to include a bentonite mat in the sealing layer.

In this study, the performance of a sealing layer composed of a bentonite mat associated with a layer of either compacted or uncompacted till is evaluated. The cover is evaluated using numerical modelling and laboratory columns built as a replicate of a field trial.

The cold climatic conditions of boreal areas are characterised by a dry winter period accumulating precipitations that are released during a short and wet snowmelt period. The objective of the research is to simulate and understand the effect of such rapid succession of water regimes, including the effect of snow cover, on the water balance in the cover and its effect on the performance of the cover. Field trial monitoring data obtained from soil moisture sensors were used to calibrate and validate the numerical model, ensuring its accuracy and reliability in predicting the performance of multilayer cover systems under real weather conditions.

This approach allows a better understanding of how a multilayer cover will perform during the dry winter, the wet snowmelt, and the humid summer and autumn. Combining laboratory columns and numerical modelling is hypothesised to provide an efficient way to assess the performance of different designs.

Keywords: mine cover system, numerical model, field pilot test, laboratory column test

1 Introduction

The demand for raw materials is significantly increasing and Europe is aiming to develop its production capacity for critical minerals, looking to the Arctic regions and their documented vast resources (International Energy Agency 2023; European Commission 2023).

In Sweden, the mining industry is the largest producer of solid waste (Swedish Environmental Protection Agency 2020); a large fraction of which contains sulphidic minerals that have the potential to produce acid rock drainage (ARD) if in contact with water, oxygen and microorganisms (Akciil & Koldas 2006; Moodley et al. 2018; Nigéus et al. 2023; Saria et al. 2006). ARD, due to its low pH and content of trace elements, is a threat to the aquatic environment (Moodley et al. 2018; Saria et al. 2006). Mine site reclamation is therefore considered the most critical and challenging phase of mining operations (Aubertin et al. 2016), and must be long-lasting and resilient to climate change (Bresson et al. 2022) – especially in Arctic conditions (Box et al. 2019).

The multilayer cover system is a common closure measure used to mitigate the formation of ARD, limit the infiltration of water and oxygen into mine waste, and reduce ARD formation (Bussi re et al. 2003; Nig us 2023). These soil covers and laboratory columns are illustrated in Figure 1, consist generally of several layers

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with different hydraulic properties, e.g. a low permeable sealing layer placed on top of the mine waste, and a protection layer placed above the sealing layer to protect it from erosion and root penetration. Finally, the vegetation layer is placed as the top layer of the mine cover for enhancing vegetation establishment.

A major challenge in Arctic regions is the scarcity of raw materials for constructing engineered cover systems, especially material with low hydraulic conductivity. Maintaining a high degree of saturation above 85% efficiency limits oxygen diffusion because the air phase in the soil layer becomes discontinuous (Corey 1957), forcing oxygen to be transported through the water phase (Aubertin & Mbonimpa 2001). Therefore, the requirements for the saturated hydraulic conductivity of cover soil are commonly set to $< 10^{-8}$ to 10^{-9} m/s in Sweden, even though they are site-specific.

Extraction and transport of large quantities of natural materials have significant environmental and economic impacts. Therefore, a responsible mine site restoration needs to take material availability into account using locally available materials. One identified option to build low-permeability barriers is the use of bentonite mats to improve local soil. Such approach would consequently be beneficial and help reduce long-distance transport of impermeable soil while minimising pollution, energy consumption and emissions.

Further, Arctic conditions, characterised by long winters with frozen water in the cover, and short and intense snowmelt periods with an excess of water, are challenging for the function of mine cover systems. To assess the performance of a cover system in specific climatic conditions, the SEEP/W (GeoStudio 2024.2.1) software can be used to model the water infiltration and drainage behaviour of soil cover systems. Modelling can also be used to simulate the hydraulic behaviour of soil cover under varying climatic conditions, providing insights into the long-term performance of soil cover system requirements (Ziagharib 2024).

The aim of the study was to simulate and assess the effect of such a rapid succession of water regimes, including the effect of snow cover and its melting, on the water balance in the cover and on the performance of the cover. The goal of the project is to facilitate the design of cover geometry with available soils in boreal regions, i.e. glacial till.

Using both numerical seepage finite element modelling (SEEP/W) and laboratory columns replicating a field trial, the effect of snowmelt and seasonal precipitation fluctuations on the water balance and effectiveness of the sealing layer was assessed.

2 Materials and methods

In this study, monitoring data and weather data from a field site constructed in 2021 at Boliden Mine in Garpenberg (latitude 60°37'06" north) were used to validate the model. Weather data from the Avesta weather station served as the field data. Multilayer covers composed of a bentonite mat, 50 cm compacted or uncompacted glacial till as a sealing layer and 150 cm uncompacted glacial till as a protection layer were studied, monitoring the volumetric water content (VWC), soil temperature and soil water potential.

In a second phase of the study, weather data from Luleå in Northern Sweden (latitude 65°58'48") were applied in the SEEP/W numerical analysis for the same mine cover design to compare the performance of the cover in cold climatic conditions (2°C colder on average, snowmelt one month later than in Garpenberg), i.e. across long and dry winters with rapid snowmelt periods and humid summers.

2.1 Column test set-up

A column test was built at Luleå University of Technology using glacial till soil from the Garpenberg Boliden Mine. The column structure, presented in Figure 1, was constructed using polyvinyl chloride (PVC) tubes with an internal diameter of 30 cm and a total height of 190 cm. Each column was assembled by connecting a 130 cm long PVC tube with a 60 cm segment using appropriate connectors. A water outlet was placed at the base of each column, with a water tap installed 25 cm from the bottom to enable water sampling and drainage control. The bottom of the column was sealed using a designated stopper to prevent leakage during testing.

2.1.1 Drainage layer

The 25 cm base of the column was filled with coarse gravel (8–16 mm) to act as a drainage layer. This layer was consistent with the field trial design to ensure alignment between laboratory and field conditions for accurate evaluation. A geotextile fabric was placed above the gravel to prevent downward migration of fine soil particles and to protect the water tap from clogging, then mine waste placed above the gravel.

2.1.2 Sealing layer

The sealing system consisted of a 1 cm-thick bentonite mat followed by a 50 cm layer of compacted or uncompacted till, resulting in a total sealing thickness of 51 cm. This layer was divided into five 10 cm sublayers. Each was compacted to a target dry density of 2.05 g/cm³ for compacted till or 1.85 g/cm³ for uncompacted till. Soil moisture Campbell CS655 sensors and water potential Campbell 229 L sensors were embedded at two strategic positions: 15 cm from the bottom and 15 cm from the top of the sealing layer.

2.1.3 Protection layer

A 70 cm thick protection layer of till soil was placed on top of the sealing layer. This layer was also divided into seven 10 cm sublayers. Each sublayer was compacted to a dry density of 1.85 g/cm³, with a moisture content range between 6 and 9%. Sensors were installed at two locations to monitor long-term performance: 15 cm from the bottom and 15 cm from the top of the protection layer.

Prior to placement, the soil was screened to remove oversized gravel particles and cobbles. Each soil layer was placed in a loose state at the desired moisture content before compaction. Care was taken to ensure homogeneity and uniform layer thickness throughout the column, as illustrated in Figure 1a.

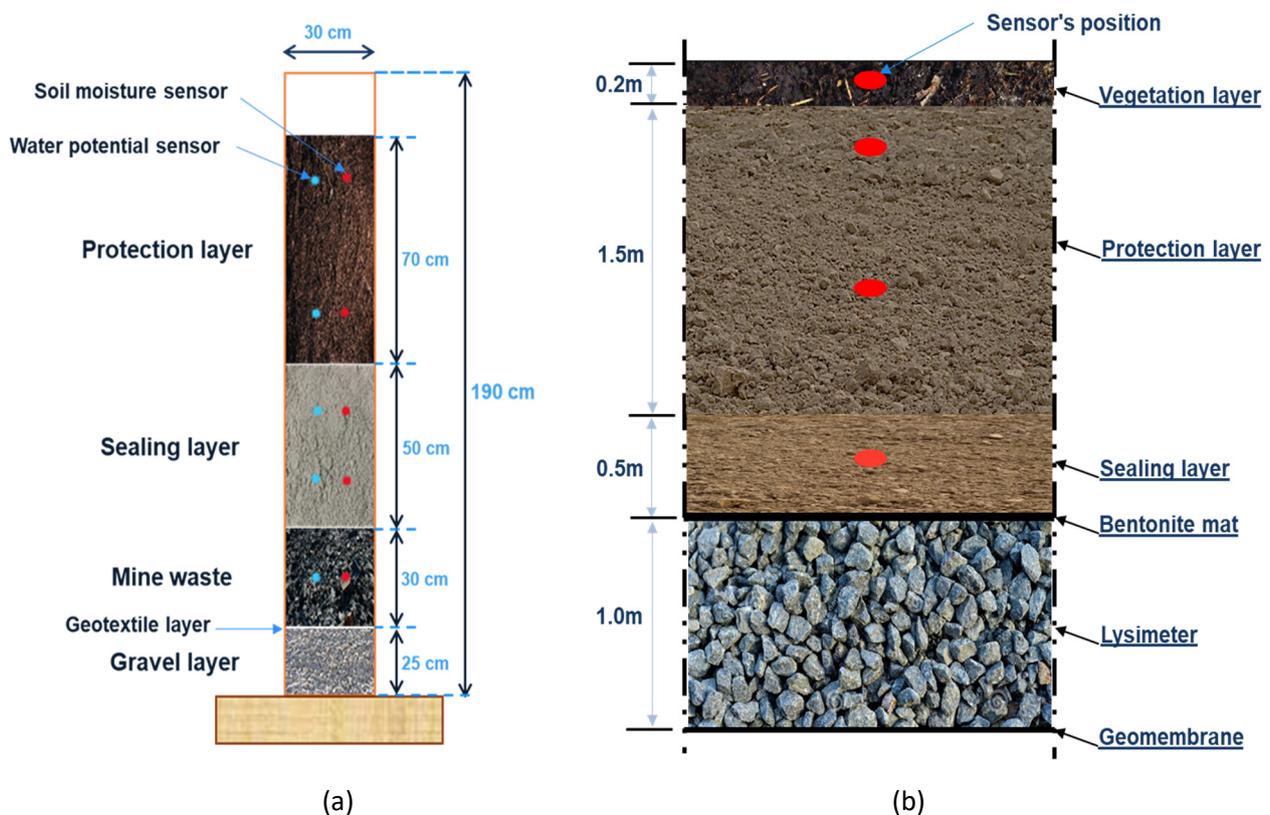


Figure 1 (a) Laboratory column set-up showing sensor positions indicated by red and blue dots; (b) Geometry of the mine field trial showing sensor positions indicated by red dots

2.2 Field trial

The field pilot trial was conducted at Boliden Mine in Garpenberg. After excavating soil, a lysimeter with a depth of 1 m was installed. The base of the lysimeter measured 8 m in width and featured side slopes with a gradient of 1V:2H to ensure appropriate surface drainage behaviour. To isolate the lysimeter and prevent lateral water infiltration, an impermeable geomembrane layer was installed across the entire bottom and sidewalls of the lysimeter. A drainage outlet was installed at the lowest point of the lysimeter to collect the water, in a tipping bucket, to measure water percolation through the sealing layer.

The lysimeter was backfilled with a layer of coarse gravel to facilitate drainage. A second geotextile layer was then placed above the gravel to act as a filter barrier, preventing the migration of fine particles into the drainage layer.

The sealing layer, which forms the low-permeability component of the cover system, consisted of a bentonite mat layer combined with till material having a grain size fraction of 0–50 mm. This layer was constructed and compacted in two separate lifts. Each lift was compacted to meet the target density requirements specified in the sealing layer design, ensuring sufficient density and impermeability. Above the sealing layer, a 150 cm uncompacted till layer was placed to serve as the protective layer. This layer was also constructed in two lifts and left uncompacted to promote water retention. A 20 cm vegetation layer was subsequently established on top, in accordance with the cover design principles. The configuration of the lysimeter and cover system is illustrated in Figure 1b.

2.3 Numerical modelling

The SEEP/W model in GeoStudio 2024.2.1 was used to develop 2D axisymmetric seepage models with 1 cm mesh size, representing the laboratory column test which was also modelled using SEEP/W, with the same soil hydraulic properties used in the field model applied, as summarised in Table 1. These properties were estimated from pressure plate tests according to the ASTM D6836 (Method B) standard (ASTM International 2016) and constant head tests per the ASTM D5084 standard (ASTM International 2024), for both compacted and uncompacted till. The bentonite mat properties were provided by the supplier, while the coarse gravel properties were approximated based on typical literature values and material specifications.

The model incorporated time-varying water flux boundary conditions to simulate the application of water and evaporation processes occurring over the experimental period from February 2025 to April 2025. These flux conditions, representing water addition and surface evaporation, are illustrated in Figure 2 and were applied to the top boundary of the column model.

Table 1 Soil hydraulic parameters, including van Genuchten hydraulic parameters and saturated hydraulic conductivity for mine cover soils

Soils	van Genuchten parameter				
	Alpha (α)	Theta s (θ_s)	Theta r (θ_r)	n	k sat (m/s)
Uncompacted till	0.679	0.303	0.006	1.666	1e-5
Compacted till	0.5	0.25	0.006	1.55	1e-6
Coarse gravel	30	0.25	0.01	3.5	1
Bentonite mat	0.008	0.55	0.06	1.25	2.5e-11

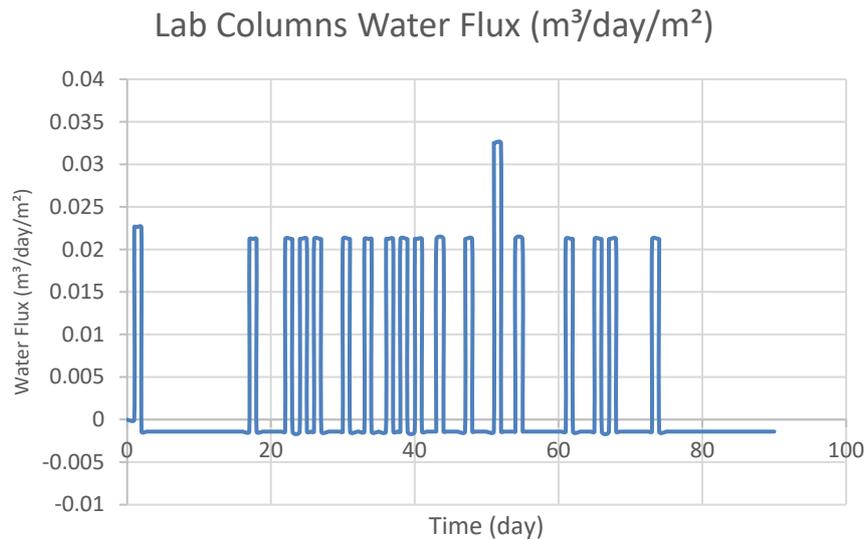


Figure 2 Adding water and evaporation data from February 2025 to April 2025 for the laboratory columns test

The field trial used 2D seepage models with 2 cm mesh size and the geometry used in the numerical model was consistent with that illustrated in Figure 3, including the uncompacted sealing layer design. In this model the vegetation layer was represented as uncompacted till. Soil hydraulic properties for each layer were defined as summarised in Table 1. Boundary conditions were applied based on experimental set-up and field observations. To start the model, field-monitored data were utilised in conjunction with weather data from Garpenberg, including snow cover depth (m), wind temperature (°C), relative humidity (%) and precipitation (m). These parameters were incorporated to simulate realistic hydrological behaviour under actual field conditions.

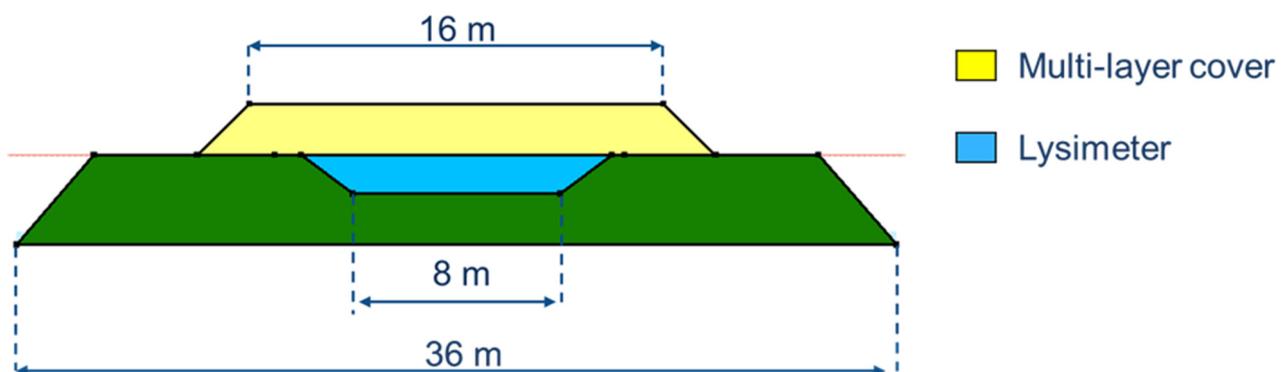


Figure 3 Numerical model geometry

Additionally, weather data from Luleå, which represents a cold climate region, were applied to the same model set-up. This allowed for a comparative analysis of the cover system's performance under different climatic scenarios, particularly evaluating its effectiveness in limiting seepage during freeze-thaw cycles and periods of snow accumulation and melting.

Weather data for model simulation are collected from the Swedish Meteorological and Hydrological Institute webpage. All data was submitted to the model each day. Also, wind speed, precipitation, air temperature, relative humidity and net radiation average values every day from June 2022 to August 2023 were managed by Python code as shown in Figures 4–7.

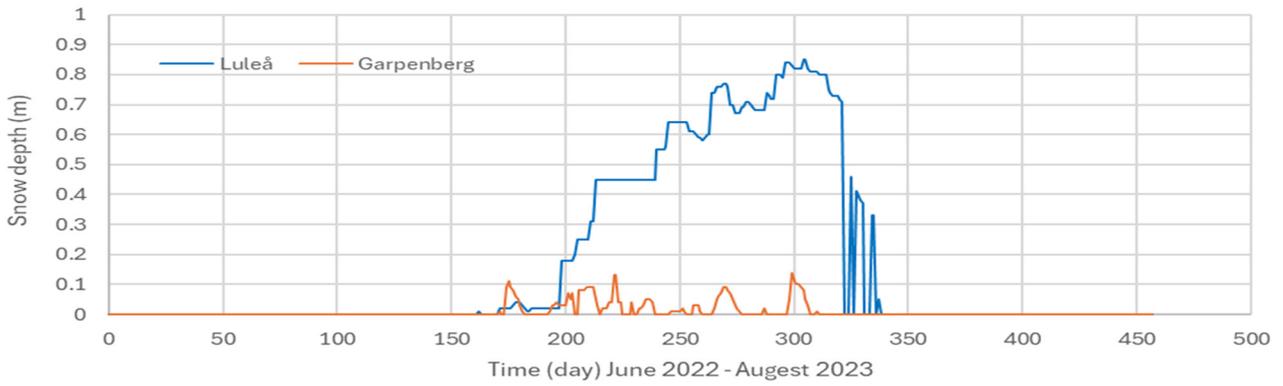


Figure 4 Garpenberg and Luleå snow depth data from June 2022 to August 2023

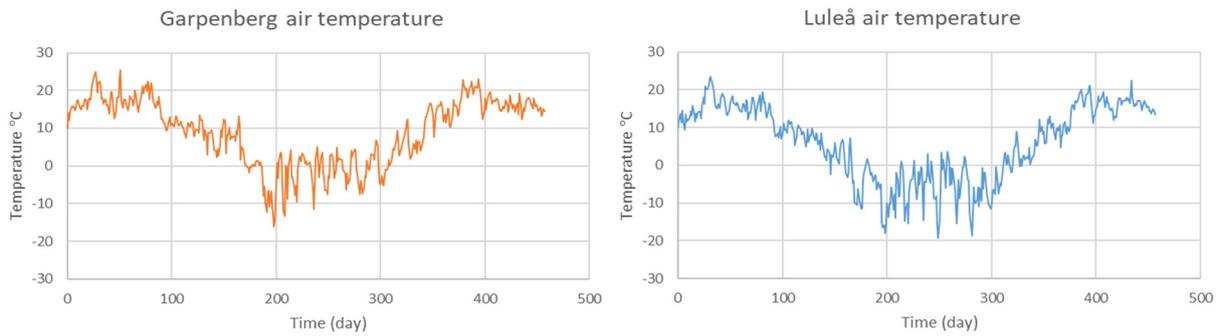


Figure 5 Garpenberg and Luleå air temperature data from June 2022 to August 2023

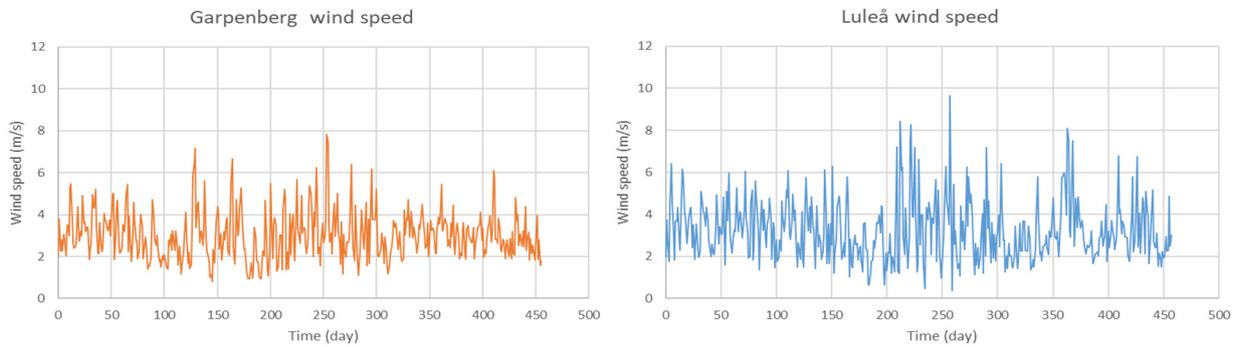


Figure 6 Garpenberg and Luleå wind speed data from June 2022 to August 2023

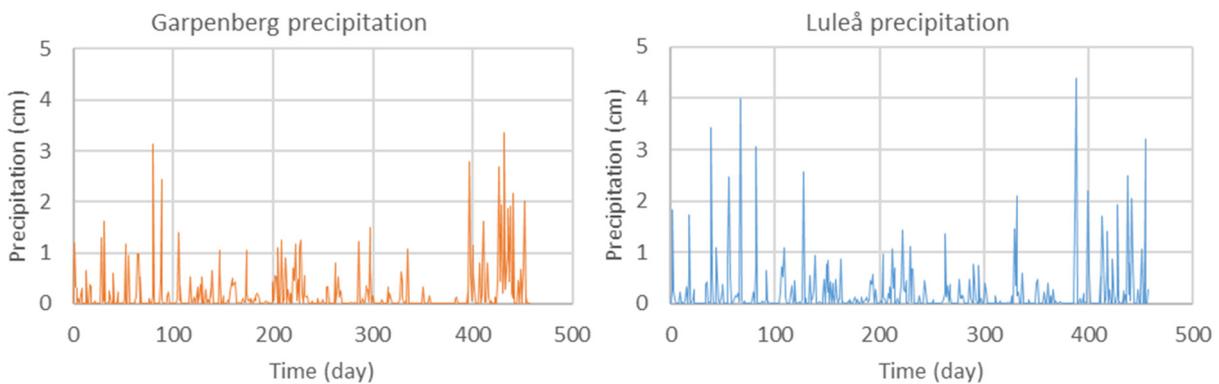


Figure 7 Garpenberg and Luleå precipitation data from June 2022 to August 2023

3 Results

The results from the SEEP/W simulations of the two laboratory column cover designs are presented in this section. Figure 8 illustrates the numerical model outputs for the cover system composed of a bentonite mat overlaid by a 50 cm compacted till sealing layer. The simulation results are compared with VWC data recorded by sensors installed at various depths within the sealing layer during the water addition phase. These sensor positions, labelled C5 (top of the cover) and C2 (within the sealing layer), correspond to the layout shown in Figure 1a. The same data from a bentonite mat with uncompacted till cover design are shown in Figure 9. During the first 50 days, the modelled VWC is lower than the measured VWC. The difference is higher in the column with compacted glacial till compared to the uncompacted one. The modelled VWC follows the measured data, varying in accordance with the watering cycles. After two months, the situation is the opposite as the modelled VWC is higher and indicates full saturation.

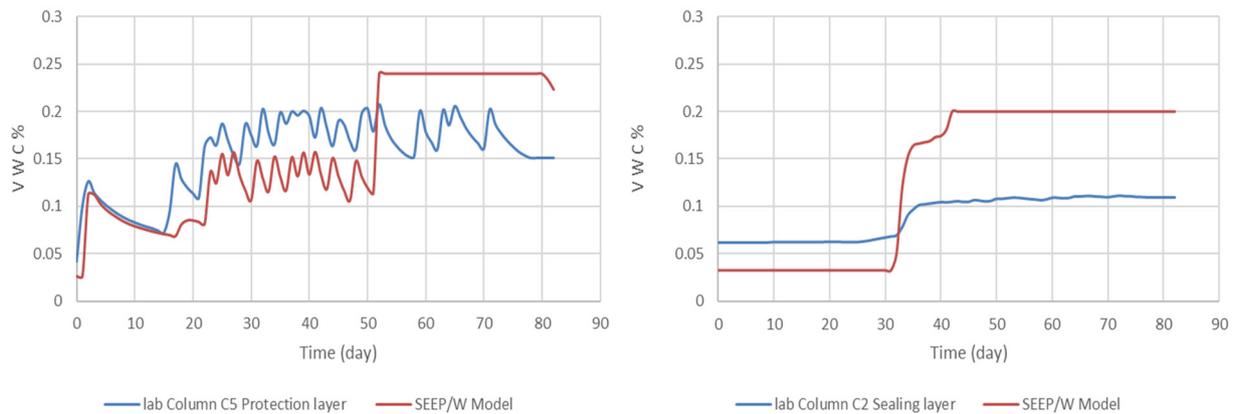


Figure 8 Laboratory column and SEEP/W model data for a bentonite mat with a compacted till cover

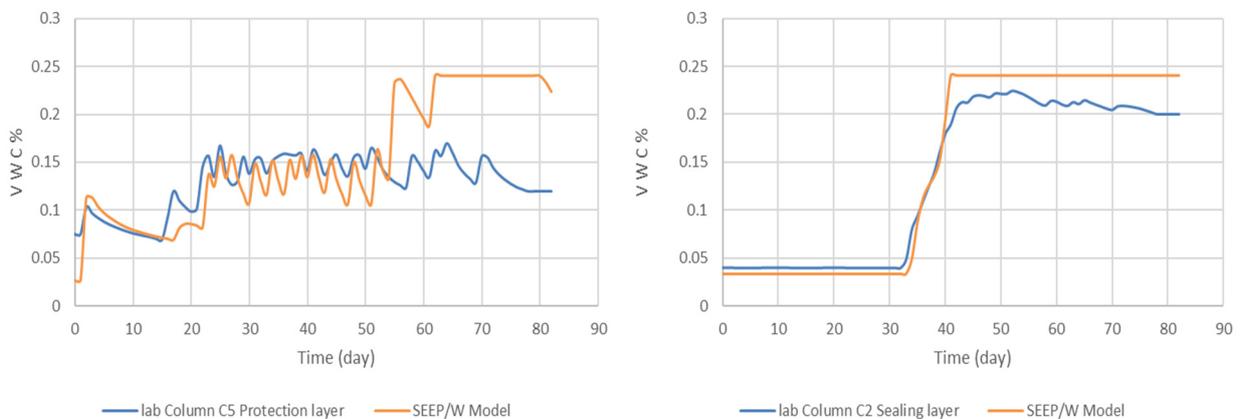


Figure 9 Laboratory column and SEEP/W model data for a bentonite mat with an uncompacted till cover

Figure 10 presents the simulated VWC over time from the SEEP/W model for the bentonite mat with uncompacted till cover design. The degree of saturation is related to VWC and soil porosity by Equation 1:

$$\Theta = S * n \tag{1}$$

where:

- Θ = volumetric water content
- S = degree of saturation
- n = soil porosity.

The simulated VWC results were compared with field monitoring data recorded at various depths within the cover system. However, data from monitoring stations were unavailable for the period between day 216 (5 January 2023) and day 361 (4 June 2023). At the surface, the modelled VWC follows the precipitation pattern with good accordance. The modelled VWC is lower than the measured. Above the sealing layer, the VWC is stable. The modelled values are lower than the measured during the first period. After 400 days, the model is able to predict the measured values.

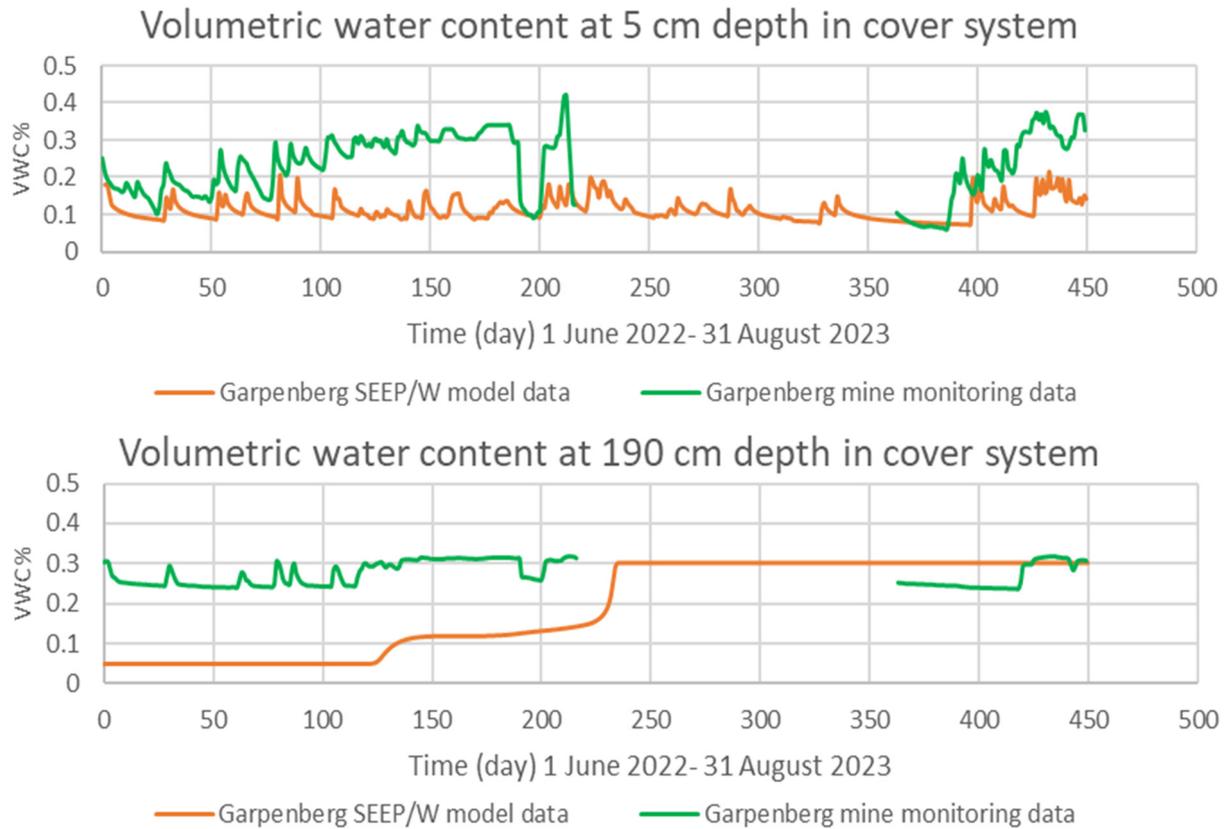


Figure 10 SEEP/W model and field monitoring data for the uncompacted cover design

Figure 11 presents SEEP/W model results for VWC at different depths of the mine cover over the same duration, comparing the two climate boundary conditions: one based on weather data from Garpenberg and the other at Luleå. During the first 300 days in the upper levels the difference between the sites is small. After the snowmelt (days 325–350) the model diverged and the Luleå scenario was fully saturated.

In the deeper level the divergence occurred earlier (day 75) and both scenarios were fully saturated after day 225.

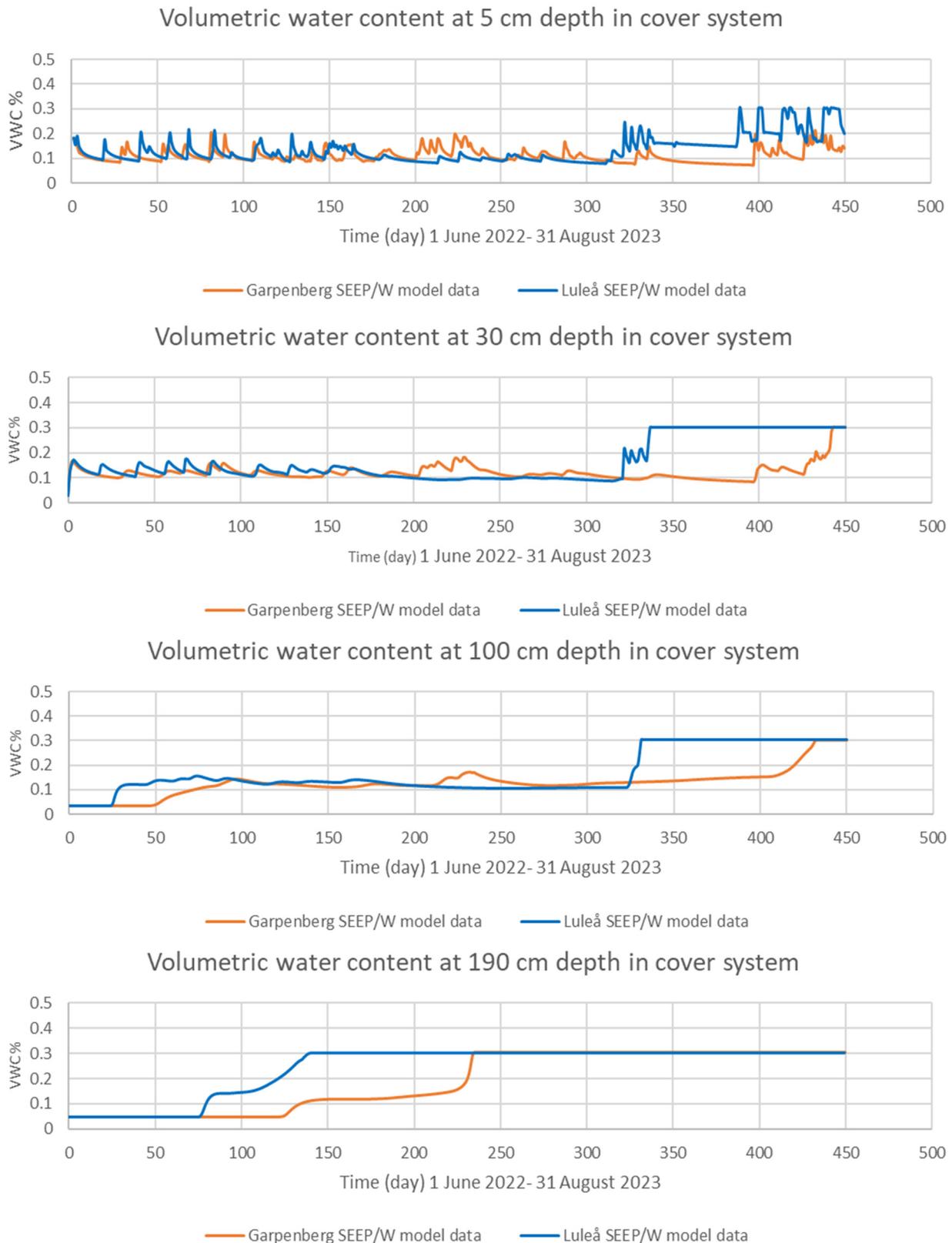


Figure 11 SEEP/W model data for two different climate conditions at different depths of a bentonite mat with an uncompacted till mine cover

4 Discussion

The results from modelling the columns follow the same pattern as the monitoring data with acceptable accordance, although notable discrepancies are present, i.e. the modelled VWC is lower than the measured. In the initial phase of the experiment (0–50 days), the observed VWC in the laboratory column was consistently higher than the values predicted by the SEEP/W model. This discrepancy is attributed to differences in initial moisture conditions between the column and model, and a difference in the degree of compaction. After 50 days the model's VWC values became higher and more stable compared to the column measurements. This is hypothesised to be caused by the porosity applied in the model being higher than that achieved in the actual column. Additionally, fluctuations observed in the column's VWC data after 50 days may be indicative of water leakage from the column set-up, potentially due to flow along the PVC tube; an artefact not accounted for in the model as the bentonite mat was assumed to be continuous. The lower VWC in the initial phase is attributed to a difference in initial water content in the soil, i.e. the modelled soil was dry while the soil in the column was humid.

The modelled VWC in the surface of the cover followed the same pattern as the monitored data, taking into account precipitation events. Furthermore, model convergence was verified as all computed points aligned accurately along the hydraulic conductivity function, confirming numerical stability and consistency of the simulation. To improve model accuracy, the effect on the measured hydraulic properties of screening large particles from cover material laboratory samples, and measuring radiation and evaporation at the site, should be considered. A better characterisation of initial soil moisture condition and considering the long-term changes in physical properties may, together with including surface run-off in the modelling framework and the effect of vegetation (e.g. the existing moss layer), improve the prediction of the model.

The effect of different climate conditions, i.e. the snow cover duration, is shown by the data in Figure 11. The modelled VWC with cold climate data (Luleå) is stable during the winter period (snow cover time) in the upper metre of the cover, while the VWC is lower in the climatic conditions of Garpenberg. When snowmelt occurs, the stored precipitation is released in a short period (days 325–345) and generates a high VWC for a short duration compared to Garpenberg, where the snowmelt occurred one month earlier and the ground was periodically free from snow.

Also, the modelled data indicate that the degree of saturation (> 85%) was reached faster in the deeper part of the cover with the cold climate model (Luleå), than the temperate climate model (Garpenberg). This difference is attributed to the cumulative amount of precipitation and the boundary conditions at the starting point of the modelled period, i.e. a spring without the water storage from the snow cover. In a full-scale construction, ending the construction in the autumn when the ground freezes and is rapidly covered by snow may reduce early infiltration and delay the saturation of the cover compared to a situation where autumn rain may infiltrate in the soil. The multilayer cover system reached saturation after autumn precipitations and the VWC was maintained as stable under both simulated climate scenarios. The results indicate that the cover system has the potential to efficiently maintain high degree of saturation (> 85%) over time and that winter does not appear to alter its function. However, these observations are based on modelled scenarios that may not fully capture the complexities of long-term environmental interactions and material behaviour on a cover. Further work is needed to validate the model and better capture the effect of vegetation and run-off on the water balance.

Future investigations should also focus on the impact of slope inclination on water infiltration through each layer of a multilayer cover. Understanding these effects would offer insights for optimising cover system performance across varying topographical conditions.

5 Conclusion

This study focused on assessing the hydraulic performance of a multilayer mine cover system incorporating a bentonite mat combined with till material under two different climatic conditions. The assessment was conducted by integrating laboratory column experiments with SEEP/W numerical modelling and data from a

field pilot trial. The SEEP/W modelling of the VWC of the column generally followed the pattern of the monitored VWC, indicating that the model can reasonably capture the water flow behaviour in the cover system. However, discrepancies in the VWC values highlight the limitations of modelling, i.e. assuming homogeneity and high density of the soil layers, especially given the variability in compaction across different field locations.

Differences between the simulated and observed data are primarily attributed to variations in the initial soil water content, the use of non-local weather data (i.e. from the Avesta weather station) and natural changes in the soil's physical properties, such as consolidation over time. Furthermore, the exclusion of surface run-off in the model is expected to contribute to deviations from the field measurements.

Climatic conditions, especially the snow cover duration, significantly influence VWC dynamics. In colder climates (Luleå), the VWC stays stable during winter and spikes sharply during the spring snowmelt. The cold climate model also reached saturation (> 85%) faster in deeper layers due to higher cumulative precipitation. Conversely, the shorter winter, with several snowmelt events in Garpenberg, led to a more gradual VWC response. These findings highlight the need to consider local weather, construction timing, and soil variability in cover system design and modelling.

The use of numerical modelling to simulate the multilayer mine cover system under different climate conditions is valuable to assess the cover performance, and the model showed an accurate response to changes in weather data and the effect of snow cover in a cold climate area on a multilayer cover design. This approach allows a better understanding of how a multilayer cover will perform during the dry winter, the wet snowmelt, and the humid summer and autumn. Combining laboratory columns and numerical modelling is hypothesised to provide an efficient way to assess the performance of different designs.

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