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POLYTECHNIQUE MONTRÉAL

affiliée à l'Université de Montréal

et

l'Université du Québec en Abitibi-Témiscamingue

**Optimisation of snow management practices on tailings storage facilities to reduce
spring freshet intensity and geoenvironmental risks**

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Mémoire présenté en vue de l'obtention du diplôme de Maîtrise ès sciences appliquées

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Ce mémoire intitulé:

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présenté par **Mohammad Mahdi Karamouzian**

en vue de l'obtention du diplôme de Maîtrise ès sciences appliquées

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DEDICATION

My dearest, your unwavering love and support have been my rock throughout this academic journey. This achievement is as much yours as it is mine.

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RÉSUMÉ

La gestion de l'eau est un défi important pour l'industrie minière et plus particulièrement au printemps lors de la fonte de la neige. Une quantité importante de l'inventaire annuel de l'eau peut être stocké sous forme de neige à la surface des parcs à résidus miniers. Ceci fait qu'au dégel, une quantité d'eau importante est libérée sur une période relativement courte, appelée crue printanière. La durée et l'intensité de la crue peut varier d'une année à l'autre, mais entraîne des défis importants en gestion de l'eau sur les parcs à résidus. La grande quantité d'eau à gérer fait que les infrastructures de gestion et de traitements des eaux ainsi que les ouvrages de retenue des résidus miniers sont sollicités à pleine capacité durant cette période. Dans un contexte de changements climatiques où il y a une augmentation dans la variabilité et les extrêmes de plusieurs variables du cycle de l'eau, les crues printanières représentent un risque grandissant sur la stabilité des infrastructures de gestion de l'eau et des rejets miniers. Cette étude explore l'utilisation de piles de gestion de la neige comme solution pour contrôler l'intensité et les taux de fonte de la neige lors de la crue printanière. Ces piles sont conçues pour contrôler le taux de fonte et ainsi réduire les débits de pointe des eaux de fonte. En gérant le moment et le volume d'eau entrant dans les installations de stockage des résidus, les piles de gestion de la neige peuvent aider à maintenir l'intégrité des infrastructures de gestion des rejets miniers et à atténuer les risques géotechniques et environnementaux qui y sont associés.

L'objectif principal de cette recherche est d'évaluer l'efficacité des piles de gestion de la neige à contrôler la fonte de la neige sur les parcs à résidus miniers. Plus précisément, l'étude vise à évaluer comment les piles de gestion de la neige peuvent contrôler les taux de fonte de la neige, réduire les pics de débit de fonte et prolonger le temps de fonte. Pour ce faire, six piles de gestion de la neige ont été construites à l'échelle pilote sur deux sites miniers sur une période de deux ans. Les méthodes utilisées ont évalué la capacité d'équipements civils conventionnels et d'équipement spécialisés à construire des piles de gestion de la neige de manière optimale. Les piles de gestion de la neige ont été conçues avec des profils cubiques, coniques et en crête. La fonte des piles de gestion de la neige a été suivie par des mesures de changements de volume, hauteur et d'empreinte à l'aide de

techniques de photogrammétrie et de relevés LiDAR. Des mesures de densité de la neige ont également été obtenues par échantillonnage de carottes de neige à différents intervalles.

Les résultats ont indiqué que les piles de gestion de la neige permettent d'augmenter la durée de la fonte de la neige en prolongeant le processus d'environ quatre à six semaines. Le volume et la hauteur des piles de gestion de la neige se sont révélés être des facteurs critiques influençant leur capacité à réguler la fonte des neiges.

Un modèle numérique simplifié décrivant la fonte des piles de gestion de la neige a été développé. Les résultats ont montré que la prédiction du comportement en fonte avait une erreur moyenne de 6,75 % par rapport aux mesures de terrain, tandis l'erreur de la prédiction de la durée totale de la période de fonte des piles de gestion de la neige était inférieur à 4 %. Sur la base de ces résultats de modélisation, des graphiques de prédiction de la fonte des piles de gestion de la neige ont été développés, prenant en compte les dimensions, la forme et le coût de construction des piles de neige. Des équations décrivant la performance anticipée de piles de gestion de la neige en fonction de la hauteur ou du volume des piles de gestion de la neige ont été développées basées sur les résultats de 35 configurations de piles modélisées. Il a été constaté que les piles de gestion de la neige en forme de cône sont très sensibles aux changements de température, tandis que les piles de gestion de la neige en forme de crête sont moins sensibles et présentent des performances plus stables sous différentes sollicitations climatiques. Ces graphiques pourraient être utilisés pour concevoir des piles de gestion de la neige et réduire les risques géotechniques des parcs à résidus miniers durant la fonte printanière.

L'étude a conclu que les piles de gestion de la neige peuvent aider à atténuer les risques environnementaux et géotechniques associés à la fonte rapide des neiges, réduisant potentiellement le besoin d'installations de stockage et de traitement supplémentaires lors d'événements extrêmes. Cela est particulièrement important dans le contexte des changements climatiques, où la prévision des futurs schémas météorologiques devient de plus en plus difficile. En abordant ces aspects, l'étude améliore la compréhension des dynamiques de fonte des neiges et fournit des solutions pratiques pour améliorer la résilience des infrastructures minières dans un contexte des changements climatiques.

ABSTRACT

Water management is among the main challenges facing the mining industry, particularly in the spring when the snow melts. A significant amount of the annual water inventory can be stored as snow on the surface of tailings storage facilities. As a result, a significant part of the water balance is released over a relatively short period, known as spring freshet. The duration and intensity of spring freshet can vary from year to year, but typically represent significant water management challenges for tailings storage facilities. The large quantity of water to be managed means that water management and treatment infrastructures, as well as tailings storage facilities, are highly solicited during this period. In a context of climate change, where variability and extremes of most water balance variables are on the rise, spring runoff represent a growing risk to the stability of water management and tailings storage facilities. This study explores the use of snow management piles as a solution for controlling snowmelt intensity and rates during spring freshet. Snow management piles are designed to control meltwater release rates and thus reduce peak meltwater flows and prolong runoff. By managing the timing and volume of water to be managed on tailings storage facilities, snow management piles can help maintain the integrity of mine waste management infrastructures and mitigate associated geotechnical and environmental risks.

The primary objective of this research was to evaluate the effectiveness of snow management piles in controlling spring runoff on tailings storage facilities. Specifically, the study aims to assess how snow management piles can control snowmelt rates, reduce peak meltwater flows, and extend spring runoff. To achieve this, six pilot-scale snow management piles were constructed at mine sites over a two-year period. The ability of conventional civil equipment as well as specialized equipment to construct snow management piles was also investigated. The snow management piles were designed with cubic, conical, and ridge-shaped configurations. Snow melt was monitored for changes in volume, height, and footprint using LiDAR and Structure-from-Motion (SfM) photogrammetry techniques. Snow density measurements were also obtained through core sampling at different intervals.

The results indicated that snow management piles effectively increased the duration of snowmelt, prolonging the process by approximately four to six weeks. The volume and

height of snow management piles emerged as critical factors influencing their ability to regulate snowmelt. Simplified phase change numerical modeling was done to represent field observations. The results showed that the prediction of the snowmelt process had an average error of 6.75% with respect to in situ results, while the error for predicting the entire length of the snow melting period was less than 4%. Based on these modeling results, snowmelt prediction charts were developed, considering the dimensions, shape, and cost of snow pile construction. Equations were developed to predict the melting behaviour of snow management piles configurations based on air temperature. To do so, the snowmelt of 35 piles configurations was modeled. It was found that cone-shaped snow management piles are highly sensitive to temperature changes, while ridge-shaped snow management piles are less sensitive and exhibit consistent performance across different temperature settings. This study concludes that snow management piles can help mitigate environmental and geotechnical risks associated with rapid snowmelts. This is particularly important in the context of climate change, where predicting future weather patterns is becoming increasingly challenging. By addressing these aspects, the study enhances the understanding of snow melting dynamics and provides practical solutions for improving the resilience of mine storage structures in the context of climate change.

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LIST OF ACRONYMS AND ABBREVIATIONS

$(\rho_f C_{pf})_{\text{eff}}$	Effective Volumetric Heat Capacity at Constant Pressure [$\text{J m}^{-3} \text{K}^{-1}$]
\emptyset	Volumetric Liquid Water Content in Snow [$\text{m}^3 \text{m}^{-3}$]
a_r	Adjusted Degree-Day Factor [$\text{cm} \cdot \text{C}^{-1} \text{day}^{-1}$]
C_a	Specific Heat of Air at Constant Pressure [$\text{J kg}^{-1} \text{K}^{-1}$]
C_i	Specific Heat Capacity of Ice [$\text{J kg}^{-1} \text{K}^{-1}$]
COE	Army Corps of Engineers
$C_{p,f}$	Fluid Heat Capacity at Constant Pressure [$\text{J kg}^{-1} \text{K}^{-1}$]
$C_{p,\text{solid}}$	Solid Heat Capacity at Constant Pressure [$\text{J kg}^{-1} \text{K}^{-1}$]
CRSNG	Conseil de Recherches en Sciences Naturelles et en Génie du Canada
C_s	Specific Heat Capacity of Snow [$\text{J kg}^{-1} \text{K}^{-1}$]
D	Melting Duration [Day]
d	Average Particle Diameter [m]
D_0	Coefficient of Water Vapor Diffusion in Air [$\text{m}^2 \text{s}^{-1}$]
Da	Darcy Number
DD	Degree-Day [$^{\circ}\text{C day}$]
DDF	Degree-Day Factor for Snowmelt [$\text{cm } ^{\circ}\text{C}^{-1} \text{day}^{-1}$]
DEM	Digital Elevation Model
DF	Decomposing and Fragmented Precipitation Particles
DH	Depth Hoar
DHSVM	Distributed Hydrology Soil Vegetation Model
DWHC	Distributed Water-Heat Coupling Model
e_a	Saturation Vapor Pressure [Pa]
E_i	Poisson's ration

FC	Faceted Crystals
FT	Net Turbulent Flux [W m^{-2}]
g	Acceleration of Gravity [m s^{-2}]
G	Incoming or Global Shortwave Radiation [W m^{-2}]
GBHM	Geomorphology-Based Hydrological Model
G_{con}	Conductive Energy Flux [W m^{-2}]
G_{h}	Ground Heat Flux [W m^{-2}]
GIS	Geographic Information Systems
GPR	Gaussian Process Regression
H	Snow Management Pile Height [m]
H_{i}	Ice Thickness [m]
H_{t}	Layer Thickness [m]
H_{s}	Snow Thickness or Snow Depth [m]
H_{sen}	Sensible Energy Flux [W m^{-2}]
h_{sf}	Interstitial Heat Transfer Coefficient between Solid and Fluid Phases [$\text{J m}^{-2} \text{K}^{-1}$]
HSPF	Hydrological Simulation Program – HFORTAN
ICSSG	The International Classification for Seasonal Snow on the Ground
IDE	Integrated Development Environment
IDS	Integrated Drainage Systems
IF	Ice Formations
IR	Infrared Reflectance
K	Permeability [m^2]
K_{a}	Coefficient of Air Permeability [m s^{-1}]

K_h	Coefficient of Eddy Conductivity [$\text{m}^2 \text{s}^{-1}$]
K_m	Vertical Transfer of Momentum [$\text{m}^2 \text{s}^{-1}$]
K_v	Coefficient of Volumetric Expansion
L	Latent Energy Flux [W m^{-2}]
Lidar	Light Detection and Ranging
L_s	Latent Heat of Sublimation [J m^{-2}]
LSTM	Long Short-Term Memory
LTE	Local Thermal Equilibrium
LTNE	Local Thermal Nonequilibrium
M	Snow Ablation Quantity [cm day^{-1}]
M_{adv}	Advective Energy Flux [W m^{-2}]
MF	Melt Forms
MLP	Multilayer Perceptron Neural Network
MM	Machine Made Snow
M_{mel}	Quantity of Melted Snow [cm day^{-1}]
m_Q	Depth-Specific Energy-to-Water Conversion Constant [$\text{cm m}^2 \text{J}^{-1} \text{day}^{-1}$]
n	Porosity
NARX	Nonlinear Autoregressive Exogenous
n_i	Ice Porosity
n_s	Snow Porosity
n_{solid}	Solid Porosity
θ_a	Air Volume Fraction [-]
θ_f	Fluid Volume Fraction [-]
θ_i	Ice Volume Fraction [-]

θ_p	Volume Fraction of Solid Material in Porous Media [-]
θ_s	Snow Volume Fraction [-]
θ_{solid}	Solid Volume Fraction [-]
θ_w	Water Volume Fraction [-]
OGS	Optical-equivalent Grain Size
Pa	Atmospheric Pressure [Pa]
PBSM	Prairie Blowing Snow Model
PP	Precipitation Particles
Pr	Prandtl Number
PRMS	Precipitation Runoff Modelling System
Q	Complete Runoff Quantity
q	Conductive Heat Flux [$W m^{-2}$]
Q_{cc}	Amount of Energy Necessary to Raise the Temperature of Snow to its Melting Point
q_f	Fluid Conductive Heat Flux [$W m^{-2}$]
Q_f	Solid Heat Source [$W m^{-2}$]
Q_G	Heat Flux from the Soil [$W m^{-2}$]
Q_I	Change in Heat Storage of Snowdrifts [$W m^{-2}$]
Q_{Lin}	Incoming Longwave Radiation [$W m^{-2}$]
Q_{Lout}	Outgoing Longwave Radiation [$W m^{-2}$]
Q_m	Amount of Energy Accessible for Snow Melting [$W m^{-2}$]
Q_n	Net All-Wave Radiation at the Surface [$W m^{-2}$]
Q_{NR}	Net Radiant Flux [$W m^{-2}$]
Q_P	Heat Transferred into the Snow Pile by Rainfall [$W m^{-2}$]

Q_{Sin}	Incoming Shortwave Radiation [J m^{-2}]
Q_{solid}	Fluid Heat Source [W m^{-2}]
q_{solid}	Solid Conductive Heat Flux [W m^{-2}]
Q_{Sout}	Reflected Shortwave Radiation [W m^{-2}]
r	Dry Adiabatic Lapse Rate [K km^{-1}]
r_o	Grain Size
Ra	Rayleigh Number
Re_p	Particle Reynolds Number
RG	Rounded Grains
r_h	hydraulic radius [m]
r_H	Resistance to Heat Flux [s m^{-1}]
r_{opt}	Effective Radius [μm]
ROS	Rain-on-Snow
SAC	Sacramento Model
SCA	Snow-Covered Area
SEM	Scanning Electron Microscopy
SFM	Structure from Motion
S_g	Conducted Heat from Underlying Ground
SH	Surface Hoar
$SHAW$	Simultaneous Heat and Water Model
SHE	European Hydrological System
S_l	Latent Heat of Vaporization from Condensation or Evaporation /Sublimation [W m^{-2}]
SMP	Snow management piles

$S_{\text{net,lw}}$	Net Thermal Radiation [W m^{-2}]
$S_{\text{net,sol}}$	Net Solar Radiation [W m^{-2}]
S_p	Sparrow Number
SRM	Snow Runoff Model
SSA	Specific Surface Area [$\text{m}^2 \text{kg}^{-1}$]
S_{sen}	Sensible Heat Flux [W m^{-2}]
SVR	Support Vector Regression Model
SWAT	Soil and Water Assessment Tool
SWE	Snow water equivalent [mm]
T_a	Air Temperature [$^{\circ}\text{C}$]
T_{avg}	Average Temperature of the Day [$^{\circ}\text{C}$]
T_b	Temperature Threshold [$^{\circ}\text{C}$]
T_d	Degree-Day Index [$^{\circ}\text{C}$]
T_f	Freezing Temperature [$^{\circ}\text{C}$]
T_i	Ice Temperature [$^{\circ}\text{C}$]
T_m	Melting Temperature or Melting Point [$^{\circ}\text{C}$]
$T_{\text{pc}, 1 \rightarrow 2}$	Phase Change Temperature Between Phase 1 and Phase 2 [$^{\circ}\text{C}$]
T_{ref}	Reference Temperature [$^{\circ}\text{C}$]
T_{SF}	Tailings storage facilities
T_{solid}	Temperature of Solid Phase [$^{\circ}\text{C}$]
T_{sr}	Radiometric Snow Surface Temperature [K]
T_{ss}	Aerodynamic Surface Temperature [$^{\circ}\text{C}$]
u	Velocity Field [m s^{-1}]
UEB	Utah Energy Balance

u_f	Fluid Velocity Field [$m\ s^{-1}$]
UNECE	United Nations Economic Commission for Europe
u_p	Porous Velocity [$m\ s^{-1}$]
UQAT	Université du Québec en Abitibi-Témiscamingue
URSTM	Unité de Recherche et de Service en Technologie Minérale
U_z	Wind Velocity [$m\ s^{-1}$]
V	Snow Management Pile Volume
V_h	Heat of Vaporization of Water [$KJ\ mol^{-1}$]
V_i	Ice Volume [m^3]
VIC	Variable Infiltration Capacity
V_s	Snow Volume [m^3]
V_{solid}	Solid Volume [m^3]
V_z	Vertical Wind Speed [$m\ s^{-1}$]
Z_o	Roughness Parameter
α	Standard Deviation of the Elements from the Symmetry Axes
γ	Psychrometric Constant [$Kpa\ K^{-1}$]
δ	Phase Lag Angle Between Stress and Strain [$^\circ$]
ΔQ	Change in Snowpack Energy [$W\ m^{-2}$]
ΔT	Temperature Difference [$^\circ C$]
ε	Emissivity of Snow
ε_o	Strain
η	Dynamic Viscosity [$Pa\ s$]
κ_{2p}	Empirical Parameter
λ	Thermal Conductivity [$W\ m^{-1}\ K^{-1}$]

λ_a	Air Thermal Conductivity [$\text{W m}^{-1} \text{K}^{-1}$]
λ_{eff}	Effective Thermal Conductivity [$\text{W m}^{-1} \text{K}^{-1}$]
λ_f	Fluid Thermal Conductivity [$\text{W m}^{-1} \text{K}^{-1}$]
λ_m	Porous Medium Thermal Conductivity [$\text{W m}^{-1} \text{K}^{-1}$]
λ_{peff}	Equivalent Thermal Conductivity of Porous Medium [$\text{W m}^{-1} \text{K}^{-1}$]
λ_{rel}	Relative Thermal Conductivity [$\text{W m}^{-1} \text{K}^{-1}$]
λ_s	Snow Thermal Conductivity [$\text{W m}^{-1} \text{K}^{-1}$]
$\lambda_{s,f \text{ eff}}$	Solid-Fluid Thermal Conductivity [$\text{W m}^{-1} \text{K}^{-1}$]
λ_{solid}	Solid Thermal Conductivity [$\text{W m}^{-1} \text{K}^{-1}$]
ν_i	Young's modulus [Pa]
ρ_a	Air Density [Kg m^{-3}]
ρ_f	Fluid Density [Kg m^{-3}]
ρ_i	Ice Density [Kg m^{-3}]
ρ_s	Snow Density [Kg m^{-3}]
ρ_{solid}	Solid Density [Kg m^{-3}]
ρ_v	Water Vapor Density [Kg m^{-3}]
ρ_w	Water Density [Kg m^{-3}]
φ	Heat Source [J]

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CHAPTER 1 INTRODUCTION

The methods employed to extract valuable minerals from ore generate substantial volumes of solid and liquid waste, such as mine tailings, throughout the mining of mineral deposits (Bussiere and Guitonny, 2020). Tailings are typically stored at the surface in large areas designated as tailings storage facilities (TSFs). Despite advancements in TSF design (e.g., Azam and Li, 2010; Caldwell, 2017), geotechnical instability and TSF failures still occur. Although the causes of these failures vary, inadequate water management often plays a significant role (Strachan and Goodwin, 2015). Therefore, careful planning and effective implementation of water management infrastructure are crucial to TSF safety, from construction to reclamation (Kuyucak, 2021). This includes integrating measures for controlling surface water flows and managing water levels into the design and operation of water management practices, storage, and treatment facilities (Environment Canada, 2009).

Regular assessment and maintenance of tailings dams are important for long-term performance. Water balances for tailings dams should be developed and updated often as the centerpiece of these efforts. To minimize the risk of catastrophic failure in a TSF, it is crucial to reduce the water content. This includes supernatant water released from the slurry and held in the tailing's basin, pore water within the tailings' interstices, and water from rainfall and surface runoff (East and Fernandez, 2021). Quantifying and contrasting all water inflows and outflows is necessary to build a water balance for a specific tailings dam (Figure 1.1). Precipitation, infiltration, evaporation, seepage, groundwater flow, and potential flood events are variables that need to be quantified (Geris et al., 2022).

1.1 Water balance on TSFs

The surface area of TSFs can vary significantly depending on the size of the mining operation and the number of tailings produced. The surface area of TSFs can range from a few hectares to several square kilometers (Williams, 2016). For example, smaller TSFs might cover around 10-20 hectares, while larger TSFs can extend over several hundred hectares. Some of the largest TSFs in the world can even exceed 1,000 hectares (Williams, 2016). In cold regions, where seasonal freezing and thawing occurs, snow is critical to

many hydrological processes, including water supply, erosion, and flood control (Gray and Male 1981; Walter et al., 2005). In these regions, there are generally two periods of high-water flows: the spring runoff and the significant fall precipitation (Boulanger-Martel et al., 2022). During winter, substantial snow accumulates on the surface of TSFs, contributing notably to the annual water inventory such as reservoir storage, and groundwater recharge. As a result, TSFs frequently have the highest annual flow rates during spring snowmelt, which puts potentially excessive demands on the water management infrastructure and puts tailings dams, flumes, and treatment capacity at risk (Boulanger-Martel et al., 2022).

To effectively manage precipitation, infiltration, evaporation, seepage, ground water flow, and potential flood events in tailings dams, several strategies can be employed (Kiedrzyńska et al., 2015). Implementing diversion channels and drainage systems helps manage rainfall, while covering the tailings surface with impermeable materials reduces infiltration. Enhancing evaporation can be achieved by increasing the surface area of water exposed to air, such as through shallow ponds or spraying techniques (Hu et al., 2024). Seepage can be controlled by installing collection systems like drains and wells and monitoring seepage rates and water quality. Groundwater flow can be managed using interception wells and cutoff walls, with regular monitoring to assess effectiveness. Designing the tailings dam to withstand extreme weather events, including constructing spillways and overflow channels, is crucial for managing potential flood events. Figure 1.1 shows the main elements of water balance of a tailings dam.

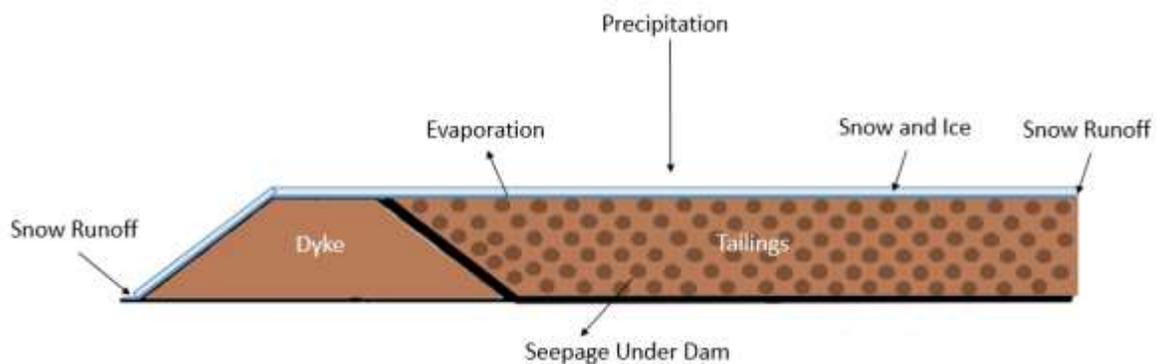


Figure 1.1 Elements of the water balance of a tailings dam.

The management of water resources and the assessment of the risk of spring snowmelt flooding depends on accurate snowfall and melt forecasting. A comprehensive water balance management system includes all waters and water cycles on a mine site, as well as those affected by the mine site, interconnected as building blocks (Figure 1.2). Generally, mine-site water cycles can be categorized into two main types (Punkkinen et al., 2016):

- Natural waters encompass groundwater, surface water, rainfall, snowfall, and evaporation, collectively referred to as clean waters. Mine dewatering waters, primarily groundwater, often require treatment due to potential salinity, high concentrations of metals and metalloids, and significant levels of nitrogen compounds.
- Tailings, dams, ponds, and seepage waters, which include wastewaters and used waters that may require treatment, along with the associated treatment facilities.

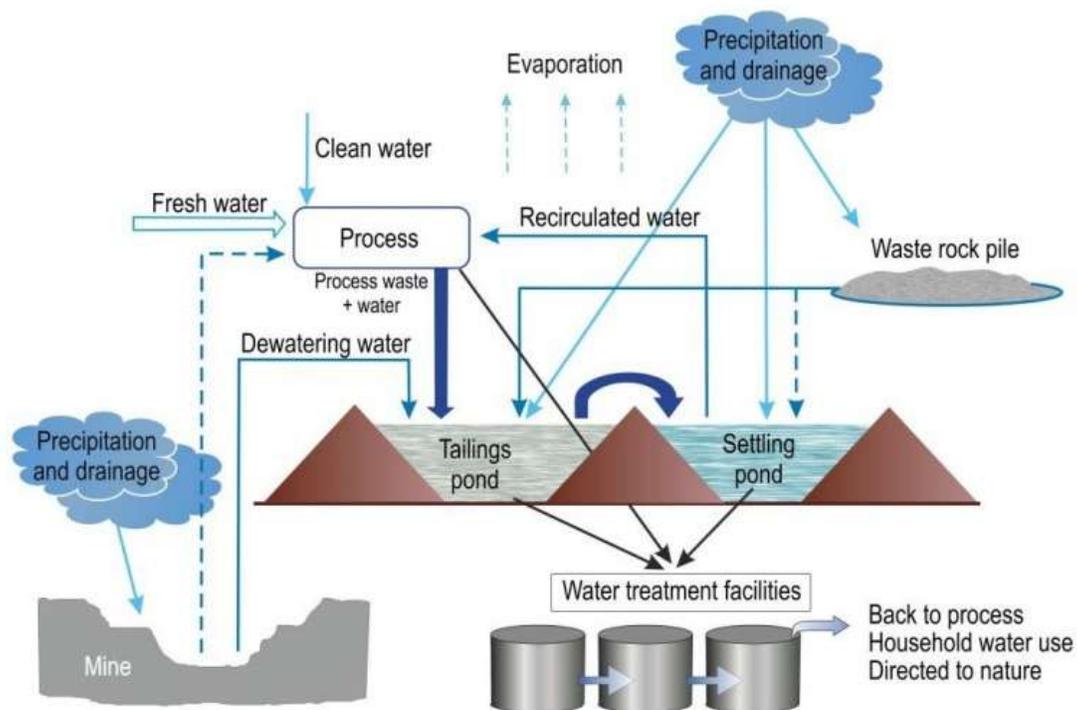


Figure 1.2 Examples of various mine water sources and streams (from Punkkinen et al., 2016).

Temperature, snow conditions, water system freezing, rapid melting periods, and ice depth are closely linked to mines' water balances (Punkkinen et al., 2016). Temporal variations

in precipitation, melting periods, and cold temperatures can complicate mining operations (Punkkinen et al., 2016). In cold climates, freezing condition can make water resources unusable for mining and processing operations. Additionally, seasonal changes can impact the water balance and should be considered (Department of Water Affairs and Forestry 2006b). Thus ensuring the long-term sustainability of mining processes necessitates responsible mine water management. This is currently one of the most critical challenges of the mining industry. Authorities worldwide are also striving to enhance the effectiveness of existing management practices.

In the mining industry, water balance and water management are crucial but distinct. The water balance involves accounting for all water inflows and outflows within a mining site over a specific period, including precipitation, evaporation, infiltration, and runoff (Kunz, 2016). This helps assess water availability and predict shortages or surpluses (Kunz, 2016). Water management, on the other hand, involves the strategic planning, development, distribution, and regulation of water resources to meet operational needs like ore processing, dust suppression, and environmental protection (Kunz, 2016). It aims for sustainable and efficient water use, addressing issues like scarcity and quality. Practices include water recycling, treatment of contaminated water, infrastructure development, policy-making, and stakeholder engagement (Kunz, 2016). While water balance helps understand water dynamics, water management encompasses broader strategies to utilize and protect water resources effectively (Kunz, 2016).

1.2 Impact of climate change on the components of the water balance

The global climate is undergoing changes. Since the start of the century, global temperatures have increased by approximately 0.5°C , with some regions in Canada (e.g., British Columbia) experiencing up to a 1°C rise (Pollock, 2009). A notable rise in the average annual air temperature from 1900 to 2010 is observed across the East Coast region (Savard et al., 2016). The data indicate a general warming trend with significant year-to-year and decade-to-decade variability (Savard et al., 2016). Over the 110-year period, the East Coast region experienced an average temperature increase of $0.90 \pm 0.37^{\circ}\text{C}$ (Savard et al., 2016). Stations along the Atlantic Ocean saw a rise of $0.75 \pm 0.34^{\circ}\text{C}$, while those along the Gulf of St. Lawrence coast experienced a warming of $1.12 \pm 0.43^{\circ}\text{C}$. Other research

(Galbraith and Larouche, 2013) also highlights an increasing temperature change from the southeast to the northwest across the region. These temperature increases are comparable to or exceed the global average warming during the same period (e.g., IPCC, 2013).

If atmospheric greenhouse gas concentrations continue to rise unchecked, we can expect more rapid climate change in the coming generations. This increase, driven by a growing global population consuming vast amounts of energy and altering natural carbon cycles, traps heat in the atmosphere, leading to climate change. Canada will not be exempt from these changes, which are anticipated to result in a warming rate unprecedented in the last 10,000 years. Flooding has been the most prevalent disaster in the East Coast region, followed by hurricanes and winter storms (Public Safety Canada, 2014). The region is expected to face increasing catastrophic losses due to rising water levels and weather events, such as more frequent rain-on-snow flooding and winter thaws, which are likely to impact ice-jam flooding and river/estuarine drainage (Savard et al., 2016). These changes, combined with current development pressures and practices, could lead to greater damage to infrastructure and services (e.g., PIEVC, 2008), including mining infrastructures.

Snow cover plays a crucial role in the meteorological system, being highly responsive to shifts in climate and ecological conditions. It serves as a vital source of water for glacier runoff, particularly in arid regions (Immerzeel et al., 2010). Among various environmental factors, snow cover is the most reactive to intricate climate changes (Zhang, 2005).

In addition to its role in hydrology, the snow cover significantly influences local and global weather patterns. It affects albedo, which is the reflection of solar radiation, thereby impacting temperature regulation. Changes in snow cover can also alter the timing and volume of water availability, affecting agriculture, water resources, and ecosystems (Robinson et Frei, 2000). Understanding and monitoring snow cover is essential for predicting and mitigating the impacts of climate change (Che et al., 2008; Takala et al., 2011).

1.3 Mine water management methods

There are several methods that can be used to manage water in TSFs (Cacciuttolo et al., 2023). One method involves using flumes, which are engineered structures designed to

measure and control water flow (Cacciuttolo et al., 2023). Flumes ensure accurate monitoring and help prevent erosion by handling peak flow conditions (Vanani and Ostad-Ali-Askari, 2022). By accurately measuring water flow, flumes help maintain the water balance within the TSF, detecting any changes in flow rates early, which is crucial for preventing erosion and managing sediment transport effectively (Cacciuttolo et al., 2023).

Another method is the use of ditches, which are essential for drainage within TSFs (Cacciuttolo and Tabra, 2015). Ditches are designed to collect and divert surface water away from the tailings area, reducing the risk of water accumulation and erosion (Cacciuttolo and Tabra, 2015). The slope and gradient of the ditches are calculated to ensure efficient water flow without causing erosion. To maintain their structural integrity, ditches may be lined with materials like riprap or geotextiles, which help reduce erosion and ensure the ditches remain effective over time (Cacciuttolo and Tabra, 2015).

Spillways are also critical for managing water in TSFs (Cacciuttolo and Tabra, 2015). They are designed to safely discharge excess water, particularly during heavy rainfall or storm events. The capacity of spillways must be sufficient to handle the maximum expected flow, including extreme weather conditions (Cacciuttolo and Tabra, 2015). To prevent downstream erosion, spillways often include features like stilling basins or stepped chutes that dissipate the energy of the flowing water. This controlled release reduces the risk of structural failure and environmental damage (Cacciuttolo and Tabra, 2015).

The design of these components involves careful consideration of factors such as flow rates, material durability, slope gradients, and capacity to handle extreme weather events. Effective water management in TSFs combines these structures to ensure safe and efficient water handling, thereby enhancing the facility's stability and environmental safety (Trevelyan, 2021).

During high flow periods, mining operations can implement practices to manage water effectively and prevent flooding, erosion, and contamination. Diversion channels and ditches are used to redirect surface water away from storage areas, thus reducing the risk of water accumulation. Retention ponds capture and store excess water, allowing for controlled release and sediment settling (Spitz and Trudinger, 2019). Pumping systems are deployed to remove excess water, often automated to respond to rising levels (Cacciuttolo

and Marinovic, 2022). Integrated Drainage Systems (IDS) combine pumps, valves, monitoring devices, and drainage pipes to control water flow comprehensively (Anderson and Tinkler, 2021). Water treatment facilities ensure that discharged water meets regulatory standards by removing contaminants (Punkkinen et al., 2016, Hermassi et al., 2016). Advanced monitoring and early warning systems track water levels and flow rates in real-time, providing early alerts to enable proactive measures. These combined practices ensure operational stability and minimize environmental impact during high flow periods (Punkkinen et al., 2016).

1.4 Challenges in mine water management

Managing water in mining operations during periods of snowmelt and precipitation presents several challenges and unknowns, particularly in the context of climate change. For example, certain conditions such as a large snowpack combined with a warm and rainy spring could be critical to the performance and integrity of mine water management infrastructures.

Climate change is causing shifts in snowfall patterns and melting rates, making it difficult to predict when and how much snow will melt. This unpredictability can lead to sudden and unexpected increases in water flow, which can overwhelm existing water management systems (Ryberg, 2024).

Variability in precipitation is another significant challenge (Tang et al., 2024). Climate change is expected to increase the frequency and intensity of extreme weather events, including heavy rainfall (Trottier et al., 2023). This can result in rapid water accumulation and potential flooding, which can be difficult to manage without robust infrastructure (Trottier et al., 2023). Additionally, the seasonal distribution of precipitation is changing, with some regions experiencing more intense wet seasons and prolonged dry periods (Bulovic et al., 2024). This variability complicates the planning and management of water resources.

Temperature fluctuations also play a critical role. Warmer temperatures can lead to earlier snowmelt, which may not coincide with the peak water demand periods (Shockley, 2021). This mismatch can create challenges in storing and utilizing the available water efficiently.

Furthermore, higher temperatures can increase evaporation rates, reducing the overall availability of water for mining operations (Shockley, 2021). The interaction between groundwater and surface water during snowmelt and heavy precipitation events is another area of uncertainty (Shockley, 2021). Understanding how these interactions affect water availability and quality requires extensive monitoring and modeling, which can be complex and resource intensive (Shockley, 2021).

Lastly, long-term climate projections are inherently uncertain (Clemente and Huntsman, 2019). While models can provide general trends, the specific impacts on local water resources can be difficult to predict accurately (Clemente and Huntsman, 2019). This uncertainty makes it challenging to design and implement effective water management strategies that are resilient to future climate conditions (Clemente and Huntsman, 2019). Addressing these challenges requires adaptive management strategies, advanced monitoring technologies, and flexible infrastructure that can respond to changing conditions.

1.5 Snow management practices to help control spring runoff

The above information indicated that it is vital for mining operators to control water flows better to minimize the geotechnical and environmental risks associated with snowmelt. In some cases, mine water management systems can struggle to effectively deal with the volume of water generated during snowmelt on TSFs. Therefore, gaining control over spring water flows is particularly relevant in climate change, where accurately predicting climatic conditions is difficult. In this context, snow management practices such as snow management piles (SMPs) could contribute to the control of snowmelt and significantly decrease peak flows, providing enhanced control over mine water management and treatment during this critical time (Boulanger-Martel et al., 2022).

These piles could play a crucial role in regulating the water generated from melting snow and ice, thereby mitigating geotechnical risks. SMPs work by strategically storing snow in designated areas, allowing for a controlled and gradual release of meltwater. This method could help to prevent sudden and important influxes of water into TSFs water management and treatment systems, thus reducing the main risks associated with spring runoff. Additionally, incorporating snow management piles into the overall mine water

management strategy requires careful planning and coordination. It involves assessing the specific climatic conditions, snow accumulation patterns, and the hydrological characteristics of the mine site.

By reshaping the snow that naturally builds up at the TSFs' surface, these structures are created. SMP construction remolds and densifies snow in a way that maximizes the storage of the winter water inventory as a snow pile. Therefore, the use of SMPs for snow and meltwater management in TSFs could aid in extending the duration of spring runoff, reducing melting rates, and lowering maximum meltwater flows (Boulanger-Martel, 2022).

Figure 1.3 shows that many factors can affect the physical structure and properties of the snow. Snow grooming increases the density of snow due to compaction and yields to snow metamorphism. Such changes will modify the snow thermal properties, and most importantly the amount of latent heat that is contained within a given volume. As a result of the sun's radiation to the earth's surface, some of the snow melts on the surface of the block and flows to the lower layers. This will decrease the density at the surface of the layer and increase the density at the bottom of the snow block (due to the freezing of the runoff). Also, some amount of the snow mass evaporates due to the sun's radiation. The wind can change the surface of the snow block. Other factors that can change the heat transfer in snow are freezing rain and the falling of snow on the surface of the earth. Non-atmospheric factors such as the ground thermal regime can affect the temperature of the interface between the snow and the ground and affect snowmelt.

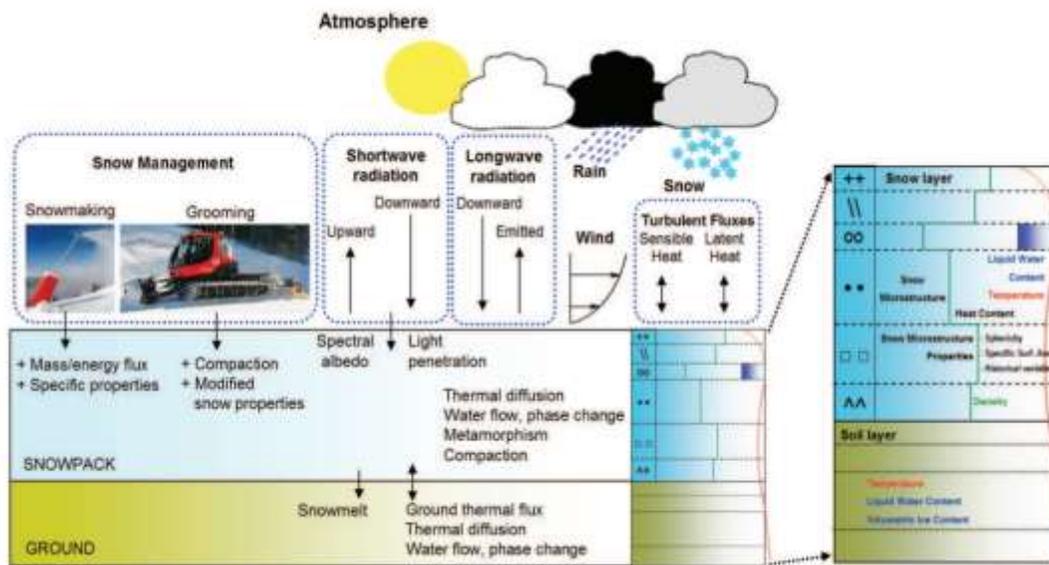


Figure 1.3 The SAFRAN-SURFEX/ISBA-Crocus scheme including grooming and snowmaking effects on snowpack physics, (adapted from Vionnet et al., 2012).

1.6 Research objectives

Preliminary field trials have demonstrated the efficacy and feasibility of engineered SMPs as a tool for proactively managing the winter water inventory of TSFs (Boulangier-Martel et al., 2022). However, more work needs to be done to further optimize the configuration and construction of snow management piles. As such, the main objective of this research project is to optimize the configuration and construction of SMPs to better control spring runoff on TSFs using pilot-scale field tests and numerical modeling. This study is structured around four specific objectives (SOs):

- SO1: Assess the performance of snow management piles constructed with conventional civil equipment and specialized groom equipment;
- SO2: Develop a simplified numerical model able to represent the observed SMPs' snowmelt-behaviour;
- SO3: Use the obtained field and numerical results to optimize the design and operation of SMPs within a spring runoff water management scheme on TSFs;

By achieving these specific objectives, this study is to investigate how different configurations of SMPs can control snowmelt and assess the main parameters affecting

their performance. Guideline for implementing SMPs in mining operations are also provided. Ultimately, the project aims to enhance the stability and safety of tailings storage facilities, contributing to the overall sustainability and efficiency of mining operations.

Using these results, this study aims to identify technically and cost-effective pile configuration for controlling snowmelt. Numerical modelling is used to better understand the parameters of influence and widen the application of the results.

1.7 Organization of the dissertation

This dissertation is organized into six comprehensive chapters, each addressing a specific aspect of the research:

- Chapter 1: Introduction

This chapter sets the stage for the dissertation by introducing the research context, outlining the central problem, and stating the primary objectives of the project. It provides a foundational understanding of the study's significance and scope.

- Chapter 2: Literature Review

The second chapter offers an in-depth review of existing literature related to snow structure, its physical properties, and the numerical modeling of snow behavior. This chapter synthesizes current knowledge and identifies gaps that this research aims to fill.

- Chapter 3: Materials and methods

This chapter outlines the key materials and methods used in pilot-scale field tests, detailing the fieldwork conducted at mine sites in 2022 and 2023. Although the author did not take part in data collection in 2022, data have been utilized for in this study. Additionally, the chapter discusses the numerical modeling method.

- Chapter 4: Field results and Numerical Modeling

This chapter present the field results and explores the concept of numerical modeling and its validation. It addresses SO1 and SO2, examining the melting of snow piles in 2022 and 2023.

- Chapter 5: General Discussion

This chapter offers a comprehensive discussion that contextualizes the results obtained from the research. It explores the practical charts and snow pile structures,

providing insights into their potential uses and benefits. This chapter addresses SO3.

- Chapter 6: Conclusion and Recommendations

The final chapter summarizes the key findings of the dissertation and presents the main conclusions. It also offers recommendations for future research and practical applications, highlighting the contributions of this study to the field.

CHAPTER 2 LITERATURE REVIEW

This chapter embarks on a comprehensive journey into the intricate world of snow, starting with a detailed exploration of its structural characteristics. It then transitions into an in-depth analysis of the various types of snow and into the fundamental physical properties of snow.

In addition, the chapter delves into the mechanisms of heat transfer within snow and discusses the various parameters that significantly influence heat transfer processes.

This chapter wraps up with an insightful discussion on the numerical modeling of snowmelt, as explored in the literature.

Overall, this chapter provides a holistic view of snow, covering its basic structure and types. It delves into the intricate physical properties and dynamic processes that govern snow's behavior in natural environments. Additionally, it reviews previous works on snowmelt numerical modeling.

2.1 Composition and types of snow

Snow is a multiphase system made up of three phases: solid, liquid, and gas (Figure 2.1). A snow cover is subjected to shifting temperature gradients in real-world conditions, and it also experiences significant mass flux from snowfalls, melting, etc. Pressure changes in different snow layers are also caused by changes in snow cover thickness. Due to these ever-changing circumstances, snow is a particularly dynamic substance. Snow is a granular material with a microstructure constantly undergoing metamorphism (Rahimi 2016). This makes it challenging to examine the phase changes that take place in snow because, in addition to the heat and mass transport, geometric issues also need to be considered (Domine et al., 2008). Snow's mechanical behavior is greatly influenced by its microstructure. The way the snow is packed depends on the size and form of the snowflakes (Gururajan, 2015).

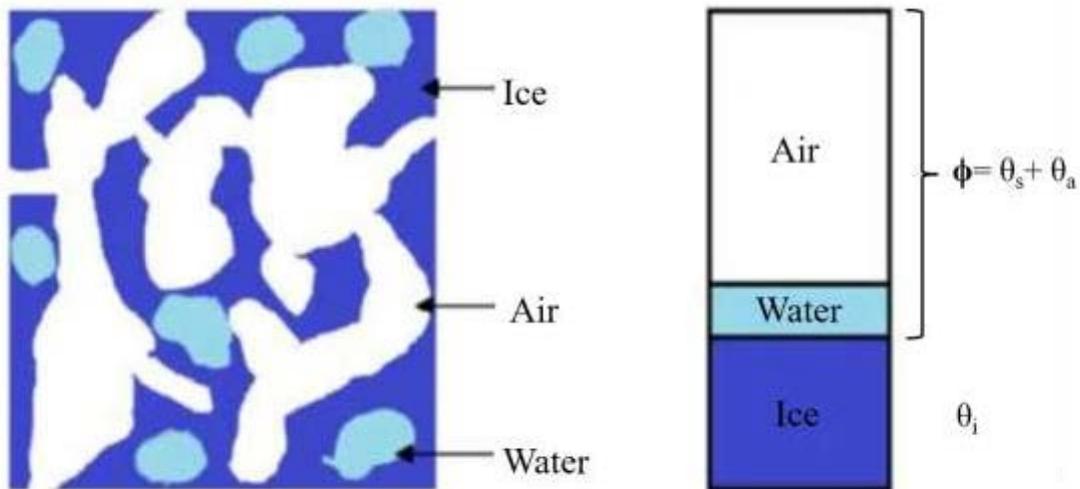


Figure 2.1 Schematic of a control volume (Rahimi 2016)

A detailed characterization of snow particles is essential to understanding snow settling behavior and modeling ground snow accumulation for various purposes, such as preventing avalanches and flooding caused by snowmelt (Li et al., 2022). Fierz et al. (2009) provides a comprehensive guide on classifying seasonal snow, including snow grain types and characteristics. It standardizes symbols for snow properties, offers multilingual terms, and includes historical perspectives on snow classification systems. This international standard aids consistent communication and data exchange among snow researchers worldwide. The nine main classes of grain shape are detailed in Table 2.1.

If different classes of grain shapes are present in a layer, they may be characterised individually, putting either symbol or abbreviation code of the minority class in round brackets. However, symbols and abbreviations should not be used together (Fierz et al., 2009) (ICSSG).

Table 2.2 presents the qualifiers given by the ICSSG for the different average grain sizes. Several methods are used to determine the size of snow grains such as stereology, sieving and image analysis, the results obtained by each of the methods being however different (Riche et al., 2012). Therefore, a grain size analysis is a measurement with a large uncertainty (Fierz et al., 2009).

Table 2.1 Class of grain forms and description of the (ICSSG) (Fierz et al., 2009).

Code ICSSG	Classes	Description
PP	Precipitation Particles (Fresh snow)	Grains of snow resulting from a recent precipitation having preserved the fine structure of the flakes (new snow)
MM	Machine made snow (Artificial snow)	Grains produced mechanically, either by production of droplets (spherical particles), or by passage of ice (flat particles)
DF	Decomposing and Fragmented precipitation particles (fresh snow in transition)	Grains partially retaining the structure of precipitation particles, but in the process of becoming a fine, spherical particle
RG	Rounded Grains (spherical grain snow)	Spherical-grained snow (as a result of structure decomposition by sublimation and metamorphism)
FC	Faceted Crystals	Crystals formed by an excess of vapor inside the layer of snow which solidifies when the temperature change
DH	Depth Hoar (Inner frost inside the snow cover)	Crystals formed by large temperature gradients resulting in excess water vapor solidifying within the layer of snow (frost)
SH	Surface Hoar (Surface Frost)	Crystals formed on the surface due to the rapid transfer of water vapor from the atmosphere to the surface (surface hoar)
MF	Melt Forms (Ice pieces)	Ice particles formed using snow containing a lot of water (which is refrozen) or during a freeze-thaw cycle
IF	Ice Formations (ice layer)	Layer of ice formed during the freezing of a layer of water on the surface (rain), at the base or inside the layer of snow

Table 2.2 ICSSG's snow grain size classification (Fierz et al., 2009).

Term	Dimensions (mm)
Very fine	<0.2
Fine	0.2 to 0.5
Medium	0.5 to 1.0
Coarse	1.0 to 2.0
Very Coarse	2.0 to 5.0
Extreme	>5.0

2.2 Evolution of the snow cover

According to Fierz et al. (2009), the snow cover area is the geographic extent of the snow cover on the land surface and is an important variable in numerous research on hydrology, climatology, and ecology. The following aims to present the main mechanisms involved in the evolution of a snow cover.

2.2.1 Accumulation of snow

Multiple temporal and spatial scales reveal strong variability in snow accumulation. Inter-annual variability in weather and climate change impact snow melt timing and magnitude (Pedersen et al., 2013). Temperature increase reduces snowfall and snow cover duration (Bavay et al., 2013) and earlier melt of snow (López-Moreno et al., 2013). The lifespan of a snow cover depends on the geographical location and weather conditions (Edwards et al, 2007). If a snow cover melts after a few days, it is an intermittent snow cover such as snow that fell at low altitude or at high altitude but early in the fall or late in the spring (Laternser and Schneebeli, 2003). If the snow cover remains all winter due to climatic conditions, it represents a seasonal snow cover (Edwards et al, 2007). If the snow cover persists during the summer and its thickness increases during the accumulation period, then it is a permanent snow cover.

During the period of snow accumulation, the energy balance in a snow cover is negative, in other words the temperature drops by releasing energy (Anderson, 1976). However, during the melting period, the energy balance is positive (Anderson, 1976). In addition, sublimation and vaporization can also produce energy mass loss (Mott et al, 2018). In Figure 2.2, energy exchange activities over a continuous snow cover (a) and additional processes over a patchy snow cover (b) are schematically described. Present for the continuous snow cover are turbulent sensible and latent heat fluxes (Q_h , Q_e), incoming and outgoing longwave radiation (Q_{Lin} , Q_{Lout}), incoming and reflected shortwave radiation (Q_{Sin} , Q_{Sout}), and terrain radiation. The snowpack energy balance can be written as (Armstrong and Brun, 2008):

$$-\frac{dH}{dt} = Q_S + Q_L + Q_h + Q_e + Q_a + Q_G \quad (2.1)$$

Where $-\frac{dH}{dt}$ is the net change rate of the snowpack internal energy per unit area. Q_S is net shortwave radiation (incoming minus reflected shortwave radiation); Q_L is the net longwave radiation (downward and upward component of longwave radiation); Q_h is the turbulent flux of sensible heat exchanged at the surface due to the temperature gradient between snow surface and atmosphere; Q_a is the flux of energy advected via precipitation or blowing snow; Q_G is the ground heat flux due to conduction.

Additionally, typical profiles of wind, air temperature, and turbulence development over snow under stable atmospheric conditions are shown. The boundary layer evolution (air temperature, turbulence, and sensible heat fluxes) over snow caused by local heat advection from the snow-free area towards the snow-covered area is shown for the scenario of patchy snow cover (Mott et al, 2018). The latter two occur during periods of accumulation or melting. The mass lost by evaporation is small compared to that caused by sublimation, which is why it is often overlooked (Lundberg and Halldin, 1994). This type of snow cover is present in the north and gradually turns into a glacier (Singh, 2001). A snow cover has a stratified structure because it is deposited gradually and in several layers after each precipitation event. Each of the layers has different physical properties depending on the meteorological conditions during the precipitation (Mellor, 1964). In other words, the snowflake can form differently depending on the temperature and wind speed during its

formation in the clouds and after precipitation. For example, the wind compresses the snowflake and causes the density of the snowflake to increase. According to the study by McKay (1970), the density of fresh snow can then vary between 4 and 340 kg m^{-3} .

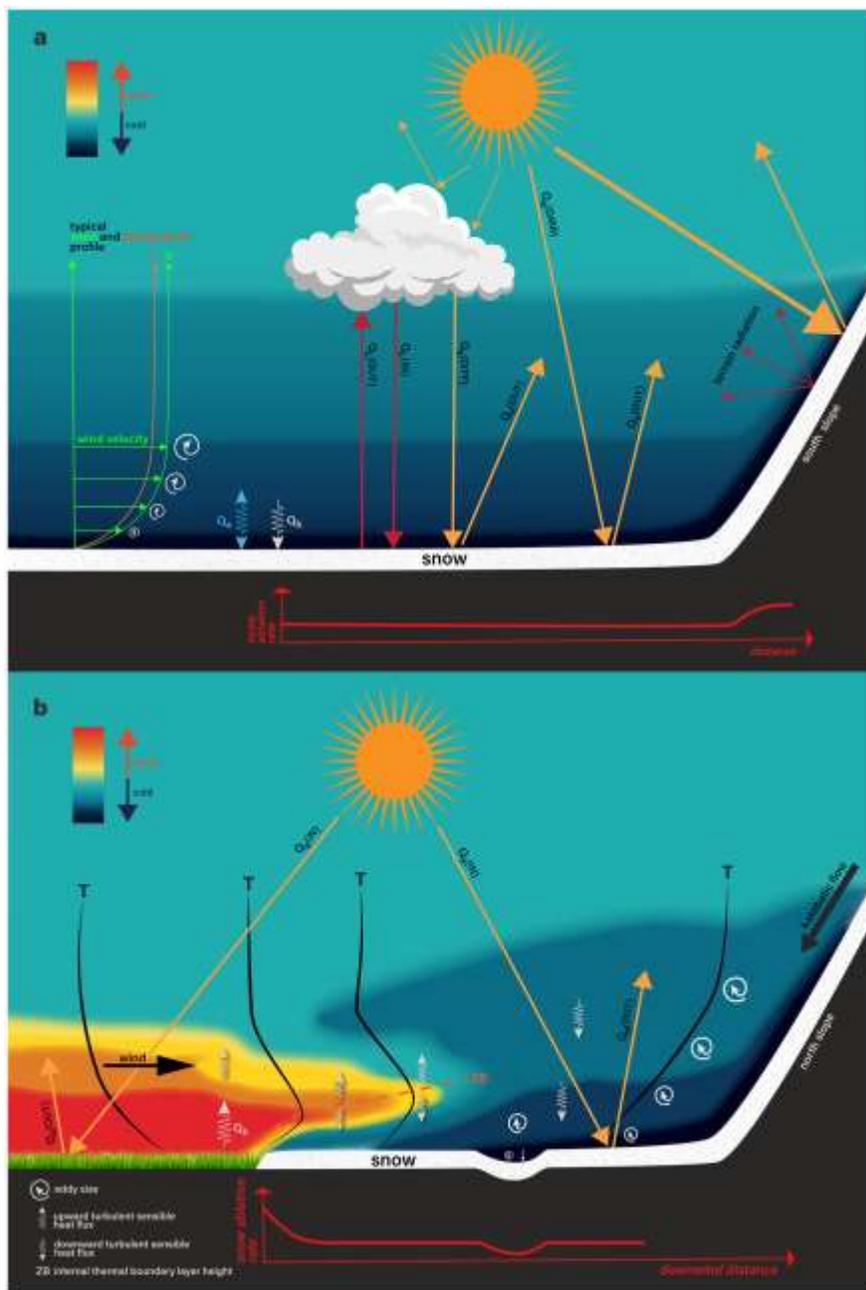


Figure 2.2 Energy exchange activities over a continuous snow cover (a) and additional processes over a patchy snow cover (b) are schematically described (Mott et al, 2018).

The complexity of snow processes across multiple scales is primarily responsible for the high variability in snow accumulation and ablation at smaller spatial and temporal scales (Clark et al., 2011). For capturing the timing and magnitude of hydrological responses in alpine catchments, the final snow cover variability at the end of the snow accumulation season is critical (Winstral et al., 2013). When the snow depth is heterogeneous at the beginning of a melting period, it produces a higher differential melt rate over time and space, faster runoff generation at the beginning of melting, and a longer melting season as more snow accumulation areas delay melting (Brauchli et al., 2017).

The evolution of a snow cover is not often homogeneous, particularly for places where the snow cover is thick, where there is wind and rain. For example, the lower part of a snow cover is often transformed into ice (depth hoar) due to the heat given off by the ground and the overload pressure imposed by its own weight. The presence of heat transferred by the ground and the presence of water vapor in the snow initiate a structural change under overload pressure, which can increase the density of the snow and change the connection between the grains. Morin et al. (2010) studied the evolution of a snow cover located in the Argentière glacier (France) and measured the density and temperature (Figure 2.3). Their results show that the density is higher in the lower part of the snow cover and lower at the surface. However, it is possible to observe an equivalent density value between 250 and 350 [kg m^{-3}] for this snow cover.

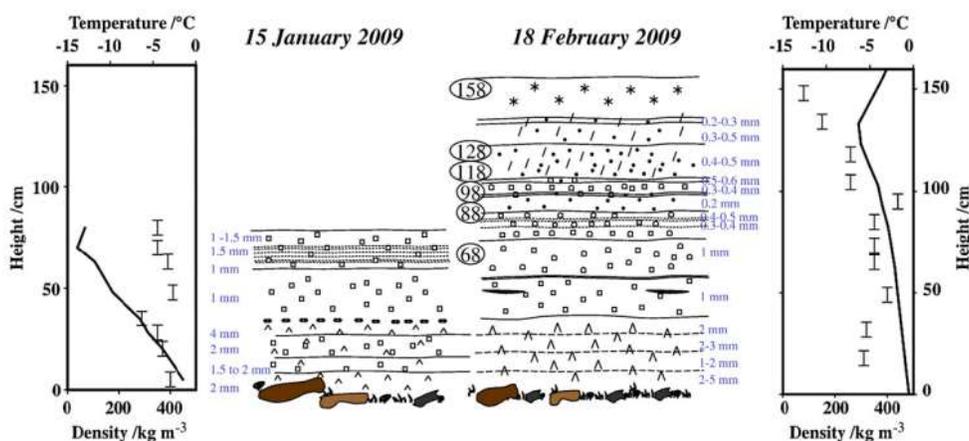


Figure 2.3 Stratification, density and temperature determined in situ on January 15, 2009 (left) and February 18, 2009 (right). (Morin et al. 2010)

Mass and energy fluxes between the snow cover and the overlying atmosphere drive spatial variability of snow at catchment and smaller scales. Pre- and post-depositional snow transport processes are determined by the interaction between the wind field, snowfall, and snow surface. Through sensible and latent heat exchange as well as blowing snow sublimation, the wind further plays an important role in the mass and energy balance of the snow cover. Furthermore, complex boundary layer flows over heterogeneous land-covers in spring strongly affect snow melt patterns (Mott et al., 2017).

2.2.2 Snow metamorphism

When snow is deposited on a surface and is immobile at the macroscopic scale, we are interested in phenomena occurring at the microscopic scale. Snow supports its own weight, which leads to densification, as well as a change in skeletal structure due to the presence of water vapor and a high thermal gradient between the ground and the snow surface. Under these conditions, the connection between snow crystals becomes different from that of fresh snow. Water vapor pressure gradients induce sublimation and/or condensation of snow crystals. This results in physical transformations of the snow crystals: the size, shape and arrangement evolve and modify the physical properties of the snow. These phenomena are known as snow metamorphism. Four mechanisms are responsible for this process: (1) destructive metamorphism, (2) constructive metamorphism, (3) melt metamorphism, and (4) pressure metamorphism (Alford, 1974).

Domine et al. (2003) and Legagneux et al. (2003) conducted several tests on snow samples stored in a cold room under isothermal conditions. They observed the morphological changes in these samples by scanning electron microscopy (SEM). Their results reveal that the structure of the snow has a visible tendency to round and is gradually evolving towards a larger and larger structure, not to mention that the connections between the grains have become larger and larger.

Metamorphism has consequences on the physical properties of the snow cover. Density tends to increase under overload pressure and due to thermodynamic grain transformations (Dibb and Fahnestock 2004). However, relating transfer properties to metamorphism is complex, as its evolution is a function of time and is related to several factors that are

difficult to estimate. This is why transfer properties have often been established as a function of density, despite the decrease in the quality of the estimate.

2.2.3 Snowmelt

Determining snow melt is crucial for various purposes, including seasonal volume estimation, stream flow predictions, designing flood control structures, and more. Snowmelt's thermodynamics are well known and have been extensively discussed in several publications. The early descriptions by (Clyde, 1931), (Light, 1941), and (Wilson, 1941) are among the lists. The U.S. Army Corps of Engineers' (COE, 1956) study, which is still frequently mentioned and recognized as a seminal work about snowmelt dynamics. The most important single indicator of melting conditions is air temperature. It is common to express snow-melt rates as functions of air temperature expressed in degree-days above freezing. But expressing snow-melt rates as a function of degree-days implies that other impacts are either insignificant, constant, or are straightforward temperature functions (Wilson, 1941).

The wind speed, latent heat released by moisture condensation on the cold snow surface, and the net effect of incoming and outgoing radiation are a few of these factors. A radiation-related example of a minimal effect is when, with a lot of cloud cover, the incoming and outgoing radiation may balance. The existence of relatively uniform wind speed over a certain basin at a given time is an illustration of a constant effect. As a result, the turbulent exchange produces little variation other than with changes in temperature and humidity. The air temperature reflects the overall impact of both incoming and outgoing radiation, and under some circumstances, the radiation effect can be represented as a straightforward function of air temperature (Wilson, 1941).

In a flat, prairie-like landscape, an ideal snowfall might have the same initial depth and melt rate everywhere (Figure 2.4.a). Any real-world landscape has hollows and stream valleys that tend to hold onto snow better than other places. Since the thinnest sections of the snowpack melt off first and the deepest parts last, even a spatially equal rate of melting will result in a gradual decrease in the snow-covered area (SCA) rather than a dramatic disappearance (Figure 2.4.b). Because the initial snowpack tends to be deeper at higher elevations and the heat supply for melting tends to be lower, snow persists for a long period

in the higher sections of mountain basins, where snow cover depletion is even more gradual (Figure 2.4.c).

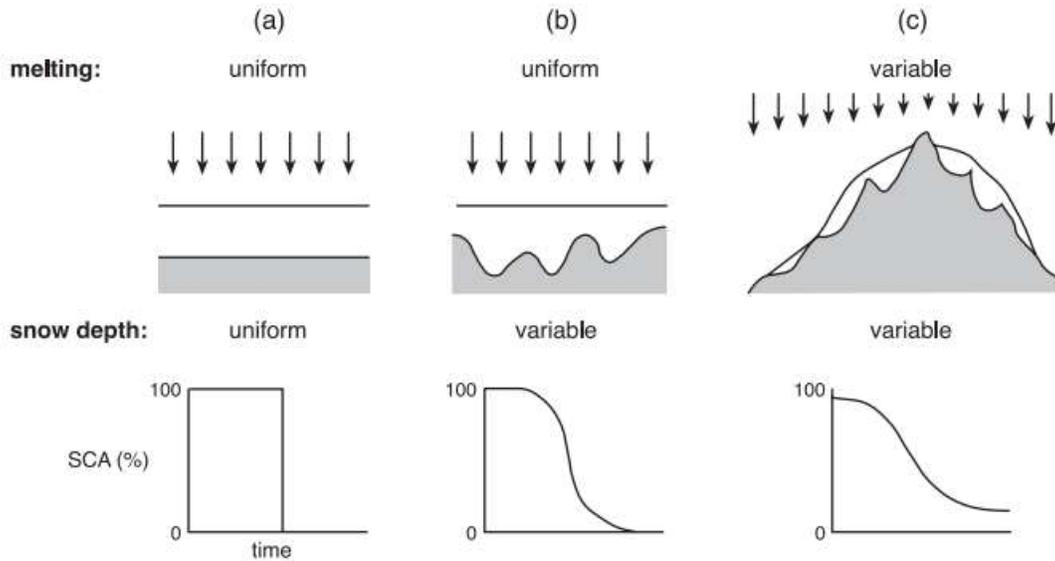


Figure 2.4 Relationship between temporal decline in a snow-covered area (lower diagrams) and spatial heterogeneity in snow depth and melt rate (upper diagrams) (Rahimi 2016).

Snowmelt is often conceptualized as an energy balance problem which can be expressed as follow (Van Mullem et al., 2004):

$$\Delta S = S_{net,sol} + S_{net,lw} + s_{sen} + S_l + S_g + Q_p \quad (2.2)$$

Where $S_{net,sol}$ ($W m^{-2}$) is the net solar radiation, $S_{net,lw}$ is the net thermal radiation ($W m^{-2}$), s_{sen} is the sensible heat transfer from air ($W m^{-2}$), S_l is the latent heat of vaporization from condensation or evaporation per sublimation ($J kg^{-1}$), S_g is the conducted heat from underlying ground ($W m^{-2}$), and Q_p is the advected heat from precipitation ($W m^{-2}$). Table 2.3 summarizes each of the terms in the energy balance equation and their relative importance.

Table 2.3 Relative importance of energy balance terms, Van Mullem et al., (2004)

Term	% ΔH	comments
H_{rs}, H_{rt}	60-90 %	Controlled by terrain, season, cloud cover, shading, air temperature, humidity. H_{rs} and H_{rt} are generally of about the same magnitude, but different sign. H_{rt} is usually negative and dominates in winter. H_{rs} is positive and dominates in spring. During a crossover period in early spring before the onset of melt, H_{rs} and H_{rt} cancel each other, and the net is near zero.
H_s, H_l	5-40 %	Controlled by temperature and humidity gradients and wind speed. H_s and H_l are usually of opposite sign, so they tend to cancel. That is, it is usually either warm ($H_s +$) and dry ($H_l -$) or cold ($H_s -$) and humid ($H_l +$). Sometimes H_s and H_l are of the same sign, but the magnitude is small (e.g., cold and dry). Occasionally both are positive and large (i.e., warm and humid), usually during high winds, such as during rain-on-snow events.
H_g	2-5 %	Usually small because the temperature of the ground is generally about the same as the temperature of the snow. During melt, both ground and snow are at 0 °C, so $H_g = 0$.
H_p	0-1 %	Heat content of precipitation is relatively small compared to latent heat required to melt snow, unless precipitation volume is very large and precipitation temperature is significantly greater than 0 °C.

2.3 Key physical attributes of snow

Among the key physical characteristics of snow, the density, porosity, snow-water equivalent, and specific surface area (SSA) area will be described further in this document. These are the main physical properties relevant to snowmelt analyses.

2.3.1 Density

When it comes to mass transport and heat transfer, the mass and volume characteristics of a porous material is a crucial factor (Meinicke et al., 2020). A layer of snow has a density

between that of air, which is approximately 1.204 kg m^{-3} at 101.325 KPa and 20°C (Cavcar, 2000), and that of ice, which is 918.9 kg m^{-3} at -10°C (Ghormley and Hochanadel, 1971). On a spatial scale of the order of a centimeter, the medium is continuous, and its apparent density (ρ_0) is usually expressed as a function of the mass of snow per unit volume (Morris, 1987; Morland et al., 1990). The volume fraction Θ_k [-] and the density ρ_k [kg m^{-3}] are directly related to the apparent density:

$$\rho_0 = \sum \Theta_k \rho_k \quad (2.3)$$

Where k can be a, w, and i for air, water, and ice respectively. The sum of its volumetric fractions for all components equals one, where:

$$\sum \Theta_k = 1 \quad (2.4)$$

Snow density is defined as the weighted average of the density of each of the components. As the mass of the gaseous components is less than 1% of the total mass, the snow density can be defined as follows (Morland et al., 1990):

$$\rho_s = \Theta_i \rho_i + \Theta_w \rho_w \quad (2.5)$$

Where ρ_s is the density of snow, ρ_i is the density of ice (918.9 kg m^{-3}), ρ_w is the density of water (1000 kg m^{-3}), Θ_i and Θ_w are the volumetric ice, and water contents, respectively.

Snow density is often required in snow hydrology (Pulliainen and Hallikainen, 2001) and climatology (Derksen and Brown, 2012). Density is related to snow mechanical parameters (Schneebeli and Johnson, 1998; Wang and Baker, 2013), and vertical density fluctuations affect snowpack stability (Schweizer et al., 2011). Most of all, it describes the amount of water contained within it, which is very important in any hydrological application. Table 2.4 provides typical density values for different types of snow (Glen, 1997).

Table 2.4 Typical snow density values for different types of snow (Glen, 1997).

Type of Snow	ρ_s (kg m ⁻³)
New snow (immediately after falling)	50-70
Damp new snow	100-200
Settled snow	200-300
Depth hoar	100-300
Wind packed snow	350-400
Firn	400-830
Very wet snow and firn	700-800
Glacier ice	830-917
Pure ice	917

2.3.2 Porosity

Snow can also be characterized by its porosity (n), which is the volume ratio of all voids (pores) to the total volume. When considering dry snow, it is appropriate to describe in terms of porosity because there is only a solid phase present (Ignoring the amount of unfrozen water, which can be large for temperatures near 0°C.) (Dozier et al, 1987):

$$n_s = 1 - \frac{\rho_s}{\rho_i} \quad (2.6)$$

Equation 2.6 connects the ice mass per unit sample volume plus the liquid mass per unit sample volume to the snow density. Therefore, using known values for S_w (liquid water saturation) and n , it is also possible to directly compute the snow density (Colbeck, 1978);

$$\rho_s = \rho_i(1 - n) + \rho_w n S_w \quad (2.7)$$

The literature provides measured values of porosity for different types of snow, some of which are summarized in Table 2.5.

Table 2.5 Porosity for different types of snow (Clifton et al, 2008)

Type of snow	Porosity (%)	Reference
New snow, wind blown	83–85	Sommerfeld and Rocchio, (1993)
Wind-packed snow	77	Albert et al., (2000)
Melt-freeze surface	63	Albert and Perron, (2000)
Melt-freeze crystals	62	Albert and Perron, (2000)

2.3.3 Snow water equivalent

The snow water equivalent (SWE) is another important parameter, especially used in watershed management (Langlois et al., 2009). The SWE essentially represents the amount of water contained in the snowpack. It is an important parameter in hydrology to calculate the amount of water entering a basin at the end of winter (Langlois et al., 2009).

$$SWE = \frac{\rho_s}{\rho_w} H_s \quad (2.8)$$

where H_s is the snow depth.

2.4 Mechanisms of heat transfer in a snow cover

Heat transfer in snow arises mainly from four processes (Bishop et al., 2011): (1) conduction through the network of interconnected ice crystals, (2) conduction through interstitial air, (3) latent heat transfers due to sublimation-condensation cycles resulting from metamorphism, and (4) airflow within the snow, either in the form of convection caused by high-temperature gradients or advection caused by wind blowing over a rough snow surface. Airflow is typically less significant, latent heat transfer plays a major role only in depth hoar, and the thermal conductivity of ice ($\lambda_{ice} = 2.3 \text{ W m}^{-1} \text{ K}^{-1}$ at -10°C) is much higher than that of air ($\lambda_{air} = 0.023 \text{ W m}^{-1} \text{ K}^{-1}$ at -10°C) (Bishop et al., 2011). Consequently, the primary heat flow in snow mainly occurs through conduction within the interconnected network of snow crystals, resulting in wind packs having considerably higher thermal conductivity than depth hoar (Bishop et al., 2011). This section presents an analysis of snow's thermal properties and their implications for snowpack stability and

snowmelt. Understanding the dominant heat transfer mechanisms makes it possible to better predict snowmelt rates.

2.4.1 Conduction

The process of heat conduction in ice and snow encompasses various mechanisms outlined in Figure 2.5, which includes conduction through snow crystals and interstitial air. As the thermal conductivity of ice (λ_{ice}) is significantly higher than that of air (λ_{air}), the primary heat transfer process in snow is often through the network of interconnected snow grains (Sturm et al., 1997). It is logical to anticipate that snow with higher thermal conductivity values would generally be the hardest type of snow (Bishop et al., 2011). Nevertheless, Sturm et al. (1997) demonstrated a significant positive correlation between snow density and thermal conductivity.

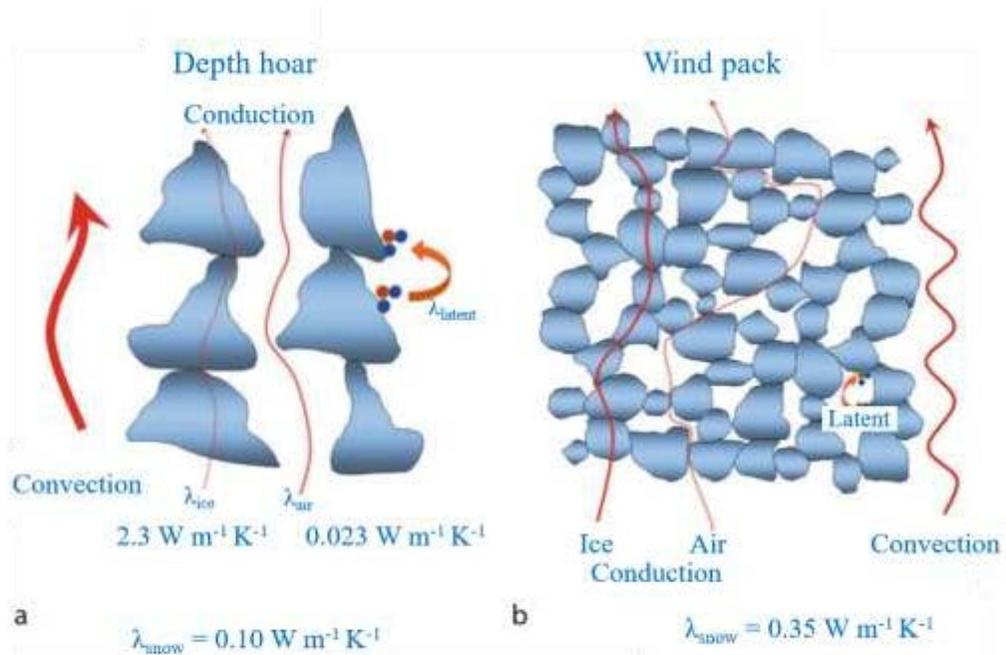


Figure 2.5 Main processes involved in heat transfer through (a) depth hoar and (b) wind-packed snow (Bishop et al., 2011).

Heat conduction in the snow cover can be described by a one-dimensional equation (Ashton, 2011):

$$\rho_s C_s \frac{\partial T_s}{\partial t} = \frac{\partial}{\partial z} (\lambda_s \frac{\partial T_s}{\partial z} + \varphi) \quad (2.9)$$

Where T_s is the temperature in the snow ($T_s \leq 0^\circ\text{C}$), ρ_s is the density of the snow, C_s is the specific heat capacity of the snow, λ_s is the thermal conductivity of the snow, and φ is an internal heat source term due to solar radiation absorption.

2.4.2 Convection

For more than 30 years, the concept of air convection in the snow has been a subject of debate (Johnson et al., 1987; Brun and Touvier, 1987). Only limited conditions have been accepted for convection at the laboratory scale (Sturm and Johnson, 1991). Akitaya (1974) failed to induce convection in natural snow samples despite applying strong temperature gradients but was able to induce convection in artificial snow samples. According to Klever (1985), convection is common in new snow, but unlikely in rounded snow. Based on Rayleigh number calculations, Brun and Touvier (1987) concluded that convection was unlikely, although none of the snow samples they tested were of high permeability.

2.4.3 Radiation

In most studies, radiation at the surface is divided into two streams: shortwave radiation from the sun, which falls between 0.3 and 2.2 μm in wavelength, and longwave radiation from the sky and surrounding terrain, which falls between 6.8 and 100 μm in wavelength (Male and Granger, 1981). Almost 5% of the total radiation occurs between 2.2 μm and 6.8 μm (Geiger, 1966). Radiation is often taken as a boundary condition, including both solar (Marks and Dozier, 1992) and thermal radiation (Marks and Dozier, 1992).

2.4.4 Sensible and Latent heat

Figure 2.6 illustrates the concept of latent and sensible heat (Skovajsa et al., 2017). Also, it shows the conversion from sensible heat to latent heat occurs during the snow-to-water phase change. During this process, the temperature of the snowpack remains constant while the thermal energy of the solid phase is transformed into the liquid phase. The latent heat of fusion for water is 334 kJ kg^{-1} .

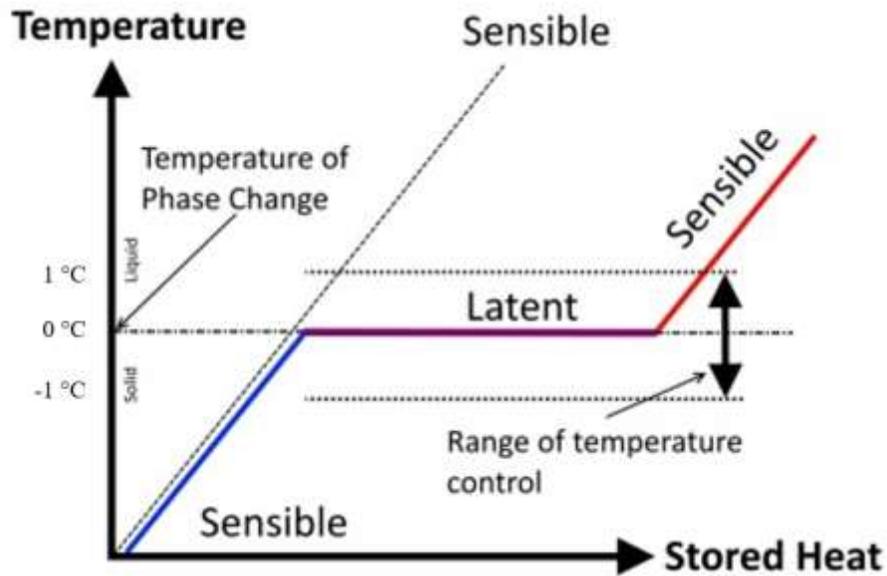


Figure 2.6 Temperature control during phase changes and a comparison of sensible heat and latent heat (adapted from Skovajsa et al., 2017).

By adopting the convention that energy influx into the snowpack is considered positive, the amount of energy accessible for snow melting, denoted as Q_m , relies on various factors including net radiation (R_n , which represents the difference between incoming and outgoing shortwave and longwave radiation), sensible heat flux (S_{sen}), latent heat flux (L), ground heat flux (G_h), and any energy flux caused by precipitation (Marks and Dozier, 1992; Burns et al., 2014).

$$Q_m + Q_{cc} = R_n + S_{sen} + L + G_h + P = R_n + F_T + G_h + P \quad (2.10)$$

Q_{cc} refers to the amount of energy necessary to raise the temperature of snow to its melting point, often referred to as the "cold content." The net turbulent flux, F_T , is the combined value of S_{sen} and L , with the latter being particularly significant in the realm of snow science as it represents sublimation, evaporation, condensation, and their connection to the overall mass balance of the snowpack. Although S_{sen} and L typically make up only a small portion of Q_m , they are still noteworthy contributors (Boon, 2009; Fitzpatrick et al., 2017).

2.5 Key thermal properties of snow

In this section, the thermal properties of snow are investigated. First, the thermal conductivity and the factors affecting it, such as density, porosity, and contact size between grains, are presented. Understanding these properties is crucial for predicting snow behavior in various environmental and engineering applications.

2.5.1 Thermal conductivity and factors of influence

The following aims to explain how snow density and porosity largely determines its thermal conductivity. However, several factors, including the relative humidity, the size and form of the grains, as well as the microstructure, affect the thermal conductivity value (Côté et al, 2012). Appendix A provides more information about available methods for computing the thermal conductivity of snow.

2.5.1.1 Effect of density and stratification on thermal conductivity

Sturm et al. (2002) conducted an in-depth study on the thermal conductivity and stratification of snow cover on the Beaufort Sea ice sheet. They measured the thermal conductivity of snow using a heated needle probe, finding values ranging from $0.078 \text{ W m}^{-1} \text{ K}^{-1}$ for fresh snow to $0.574 \text{ W m}^{-1} \text{ K}^{-1}$ for a snow-ice mixture. The study identified three major types of snow (Figure 2.7): depth hoar, wind slab, and recent snow. These types were observed in ten distinct layers at the Surface Heat Budget of the Arctic Ocean (SHEBA) site. The thermal conductivity of the snow was found to increase with density and could be estimated based on the snow's metamorphic state. Thermal conductivity measurements were made on approximately 10% of all layers measured for density, hardness, and type by Sturm et al. (2002). The thermal conductivity of snow layers measured by using a heated needle probe. This method involves inserting a thin needle into the snow layer and heating it. The rate at which the needle heats up is used to determine the thermal conductivity of the snow. The needle probe method is effective because it provides direct measurements of thermal conductivity and can be used in various types of snow, from fresh snow to snow-ice mixtures. Compared to the full set (Table 2.6), this thermal subset was slightly denser and harder, reflecting a natural bias toward layers. In Table 2.6, five of the ten layers of snow (“a”, “b”, “d”, “g”, and “j”) were under sampled,

while two layers (“c” and “f”) were oversampled. However, this bias is unimportant since (later) they derive a bulk value for the whole snowpack using layer-weighted averaging. Furthermore, Sturm et al. (1997) measured the thermal conductivity of 488 snow samples of known crystal type and density. They demonstrated that the thermal conductivity of snow composed of rounded grains correlates with their density. From these results, to demonstrate the relationship between the latter two, they established an empirical equation. Heat conduction has been shown to be less density dependent for snow subject to intense metamorphism, such as depth hoar. This happened due to the change in the connections between the grains due to metamorphism. The effect of metamorphism on thermal conductivity is not negligible, but it is not always easy to predict the variation of thermal conductivity by metamorphism. This is the reason why models of thermal conductivity are often a function of density.

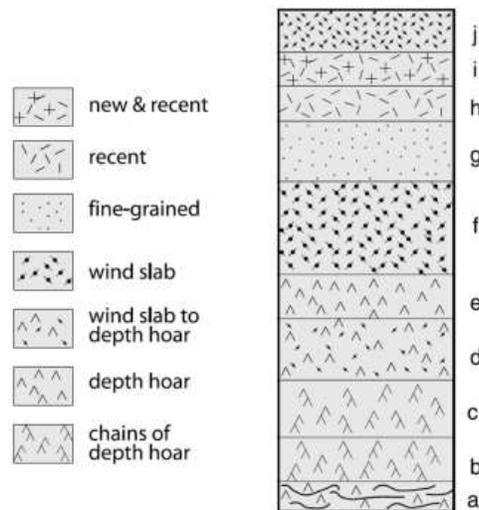


Figure 2.7 Stratification of a studied snow cover (Sturm et al., 2002)

Table 2.6 Average thermal conductivity of snow layers. (Sturm et al. 2002)

Layer	ρ (Kg m ³)	λ (W m ⁻¹ K ⁻¹)
J	390	0.203
H & I	200	0.078
G	360	0.197
F	420	0.290
E	280	0.157
D	360	0.164
C	270	0.081
B	270	0.087
A	600	0.574

2.5.1.2 Heat capacity of snow

The heat capacity is the amount of heat needed for a unit of mass to increase its temperature by one unit, either under constant pressure (c_p (J kg⁻¹ K⁻¹)) or constant volume (c_v (J kg⁻¹ K⁻¹)) conditions. Overall heat capacity is a function of the mass or volume of snow (i.s. density or porosity), calculated from that of ice. Mathematically, it is expressed as (Yen, 1981):

$$C_p = \left(\frac{\partial H}{\partial T}\right)_p \text{ or } C_v = \left(\frac{\partial U}{\partial T}\right)_v \quad (2.11)$$

Where H and U are enthalpy and internal energy per unit mass, respectively.

As the heat required to warm up the air and vapor in the gaps is negligible, the heat capacity of dry snow and ice is practically the same. The value of C_v can be derived from C_p using the following relationship (Yen, 1981):

$$C_p - C_v = \frac{K_V^2 V_i T}{\omega_T} \quad (2.12)$$

Where V_i is the volume of ice, K_V is the coefficient of volumetric expansion, and ω_T is the compressibility. At the melting point, the value of C_v is approximately 3% lower than C_p , and as the temperature decreases, the difference between C_p and C_v diminishes.

Dickinson and Osborne (1915) and Dorsey (1940) conducted a comprehensive review and compilation of the heat capacity values for ice established during the early twentieth century. In an extensive investigation, Giaque, and Stout (1936) provided C_p values for hexagonal ice across a temperature range of 15 to 273 K. Flubacher et al. (1960) determined c_p values for hexagonal ice within the range of 2 to 27 K. Additionally, Sugisaki et al. (1968) conducted comprehensive measurements of C_p for amorphous, cubic, and hexagonal ice at temperatures spanning from 20 to 250 K. Anderson (1976) presents a formulation for C_i ($\text{J kg}^{-1} \text{K}^{-1}$) as follows:

$$C_i = 1.6738 + 0.1327 T \quad (2.13)$$

where C_i is the specific heat of ice.

Ding et al. (2021) provide an equation for the heat capacity of snow, which is a function of the heat capacities of ice and air:

$$C_s = C_i \frac{\rho_s}{\rho_i} + C_a \left(1 - \frac{\rho_s}{\rho_i}\right) \quad (2.14)$$

2.6 Snowmelt numerical models

Snowmelt hydrological models simulate snow accumulation, melting, and convergence. In comparison to rainfall runoff, the snowmelt process involves more complex energy transfer and water transfer processes between the atmosphere and snow, between different snow layers, and between snow layers and soil (Marks et al., 1998). Because of the mixture of rain and snow, it is extremely difficult to simulate runoff generated by rainfall on snow. Modeling plays a critical role in forecasting snowmelt floods (Zhou et al., 2021).

2.6.1 Evolution of snowmelt models

Snowmelt models have been around for a long time. In the beginning, people estimated how much water flowed from melting snow by finding a statistical link between observed variables (like how much snow there was, how much water it contained, etc.) and snowmelt runoff (DeWalle and Rango, 2008). This period also makes frequent use of empirical equations. Air temperature and snowmelt are assumed to be linearly related by empirical equations, also called degree-day factors (Martinec, 1975). In 1975, Martinec developed the Snow Runoff Model (SRM), which is the most classic model of snowmelt based on the

degree-day method. The International Meteorological Organization recommends the SRM model, which is the most widely used model of snowmelt based on the degree-day method in more than 100 watersheds worldwide (Rango, 1995). Due to its simplicity and accuracy, the degree-day model has been widely used. Its disadvantage is that it cannot simulate snow melting physically (Zhou et al., 2021).

The US Army Corps of Engineers was the first to estimate how much snow melted based on the energy transfer process between the snow and its surroundings in the 1950s (Dunkle et al., 1956). The energy balance model is based on two fundamental concepts: the conservation of energy and water in the system. The model has been applied and improved in various studies (Anderson, 1976; Jordan, 1991), and has become more refined over time. However, the model still only represents a single point in space and does not account for spatial variability. The advancement of computer technology in the 1970s enabled the creation of more sophisticated and detailed physical hydrological models that could account for spatial variation. The first such model, called the European Hydrological System (SHE), was developed in 1986 (Abbott et al., 1986). The model divides the watershed into grid cells to capture the spatial variation of model parameters, rainfall input and hydrological outputs. The model also splits the vertical dimension into several layers to simulate the movement of soil water in different depths. The model then uses the energy balance method to estimate the snowmelt amount for each grid cell separately (Abbott et al., 1986).

There have been several distributed snowmelt models developed since the 1990s, such as SNOBAL (Marks and Dozier, 1992), Utah Energy Balance (UEB) (Tarboton and Luce, 1996), Hydrological Simulation Program - HFORTRAN (HSPF) (Johanson et al., 1984), etc. The Distributed Hydrology Soil Vegetation Model (DHSVM) (Wigmosta et al., 1994), Variable Infiltration Capacity (VIC) (Liang et al., 1994), and Soil and Water Assessment Tool (SWAT) (Arnold et al., 1998) all include snowmelt modules (degree-day snowmelt algorithm and energy balance algorithm). In addition, snowmelt models based on energy balance models, such as Snow Thermal Model (SNTHERM89) (Jordan, 1991) and SNOWPACK (Bartelt and Lehning, 2002), have been developed. Snow engineering now uses these models to consider more detailed vertical distributions. Machine learning is a

powerful and flexible technique that has transformed various fields and industries and enabled new possibilities for scientific exploration and model building. It is widely used for hydrological modeling and forecasting, becoming a new approach for hydrological research. Machine learning is evolving rapidly and creating more opportunities for snowmelt modeling, or what is also known as data-driven modeling (Zhou et al., 2021).

2.6.2 Types of Snowmelt Models

Snowmelt models can be grouped into four types based on the different methods they use to calculate the snowmelt rate: statistical, conceptual, physical, and data-driven (the green categories in Figure 2.8) (Zhou et al., 2021). Statistical snowmelt models use statistical techniques or black box modules to find the relationship between a specific snow hydrological parameter (such as snow area) and runoff, and use it to predict runoff (Zhou et al., 2021). The relationship between snowmelt and temperature is usually empirical in conceptual snowmelt models (Zhou et al., 2021). Several of these models are mature and widely used, such as SRM and HBV (Bergström, 1995). Based on the energy balance of snow cover, physical snowmelt models such as SNTHERM and SNOWPACK calculate snowmelt (Zhou et al., 2021). They have a strict physical meaning and are widely used in snowmelt modelling. Massive data and rapid computational power have enabled data-driven models to emerge (Zhou et al., 2021). Machine learning algorithms are used to select appropriate parameters from different data sources (e.g., daily rainfall, temperature, solar radiation, snow area, snow water equivalent) for these models, such as ANN (Vafakhah et al., 2014) and LSTM (Thapa et al., 2020).

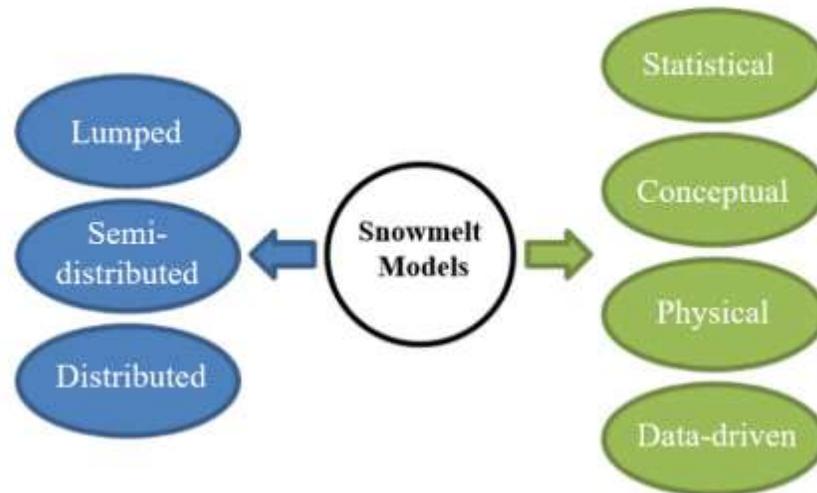


Figure 2.8 models of snowmelt categories. The models' spatial distribution features are used to produce the blue categories. Green ones are produced using various ablation algorithms (Thapa et al., 2020).

Snowmelt models can be categorized into lumped, semi-distributed, and distributed models based on the distribution features of models (Zhou et al., 2021). HBV, SWAT, and the Precipitation Runoff Modelling System (PRMS) (Leavesley and Stannard, 1995) are examples of semi-distributed models that divide the watershed into sub-watersheds or hydrological response units in accordance with a specific watershed characteristic (e.g., elevation, vegetation coverage, land use types, and topographic factors). Distributed models like SHE, DHSVM, and VIC segment the watershed into grid units, assigning distinct parameter values to each grid. These models subsequently incorporate processes involving wind, snow, and soil freezing within each grid entity (Zhou et al., 2021). Lately, driven by substantial advancements in computational capabilities, there has been a surge in the emergence of multi-layer hybrid and nested models. An example of such a model is the Water and Energy Budget-based Distributed Hydrological Model (WEB-DHM) (Wang et al., 2009). Nested calculations involving sub-catchments, grids, and slopes are employed to enhance the capacity for effectively depicting the snowmelt process (Wang et al., 2009).

2.6.3 Statistical Snowmelt Models

The prevalent statistical approach to predicting snowmelt runoff involves correlating the maximum SWE during the spring thaw with the total runoff volume, using regression

analysis to determine coefficients. SWE can be measured manually or via automated snow pillows. Another method uses runoff characteristic curves, relating spring snow cover ratio to basin runoff, which can be forecasted using remote sensing data. While these models can be accurate with sufficient observations, they may not perform well in unprecedented situations and are challenging to transfer between different watersheds due to varying hydrological characteristics (Zhou et al., 2021).

$$Q = a + b SWE \quad (2.15)$$

Where Q represents the complete runoff quantity. SWE can be derived either through manual measurement of snow depth along a designated survey line or via automated snow pillow measurements (Zhou et al., 2021). The values for coefficients 'a' and 'b' are derived through regression analysis performed on collected data.

2.6.4 Conceptual Snowmelt Models

The conceptual snowmelt model is commonly constructed using the degree-day factor approach, often termed the degree-day factor model (Zhou et al., 2021). Its fundamental premise postulates a linear correlation between alterations in the snowmelt rate and the daily average temperature surpassing a specific threshold. The typical formulation of the degree-day factor ablation algorithm is represented by Equation (2.16) (Zhou et al., 2021):

$$M_{mel} = DDF (T_{avg} - T_b) \quad (2.16)$$

In this equation, M_{mel} (cm day^{-1}) represents the quantity of melted snow, T_{avg} ($^{\circ}\text{C}$) stands for the average temperature of the day, and T_b ($^{\circ}\text{C}$) denotes the temperature threshold. Typically, the threshold temperature T_b ($^{\circ}\text{C}$) is set at 0°C , although alternative values might be employed in specific circumstances. DDF ($\text{cm }^{\circ}\text{C}^{-1} \text{ day}^{-1}$) represents the degree-day factor for snowmelt. Research has indicated substantial variability in DDF values across various areas, spanning from 0.1 to 1 ($\text{cm }^{\circ}\text{C}^{-1} \text{ day}^{-1}$). DDF can be ascertained through measured data or empirical formulas (Zhou et al., 2021):

$$DDF = 1.1 \frac{\rho_s}{\rho_w} \quad (2.17)$$

Most conventional snowmelt models based on degree-day factors ignore the spatial variability of ablation in the watershed and use lumped or semi-distributed approaches

(Zhou et al., 2021). This leads to large uncertainties in the spatial distribution of snow melting simulation. Moreover, the degree-day factor is fixed on a daily scale and cannot reflect the intra-day variation of snowmelt rate, especially the contrast between day and night in temperature and snow energy supply. The enhanced spatial distribution degree model considers the time and space differences and incorporates energy exchange terms. This allows it to simulate the changes in snowmelt runoff on a daily scale and obtain reasonable results (Zhou et al., 2021).

2.6.5 Physical Snowmelt Models

The energy balance of the snow surface consists of the components shown in Figure 2.9 (Zhou et al., 2021). Several snow models have been developed over the years, including Anderson's multi-layer model (1976), Marks et al.'s SNOBAL (2015), and Bartelt et al.'s SNOWPACK (2002). These models simulate snow characteristics like depth, density, and temperature, and can forecast avalanche risks.

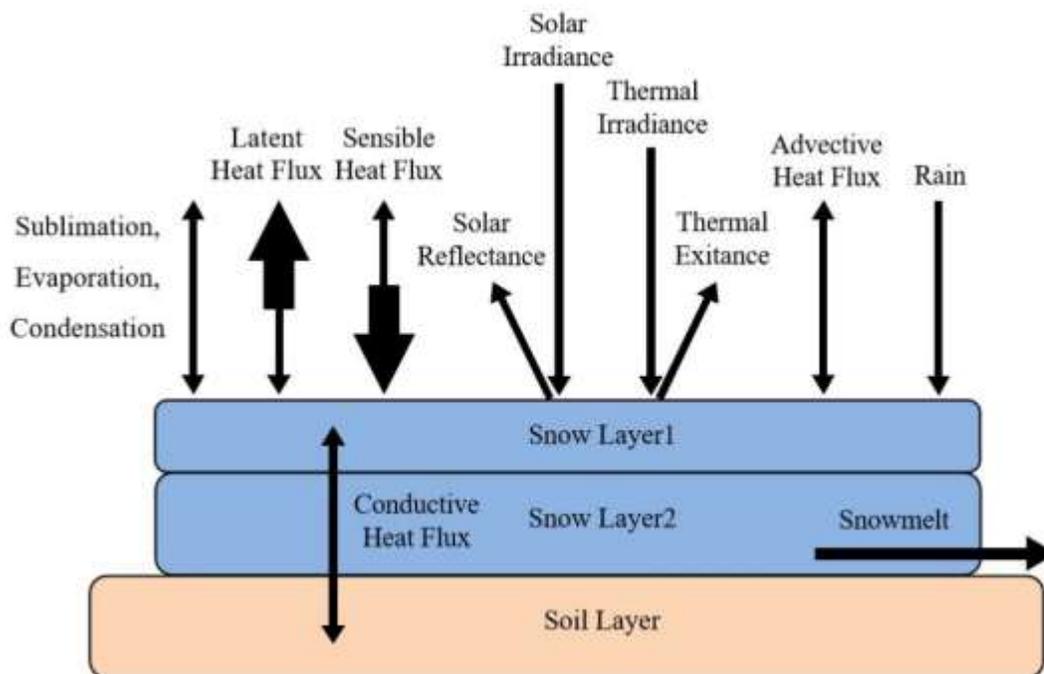


Figure 2.9 Diagram illustrating the process of exchanging energy in snow (Zhou et al., 2021).

Simulating snow ablation based on energy balance can be precise for small areas, but challenges arise for large watersheds due to data extrapolation issues and sparse monitoring stations (Zhou et al., 2021). Empirical methods are often used to estimate energy fluxes. Physically distributed snowmelt models, like SHE, DHSVM, VIC, and UEB, offer high-resolution simulations and follow strict physical principles (Zhou et al., 2021).

2.6.6 Models based on data

The development of data-driven models, enabled by data availability and machine learning advancements, focuses on enhancing prediction accuracy (Zhou et al., 2021). These models handle complex problems and identify essential inputs. Unlike physical models, data-driven models learn relationships between inputs and outputs without prior process knowledge (Zhou et al., 2021). Machine learning has been widely used for predicting snowmelt runoff and other hydrological applications. Combining data-driven and physical models can improve hydrological modeling by maintaining energy and water balance and determining model parameters. Despite challenges like unbalanced observations and limited training data, integrating machine learning with hydrological knowledge can enhance snowmelt modeling (Zhou et al., 2021).

2.6.7 Snowmelt modeling issues

Blowing snow, snow on frozen ground, and rain on snow are some of the key issues that need attention in the snowmelt model.

2.6.7.1 Blowing Snow

Snow melting varies spatially due to blowing snow, which creates uneven snow cover and impacts the snow water cycle (Zhou et al., 2021). MacDonald et al. (2010) found that 17–19% of yearly precipitation in the Rocky Mountains was due to wind-blown snow evaporation. Zhou et al. (2014) reported that blowing snow sublimation accounted for 24% of annual snowfall in western China's mountains. Hydrological studies use conceptual models based on terrain drift factors and physical models relying on wind fields. Key models include PBSM (Pomeroy et al., 1993), Snowtran-3D (Linston et al., 1998), Alpine3D (Lehning et al., 2006), and SnowDrift-3D (Schneiderbauer and Prokop, 2011). Challenges include identifying critical conditions for blowing snow, obtaining accurate

wind field data in complex terrain, and parameterizing data for widespread blowing snow (Zhou et al., 2021). Terrain significantly impacts blowing snow models, with terrain parameters crucial for snow depth estimation (Winstral et al., 2002). Integrating blowing snow models with snowmelt models remains a scientific challenge (Zhou et al., 2021).

2.6.7.2 Snow on Frozen Ground

Phase changes in soil water affect heat and water balance near the surface, impacting runoff and infiltration (Zhou et al., 2021). Frozen ground prevents infiltration, increasing surface runoff, while unfrozen soil allows high infiltration and water storage (Zhou et al., 2021). Various models, like SHAW and VIC, simulate these processes, considering factors like frost depth and snowmelt infiltration (Cherkauer and Lettenmaier, 1999). Advanced models, such as DWHC and SHAW-DHM, integrate these processes with climate models for accurate simulations in cold regions (Chen et al., 2006; Zhang et al., 2016).

Explicitly considering soil freezing and thawing enhances land surface and hydrological models (He et al., 2015). These processes adjust soil liquid water content and hydraulic conductivity, affecting evaporation, infiltration, and runoff (Zhou et al., 2021). Without a frozen ground module, models underestimate snowmelt runoff peaks in basins with strong frozen soil (Pohl et al., 2005). Accurately simulating frozen ground's influence remains challenging, requiring attention to different time scales and regional environments. Adding a frozen ground module to snowmelt models is essential for studying runoff dynamics in cold regions (Zhou et al., 2021).

2.6.7.3 Rain-on-Snow

Rain-on-Snow (ROS) events in mountainous areas cause severe mixed rain and snow floods, contributing to high flow peaks (Kattelman, 1985). Studies show ROS events caused significant floods in regions like the Willamette River, Austria, and the western U.S. (Li et al., 2019). Climate change affects ROS frequency and peak flows, increasing risks in high altitudes (Zhou et al., 2021). Ignoring ROS conditions can lead to underestimating runoff and peak flow, highlighting the need for accurate ROS-based runoff models (Zhou et al., 2021). Many factors influence ROS event runoff, including rainfall, snow temperature, and moisture conditions (Singh et al., 1997). Physics-based models are

needed to simulate snow cover development and internal processes (Kattelman, 2007). ROS enhances snowmelt runoff by reducing albedo and increasing snow energy, leading to faster melting (Ocampo Melgar and Meza, 2020). Improved hydrological models incorporating lateral flow could enhance predictions, but the mechanism of ROS-based runoff generation needs further study (Zhou et al., 2021).

2.7 Current snow management practices in mining operations and research needs

The current snow management practices during mining activities involve plowing roads and clearing access to specific parts of the operations for mining, construction or operation purposes. Some operations have snow storage facilities, that are used to keep snowmelt waters within the mine site's controlled waters. Operations dealing with filtered tailings can also adapt some snow management practices, essentially aiming to avoid the entrapment of snow in between tailings layers during deposition and provide optimal compaction conditions. However, there is not current practice aiming to manage snow as a spring runoff control strategy. The literature review has shown that the physics of snowmelt and the thermal and physical properties of snow are well known. Several snowmelt modeling approaches are available, but none is adapted to model the snowmelt of remoulded or piled snow. Based on the knowledge acquired through snow science, more research is required on snow management practices in mining operations.

CHAPTER 3 MATERIALS AND METHODS

3.1 General approach

First, the fieldwork has been completed. Using the data collected, numerical modeling was implemented. Initially, the impact of temperature variations on the melting process of SMPs will be investigated by conducting simulations with temperature data from different years. A detailed description includes the construction techniques used for creating SMPs, the climate monitoring methods employed for accurate data collection, and the specific parameters and conditions applied in the numerical modeling process.

The approach involves a comprehensive examination of the Goldex and Holt mine sites, providing site descriptions and climate monitoring data to contextualize the study. The construction and monitoring sections detail the techniques used in SMP construction, as well as the methods for monitoring snowmelt, internal and snow-surface temperatures, and snow density. Furthermore, the numerical modeling section delves into the selection of the model, the modeling approach, and the various parameters that influence the simulations, such as geometry, mesh, reference temperature, and porous medium type.

Additionally, this section outlines the calibration of a snow-surface temperature function based on measured air temperatures, which is crucial for establishing realistic surface boundary conditions in the model. The overall goal is to provide a comprehensive understanding of the materials and methods used in the study, ensuring that the approach is clearly articulated and that the results can be accurately interpreted and validated. This detailed explanation aims to provide a robust framework for analyzing the thermal dynamics and melting patterns of SMPs under varying temperature conditions.

Ultimately, this section is designed to comprehensively describe the materials and methods utilized in the study, setting the stage for the subsequent analysis and discussion of the results.

3.2 Site description and climate monitoring

The following sections will present descriptions of the Goldex and Holt mine sites, along with climate monitoring data for 2022 and 2023.

3.2.1 Goldex mine

The Goldex Mine is an underground gold mine operated by Agnico Eagle Mines Limited, and is located about 4 km west of Val d'Or, Québec. This mine produces conventional pulp tailings that were initially deposited in a TSF approximately 4 km south of the site. However, since 2008, most of these Goldex tailings have been redirected to the Manitou legacy site, which is owned by the government of Québec. While the Goldex tailings are currently mainly being used as construction material to reclaim the Manitou site (Ethier et al. 2014 b) the Goldex TSF is still used as an auxiliary TSF. Covering about 75 ha, the Goldex TSF is linked to a polishing pond capable of holding roughly 500,000 m³ of water and used for settling particles from the TSF's seepage waters and storing surface drainage waters.

The Val-d'Or region experiences a humid continental climate characterized by significant seasonal temperature variations. According to Environment and Climate Change Canada (ECCC) data recorded from 1971-2000 (www.climate.weather.gc.ca), the mean annual temperature in this area is approximately 1.2°C. The coldest months are January and February, with average temperatures typically hovering around -17°C. Val-d'Or experiences an average total precipitation of 935 mm, with approximately 635 mm rainfall and 300 mm snowfall. (MSC ID 7098603; www.climate.weather.gc.ca). The snow cover typically spans from mid-November to early May, with the majority of snowmelt occurring in April. On average, there are about 121 days each year when the snow depth is 20 cm or more (MSC ID 7098603; www.climate.weather.gc.ca). Most of snowmelt typically occurs in two weeks in the region. It is important to note that while the author did not participate in the data collection at the Goldex mine, the data from this site was used and further interpreted to achieve the study's objectives.

3.2.2 Holt mine

The Holt Mine Complex is in the Kirkland-Matheson region of Ontario, approximately 68 km by road west of Matheson and 53 km east of Kirkland Lake. The complex consists of the Holt, Holloway, and Taylor Mines. The Holt Mine was built in the late 1980s, the Holloway Mine began operations in 1996, and the Taylor Mine was commissioned in 2015.

The complex includes two TSFs with a combined capacity to handle the tailings generated by the mining operations. In this mine, the tailings facilities consist of 18 individual dam structures, covering a total watershed area of 465.4 ha and a tailings area of 212 ha (116 ha for the North TSF and 96 ha for the South TSF). The Holt TSF is connected to a polishing pond with a capacity of approximately 1,400,000 m³ of water. The Holt Mine began operations in 1988 when it was developed by Barrick Gold. Over the years, it has seen various phases of activity and ownership changes, including its acquisition by Kirkland Lake Gold in 2016 and later by Agnico Eagle Mines Limited in 2022.

The Kirkland Lake region has a humid continental climate with seasonal climatic variations similar to that of Val d'Or. According to ECCC data recorded from 1971-2000, the mean annual temperature in this area was approximately 2.7 °C. The coldest months are January and February, with average temperatures typically hovering around -17.9 °C. Precipitation in Kirkland Lake reach an average total of 970 mm, with approximately 741 mm rainfall and 229 mm snowfall (MSC ID 6074209; www.climate.weather.gc.ca). The snow-covered period and snowmelt in this area are similar to those in the Val d'Or region. On average, there are about 90 days each year when the snow depth is 20 cm or more.

3.2.3 Climate monitoring

For both sites, daily temperature, precipitation, and snow thickness data were retrieved from the nearest ECCC weather station. Climate data from the Val d'Or ECCC station (MSC ID 7098603; www.climate.weather.gc.ca) was used for the Goldex mine and covered a period spanning from February 25 to May 27, 2022. Due to the station's proximity (<4 km) to the Goldex TSF, the temperature and precipitation data were representative of in situ conditions (Boulangier-Martel et al., 2022). Climate data from the Kirkland Lake ECC station (MSC ID 6074209; www.climate.weather.gc.ca) was used for the Holt mine. For that site, retrieved data covered a period spanning from February 29 to May 29, 2023. This weather station is the closest and is located at about 40 km south-west of the Holt mine. For that case, the representativeness of snow thickness measurements at the Kirkland Lake ECCC weather station was assessed by comparing the daily thickness of snow on the ground recorded at the ECCC weather station data with manual, on-site measurements as well as LiDAR surveys. The Val d'Or ECC station (about 150 km west

from Holt mine) data were also recovered for the 2023 monitoring period for comparison purposes.

3.3 Construction and monitoring

The following section will outline the construction methods of SMPs and the techniques for monitoring snowmelt.

3.3.1 SMPs construction techniques

To assess the efficacy of SMPs at controlling snowmelt, six experimental SMPs were constructed within the TSFs of Canadian mine sites over two field seasons.

During the first field season (2022), three experimental SMP configurations were built at the Goldex TSF using common civil construction heavy equipment. Cubical, conical and ridge-shaped SMPs were selected and constructed to assess the effects of configuration on the melting behaviour. The construction occurred from mid-February to March 2022. The first step in the construction of the tested SMPs involved a pre-compaction of the natural snow accumulated at the surface of the TSFs using a snowmobile. Such approach was necessary to compact existing snow and promote the freezing of surface of the TSF. The construction of SMPs started once the surface of the TSF was frozen enough to withstand the traffic of heavy equipment. The SMPs were constructed at the beginning of March 2022 using two Caterpillar 938H wheel loaders (Figure 1a), a Caterpillar D6N LGP crawler dozer (Figure 3.1.a), and a Caterpillar 320E hydraulic excavator equipped with a long-reach boom-stick (Figure 1b). SMPs were built in a single lift mostly using a push-only approach, meaning that the snow was groomed by only pushing snow towards the SMPs (Figure 3.2.a). Footprints of 33×30 m, and 50×25 m were targeted for the cubic and ridge-shaped SMPs and snow was groomed to the maximum achievable height by the equipment (about 3.5m). For the conic SMP configuration, a conical base was first groomed to the height capacity of the dozer and loaders. Then, the hydraulic excavator was used to build a higher structure from snow that was brought by the loaders. Approximately 12,000 m² of snow was cleared to build the SMPs at this site (Figure 3.2.a). Considering that a snow depth of about 70 cm was observed at the site during construction, a volume of snow of about 8,400 m³ was stored by the grooming operations. After construction the height of the

tested SMPs was of 7.3 m, 3.5 m, and 3.5 m for the conic, cubic and ridge-shaped SMPs, respectively. The initial footprint of the SMPs were of 665, 965, and 1150 m², respectively. The ridge-shaped SMP contained the most snow, and the conic SMP was about twice the height of the cubic and ridge-shaped SMPs, but contained the least snow (Table 3.1).



Figure 3.1 (a) Crawler dozer and wheel loaders used for the construction of SMPs in 2022; (b) hydraulic excavator lifting the conic SMP in 2022 and (c) final profile of the cubic SMP in 2022; (d) snow groomer used for the construction of SMP in 2023; (e) final profile of conic SMPs as well as groomer track on the snow in 2023; and (f) final profile of the ramp-shaped SMP in 2023.

The results of the first field season were used to determine promising SMP configurations. Monitoring results (presented later in this manuscript) and operational experience resulted in conical and ramp-shaped SMPs being the two optimal SMP shapes to test further. Thus, two cones and a ramp-shaped SMPs were designed and constructed at the Holt TSF during

winter 2023. Such configurations aimed to examine the impact of diverse sizes and shapes on snowmelt dynamics. Construction of all SMPs was achieved in two lifts performed mid- and at end of March. Snow was groomed with a Prinoth Bison-X snow groomer (Figure 3.1.d) equipped with a 4.5 m wide blade. The conic SMPs were constructed by creating concentric windrows that were systematically pushed toward the pile as soon as the blade was full of snow (Figure 3.1.e; 3.2.b). Such approach allowed maximizing the proportion of time the machinery was pushing snow. SMPs were grown by piling, compacting and shaping the snow with the snow groomer. The largest cone was 7.3 m high whereas the smallest was 5.5 m high (Table 3.1). The two conic SMPs were designed to directly assess the impact of height on snowmelt. In addition, the 2022 and largest 2023 conic SMPs had the same height and will be used as a reference to assess the impact of climate and volume on the performance of SMPs to control snowmelt. The ramp-shaped SMP was groomed using a push only approach. Snow was gradually pushed and piled along a ramp that grew in height with the increasing volume of snow being groomed. Such construction approach was selected for its ease of construction. This pile had a final height (5.6 m; Table 3.1) like that of the smallest conic SMP to allow for comparison. The largest cone held the most snow (Table 3.1). The smallest conic SMP held 1050 m² less snow than the ramp-shaped SMP despite being approximately the same height (Table 3.1). At the end of construction, around 55,000 m² of snow was cleared to build the three SMPs (Table 3.1). Overall, the SMP metrics presented in Table 1 indicate that the 2023 field tests involved clearing a larger surface (5.5 hectares) than 2022 (1.2 hectares). This resulted in more important snow volumes being stored in the 2023 SMPs. Considering that there was 60 cm of snow on the ground on average prior to constructions, this resulted in an approximate volume of groomed snow of 33 000 m³.

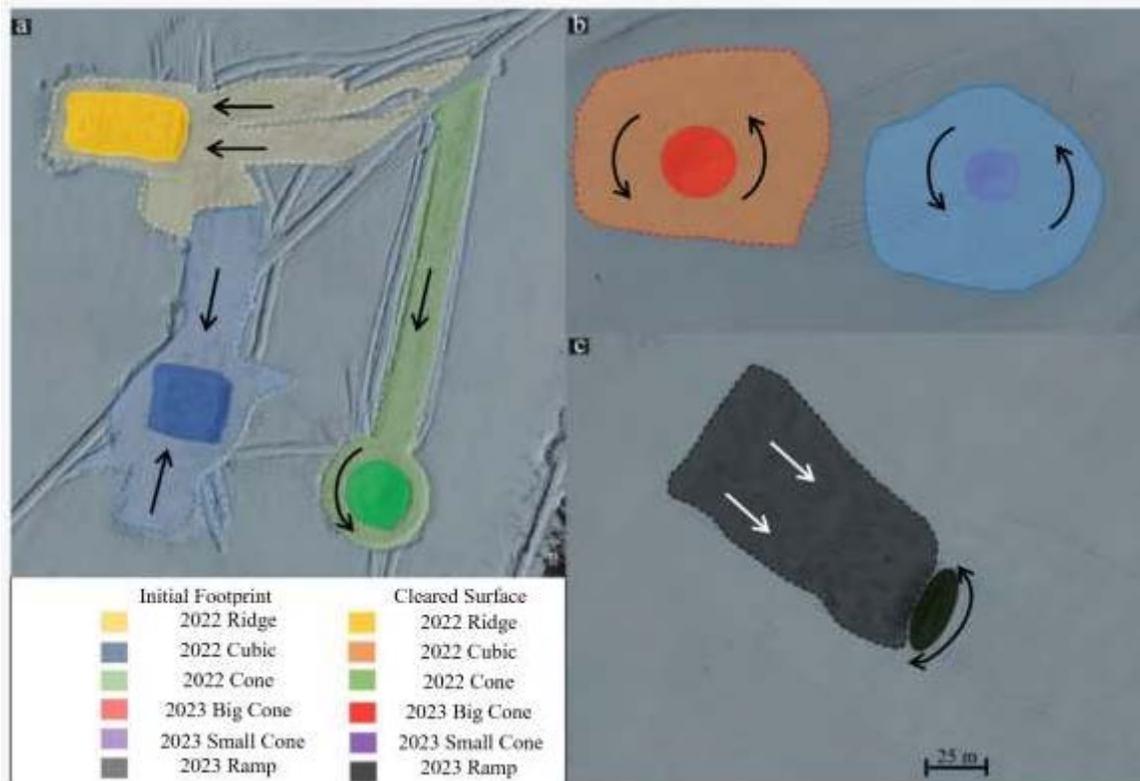


Figure 3.2 (a) Initial footprint, snow-cleared surface, and configuration of the SMPs in Goldex with arrows indicating the equipment movement for SMP construction; (b) and (c) Initial footprint, snow-cleared surface, and configuration of the SMPs in Holt with arrows indicating the equipment movement for SMP construction.

Table 3.1 Configuration, metrics and cleared surface of the tested SMPs.

Year	Shape	Cleared surface (m ²)	Initial height (m)	Initial footprint (m ²)	Initial volume (m ³)
2022	Cone	3000	7.3	665	1135
	Cubic	4260	3.5	965	2275
	Ridge-shaped	4700	3.5	1150	2565
2023	Big cone	24940	7.33	1950	4130
	Ramp-shaped	21420	5.5	1343	2650
	Small cone	9440	5.6	946	1600

3.3.2 Monitoring snowmelt

The effectiveness of the SMPs at controlling melting rates and delaying the snowmelt period was assessed through periodic measurements of the volume of snow contained in each SMP. The volume of the SMPs was measured through aerial LiDAR and SfM photogrammetry surveys acquired using an unmanned aerial vehicle (UAV). Such remote sensing tools have frequently been used to monitor snowpacks (e.g., Walker et al., 2020; Bash et al., 2020). Aerial surveys were performed with a DJI Matrice 300 RTK UAV equipped, with a DJI Zenmuse L1 Livox Lidar module installed in a single, downward gimbal configuration. The Matrice 300 RTK can operate at temperature as low as $-20\text{ }^{\circ}\text{C}$, and in relatively high-wind conditions (15 m s^{-1}). The selection of such UAV helped to minimize the no-fly conditions often encountered during winter and spring in Canada. The Zenmuse L1 LiDAR sensor has a high-precision inertial measurement unit (IMU) and boasts a ranging accuracy of 3cm at 100m. The Zenmuse L1 LiDAR module supports up to three returns. This sensor also has an RGB mechanical shutter and 1-inch complementary metal oxide semiconductor (CMOS) camera that is suitable for photogrammetry surveys. A DJI-D RTK 2 Mobile Station was connected to the UAV and served as a base station to provide real-time kinematic (RTK) position corrections during data collection. The RTK positioning accuracy was about 1 cm horizontally and 1.5 cm vertically. The automatic survey functions were used to pre-program and fly all LiDAR and SfM photogrammetry surveys performed in this study. The IMU was calibrated before each flight.

In 2022, surveys were performed eighteen times from March 11 to May 27 over an area of approximately $98,500\text{ m}^2$ (Table 3.2). The surveys performed in 2022 were configured to provide high-resolution acquisitions that were used to confirm the ability of each monitoring technique to accurately monitor the snowpack of small catchments such as TSFs and SMPs in a snowmelt scheme (see Boulanger-Martel et al., 2022). LiDAR scans were performed with a 70% lateral overlap and a three-return repetitive scanning pattern at a rate of 160 kHz. SfM photogrammetry surveys utilized 80% lateral and 70% frontal overlaps. Five to eight ground control points were surveyed to validate georeferencing and assess the accuracy of the surveys. Flights were conducted at an altitude of 50 meters to

obtain high-resolution data that yielded a point cloud density of 787 points m^{-2} and a ground sampling distance (GSD) of 1.26 cm pixel^{-1} (Table 3.2). All surveys were carried out on sunny to partly cloudy days, at roughly the same time of day, to ensure consistent lighting conditions.

In 2023, flight parameters were optimized to balance spatial resolution, acquisition, and reconstruction time. In this case, eight to ten surveys per TSF section were performed between March 23 and May 26, depending on SMP configuration. The surveyed areas were of about 277,000 and 362,000 m^2 for the conic and ramp-shaped SMP sites (Table 3.2). Flights were conducted at an altitude of 100 m to capture high-enough data over these larger areas. This resulted in an average point cloud density of 488 points m^{-2} and a GSD of 2.73 cm pixel^{-1} (Table 3.2). LiDAR and SfM acquisitions were performed using the same settings as in 2022 (Table 3.2).

DJI Terra Pro (v3.4.4) was used to do three-dimensional reconstructions and data analysis. This software uses reconstruction algorithms based on CUDA. A computer with an Intel Core i9-10900 CPU, NVIDIA GeForce RTX 3070 GPU, and 64 GB RAM was used to do the reconstructions in a standalone computation mode. The highest resolution was used for the reconstructions. The mean plane of the TSF surface was used as a reference to calculate the volume for both LiDAR and SfM photogrammetry analyses.

Table 3.2 Overview of Flight, LiDAR, and SfM Photogrammetry Survey Specifications.

Site	Survey parameter	LiDAR	SfM
2022- all SMPs	Flight altitude (m)	50	50
	Total flight distance (m)	7888	5130
	Mapping area (m ²)	98753	98143
	Lateral overlap (%)	70	80
	Frontal overlap (%)	-	70
	Number of optical images	358	560
	GSD* (cm pixel ⁻¹)	1.26	1.26
	Point cloud density (points m ⁻²)	787	-
2023- conic SMPs	Flight altitude (m)	100	100
	Total flight distance (m)	13694	6761
	Mapping area (m ²)	276675	276675
	Lateral overlap (%)	80	80
	Frontal overlap (%)	-	70
	Number of optical images	-	353
	GSD* (cm pixel ⁻¹)	-	2.73
	Point cloud density (points m ⁻²)	489	-
2023- ramp-shaped SMP	Flight altitude (m)	100	100
	Total flight distance (m)	17434	8938
	Mapping area (m ²)	361963	361963
	Lateral overlap (%)	80	80
	Frontal overlap (%)	-	70
	Number of optical images	-	472
	GSD* (cm pixel ⁻¹)	-	2.73
	Point cloud density (points m ⁻²)	487	-

3.3.3 Internal and snow-surface temperature monitoring

The temperature at the SMP-tailings interface was measured during the 2022 monitoring period for all SMPs. To do so, three custom made buried thermal monitoring setups were constructed. Such setup involved housing a ZL6 data logger (METER Group) within a waterproof protective case. Four RT-1 (METER Group) soil temperature sensors were then connected to the data logger and ran through the protective case via waterproof wire connectors. All connections were also sealed with silicon-based adhesive. The three thermal monitoring setups were started and buried at the SMP-tailings interface during construction. Data was recorded every 6 hours throughout snowmelt. In addition, the temperature of the snow-surface was also measured on the top as well as north-, south-, east- and west-facing slopes of the ridge-shaped pile using RT-1 sensors connected to ZL6 data loggers. For each station, four temperature sensors were connected to a data logger recording hourly. The temperature of the snow-surface was monitored by installing each RT-1 sensor just beneath the surface of the snow (<5-7 cm) at each site visit. Because of snowmelt, sensors were rapidly exposed to the sun, yielding in abnormally warm temperatures. Thus, a clean up of the obtained data was done to record only actual snow-surface temperature measurements. Such snow-surface temperature measurements were only performed in 2022 because the accessibility of the SMPs was very limited in 2023. However, in 2023 the internal temperatures of the ramp-shaped SMP were monitored at selected heights. Accordingly, the three buried thermal monitoring setups used in 2023 were installed within the ridge-shaped SMP during construction. Sensors were positioned at depths of 1.0, 2.5 and 3.5 m from the surface.

3.3.4 Monitoring snow density

To obtain the volume-mass relationship of the snow contained in the natural ground and within SMPs, several snow density measurements were performed throughout the two field trials (March 11 to May 12 in 2022 and March 22 to May 22 in 2023). All density measurements were taken using a large (100 × 15 cm), custom-made Adirondack-type snow sampler, was used. Made from reinforced PVC pipe with a toothed cutter at the base, the sampler could obtain samples between 15 and 55 cm in length. The mass of each snow sample was then measured using a portable electronic scale. During construction, 38

natural snow density measurements were also performed on undisturbed snow around the SMPs. During snowmelt, 105 snow density measurements (40 in 2022 and 65 in 2023) were taken at various depths, ranging from the surface to the interface between the SMP and the tailings with the SMPs.

3.4 Numerical modeling

The complexity of modeling snowmelt arises from the need to accurately simulate various interacting factors such as temperature fluctuations, solar radiation, and ground conditions, etc. Snowmelt is also a highly coupled phenomena involving several heat transfer mechanisms. In this study, a numerical code was selected to develop a simplified thermal model capable of representing the snowmelt of the tested SMPs. This section aims to present the methodological developments that were made to model the snowmelt of SMPs as well as presenting the calibration results.

3.4.1 Model selection

COMSOL Multiphysics is a comprehensive software suite designed for conducting finite element analysis, solving complex simulations, and facilitating a wide range of physics and engineering applications. Its primary focus is on addressing coupled phenomena and Multiphysics challenges. The software is used to solve conventional physics and enables the handling of interconnected systems involving partial differential equations (PDEs). COMSOL is a versatile simulation software that models various physics and engineering phenomena, including heat transfer, fluid flow, and phase change. Appendix C present General description of equations governing heat transfer in porous media in COMSOL Multiphysics.

3.4.2 Modeling approach

Snow transitions to water when it reaches a temperature close to 0°C . Due to gravity, this water flows through the spaces between snow particles and either exits the pile or refreezes if the air temperature drops during this process. Modeling this phase change and subsequent water movement within the SMP is highly complex. It requires defining the velocity of water particles, modeling the cooling process, and accounting for the refreezing of water within the pile. Additionally, as snow melts and water exit the model, the geometry of the

pile changes due to the reduction in volume. This necessitates updating the model with new geometry and boundary conditions at each step, further complicating the simulation. In this study, the aim was first to model the snowmelt process by integrating various heat transfer mechanisms. The complexity of this task stems from the need to simulate the interactions between temperature fluctuations, solar radiation, ground conditions, and phase changes. Given these challenges, a simplified modeling approach was selected. Thus, the modeling of the melting process of SMPs was simplified to a phase change and conduction problem. In order to avoid the complexity of moving boundary conditions and mass balance issues, the melting problem was simplified to a phase change from snow to a thermal diffusivity material. This approach eliminates the need to solve complex equations related to the movement and exit of water from the model. This material also simplifies the model by avoiding the complications associated with the phase change from snow to water and a downward moving boundary condition. There is no need to model the movement or exit of water, nor to update the geometry and boundary conditions of the pile continuously. By using this high thermal diffusivity material, the model remained manageable while still capturing the essential heat transfer dynamics. Figure 3.3 illustrates the process modeling involved in this project. Although highly simplified, the obtained results are expected to represent well enough the snowmelt of SMPs. Results will be used to further interpret field results and discuss future applications, keeping in mind the main limitations brought by the simplifications that were made.

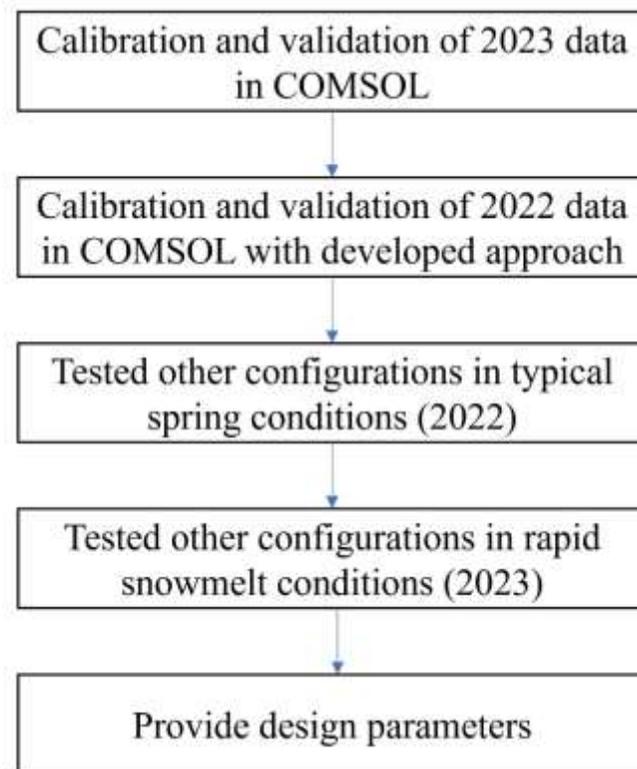


Figure 3.3 The process modeling of the project.

3.4.3 Modeling approach

In the following section, the model parameters will be presented.

3.4.3.1 Geometry

The shapes modeled in the software have approximately the same volume as those created in the field. However, the modeled piles have smooth surfaces without irregularities, whereas the field piles have surfaces with holes. Each SMP is developed and examined from multiple perspectives, with comprehensive details available in Table 3.4. Furthermore, Figure 3.4 depicts the geometry of SMPs within the COMOL software. Figures 3.4.a, 3.4.b, and 3.4.c illustrate cone, cubic, and ridge-shaped SMPs in 2022. Similarly, Figures 3.4.d, 3.4.e, and 3.4.f display the big cone, small cone, and ramp-shaped SMPs in 2023.

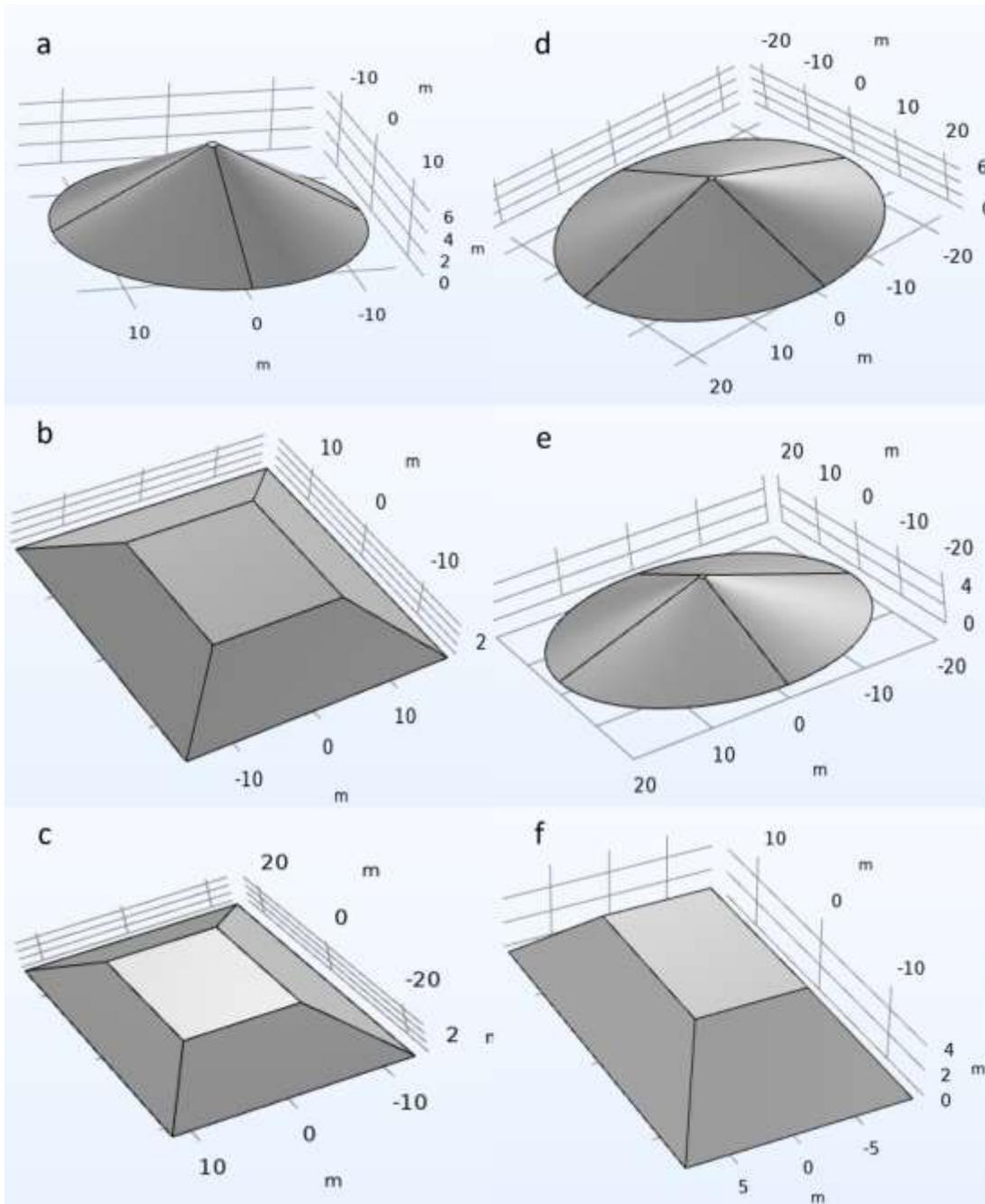


Figure 3.4 Shapes of the SMPs as defined in COMSOL (a) cone SMP, (b) cubic SMP, (c) ridge-shaped SMP in 2022, (d) big cone SMP, (e) small cone SMP, and (f) ramp-shaped SMP in 2023.

Table 3.3. Metrics of the SMPs specified in COMSOL Multiphysics.

Parametre	Cone (2022)	Cubic (2022)	Ridge-shaped (2022)	Big cone (2023)	Small cone (2023)	Ramp-shaped (2023)
Initial length (m)	-	33	50	-	-	30
Initial width (m)	-	33	25	-	-	18
Initial radius (m)	14	-	-	23	20	-
Initial height (m)	7.3	3.5	3.5	7.3	5.6	5.8
Initial footprint (m ²)	615	1089	750	1661	1256	480

3.4.3.2 Mesh

Meshing is a critical component in SMP simulation, influencing both the precision of the results and the efficiency of the computational process. Mesh size is pivotal in determining the stability and accuracy of the simulation. As the mesh becomes finer, the solution converges towards a more accurate representation of the physical phenomena, resulting in more stable numerical results.

While finer meshes enhance accuracy and stability, they also demand more computational resources, resulting in longer simulation times. For several modeling purposes, medium dimension meshes are often used to ensure that the simulations remain both accurate enough and computationally feasible, avoiding excessively long run times (Hyun et al., 2024). Overall, an optimization of the mesh size is favourable to ensure numerical stability and minimize computation time. In this study, the mesh size was optimized to balance numerical.

Figure 3.5.a illustrates the average error of numerical modeling results for SMPs in 2022 and 2023 using COMSOL, along with the total solution time depending on mesh size. According to this figure, a medium-mesh size (0.2-2m) results in an average error of 5% and a total solution time of 10 minute. Although finer mesh sizes yield slightly lower error rates, the significantly higher total solution times make the medium mesh size a more practical choice.

Figure 3.5.b shows the average error of numerical modeling results for SMPs in 2022 and 2023 using COMSOL, along with the total solution time depending on time step. According to this figure, time step of 1 hour results in an average error of 5% and a total solution time of 10 minute. Although finer time steps (30 minutes or 1 minute) yield lower error rates, the significantly higher total computation times make the time step of 1 hour a more practical choice.

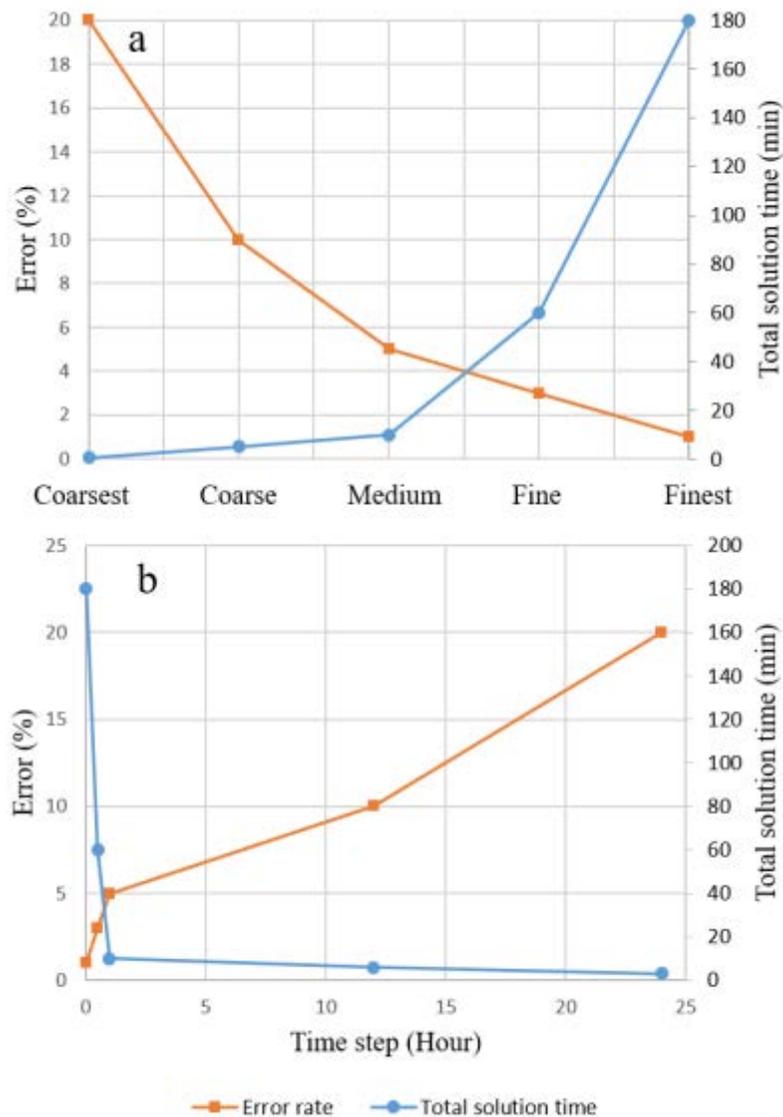


Figure 3.5 (a) Average error of numerical modeling of SMPs in 2022 and 2023 in COMSOL and total solution time depending on the mesh density, and (b) on the time step.

Given the substantial size of the snow piles, a medium-dimension mesh is employed to balance accuracy in the modeling process with manageable run times. This approach ensures that the simulations are both precise enough and efficient. The mesh sizes were set with a maximum dimension of 2 m and a minimum of 0.2 m for all the piles (Figure 3.6). In this project, time step considered in this numerical modeling is 1 hour to balance enough accuracy in the modeling process with manageable run times.

COMSOL also has features that increase numerical stability and accuracy:

- Fine Mesh Near the Surface and Coarser Deeper: COMSOL uses boundary layer meshing to create finer meshes near the surface of the snow piles and coarser meshes deeper within. This method captures important gradients more accurately close to the surface and favour convergence.
- Convergence Criteria: Convergence criteria are imposed to ensure the accuracy of the solution. This involves setting tolerances for residuals or errors in the solution, ensuring that the simulation results are reliable and accurate.

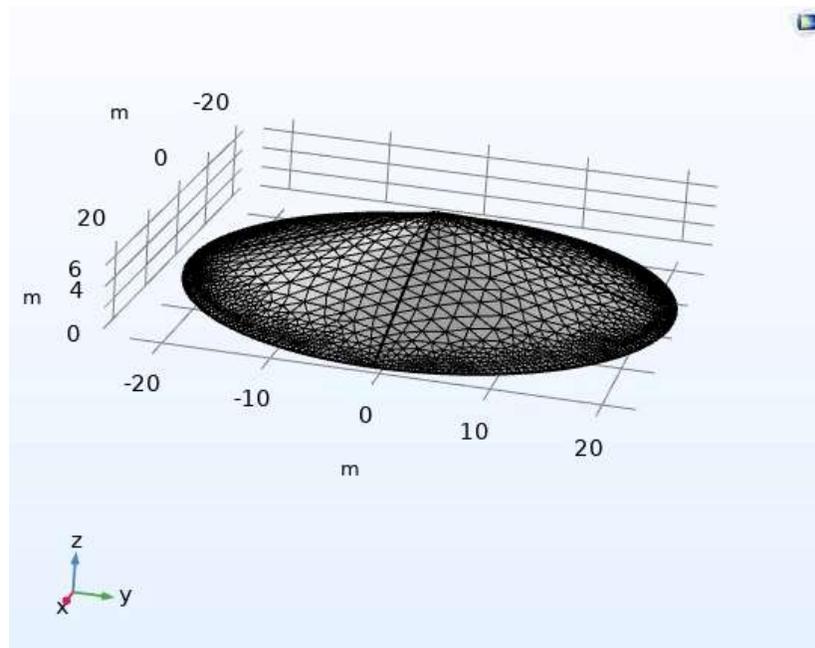


Figure 3.6 Mesh size on a SMP model.

3.4.3.3 Reference temperature, T_{ref}

When materials demonstrate temperature-dependent characteristics, such as thermal conductivity, specific heat, or material density, the reference temperature (T_{ref}) serves as a fundamental point of reference to describe how these properties change with temperature (COMSOL, 2008). As temperature influences material properties, T_{ref} enables the establishment of a standardized temperature value at which the material's properties are well-established and measured (COMSOL, 2008). The thermal strain (ϵ_{th}) due to temperature change is given by:

$$\epsilon_{th} = \alpha(T - T_{ref}) \quad (3.1)$$

Where α is the coefficient of thermal expansion.

In this project, T_{ref} is set to 0°C . By establishing T_{ref} at 0°C , mathematical models and calculations become more straightforward. This simplification allows for easier comparison of temperature-dependent properties without the need to adjust for a non-zero reference point. Setting T_{ref} to zero makes it easier to interpret changes in material properties. For instance, if the temperature is 5°C , it is immediately clear that it is 5 degrees above the reference temperature, simplifying the analysis and interpretation of results. In snow management, 0°C is particularly significant because it is the melting point of ice. Aligning your reference temperature with this critical physical property makes it easier to understand and predict the melting behavior of snow piles.

3.4.3.4 Discretization type of temperature

The PDE and weak form interfaces offer various shape functions with associated element orders, directly impacting the solution's accuracy and the number of degrees of freedom. Increasing the element order corresponds to refining the mesh uniformly. Most physics interfaces employ Lagrange elements, typically of order 1 to 5 (or 1 to 7 for the PDE and weak form interfaces), with 2 being the default order in many cases (COMSOL, 2008). In certain situations, where serendipity elements are available (e.g., in mathematics interfaces and Solid Mechanics interfaces for element orders 2, 3, and sometimes 4), they can be more efficient than Lagrange elements of the same order in terms of the number of elements and solution time, particularly for hexahedral meshes. However, they might also be more

sensitive to distorted mesh elements (COMSOL, 2008). In this case, the software automatically adjusts the numerical integration order based on the element orders specific to the physics involved in the model. Some physics interfaces utilize element types or lower element orders for specific field variables. Users can usually choose Shape function types and Element orders as Linear, Quadratic, Cubic, Quartic, or Quintic (corresponding to orders 1–5, respectively) (COMSOL, 2008).

In this project, a linear function was chosen as the shape function. Linear elements, characterized by linear shape functions, simplify the mathematical formulation and computational process. This leads to faster solution times because the calculations are less complex compared to higher-order elements (Zohdi, 2015). Linear elements require fewer degrees of freedom and less memory, making them more efficient in terms of computational resources. This is particularly beneficial when dealing with large-scale problems or limited computational power (COMSOL, 2008). For problems where the solution does not involve significant curvature or bending, linear elements can provide sufficient accuracy. They are often adequate for problems involving simple geometries and boundary conditions (COMSOL, 2008). Linear elements also simplify the mesh generation process, especially for complex geometries. This can save time and reduce potential errors in the meshing stage (COMSOL, 2008). In this project linear elements are used in this project.

3.4.3.5 Porous medium type

In this project, the local thermal equilibrium (LTE) model has been chosen over other models. (see appendix C for more details) The LTE model assumes that the solid and fluid phases within the porous matrix are at the same temperature (Bansal and Suthar, 2024). This allows for a single unified heat transfer equation, simplifying the mathematical formulation and reducing computational complexity (Bansal and Suthar, 2024). Since the LTE model involves solving only one heat transfer equation, it requires fewer computational resources compared to the local thermal nonequilibrium (LTNE) model, which necessitates solving separate equations for the solid and fluid phases. This can lead to faster simulation times and lower memory usage (Bansal and Suthar, 2024).

3.4.3.6 Materials

In the snow melting process model, the software defines two distinct materials: one representing snow and another with high thermal conductivity to simulate the downward-moving boundary condition. The high thermal conductivity ensures a minimal temperature difference between the boundary condition and the actual value slightly below it. This material represents melting water and is replaced with air in the model. Essentially, the high thermal conductivity material allows the air function to be applied to the snow surface at each step while maintaining the shape and dimensions of the snow pile. This approach helps create a satisfactory simulation of the snow melting process by effectively modeling heat transfer and the interaction with air. Table 3.4 shows the properties of the materials for snow and the high thermal conductivity material as specified in the software. Snow density was determined using the average values from field measurements. The porosity, heat capacity, and thermal conductivity of the snow were estimated using equations 2.6, 2.14, and A.5. For high thermal conductivity materials, natural options were considered. Copper, one of the most thermally conductive natural materials, can transfer heat quickly. Therefore, the high thermal conductivity material in question has properties similar to copper, and these values are predefined in the COMSOL software.

Table 3.4 Material properties used for snow and the high thermal conductivity material as specified in COMSOL Multiphysics.

Parametre	Snow	High thermal conductivity material
Heat Capacity	1714 (J Kg ⁻¹ K ⁻¹)	390 (J Kg ⁻¹ K ⁻¹)
Density	600 (Kg m ⁻³)	8900 (Kg m ⁻³)
Thermal Conductivity	0.867 (W m ⁻¹ K ⁻¹)	390 (W m ⁻¹ K ⁻¹)
Porosity	0.35	0.1

3.4.3.7 Phase change temperature and latent heat

The Phase change temperature between phase 1 and phase 2 $T_{pc, 1 \rightarrow 2}$ should be set to define the center of the first transition interval. In this project, the following function is used to

change the phase of the materials. In this function, the phase change between snow and the high thermal conductivity material begins at -1°C and completes at 0°C (equation 3.2). This transition occurs continuously and smoothly, closely mimicking the natural phenomenon. Figure 3.7 shown the shape of this phase change function that was used to describe the phase change between snow and the high thermal conductivity model. The value of latent heat of phase change from water to ice is 333 kJ kg^{-1} .

$$\alpha_{1 \rightarrow 2} = \exp\left(-\left(\frac{T-0}{0.5}\right)^2\right) * (T < 0) + 1 * (T \geq 0) \quad (3.2)$$

Where $\alpha_{1 \rightarrow 2}$ is the phase transition between phase 1 (snow) and phase 2 (high conductive material), and T is the temperature ($^{\circ}\text{C}$).

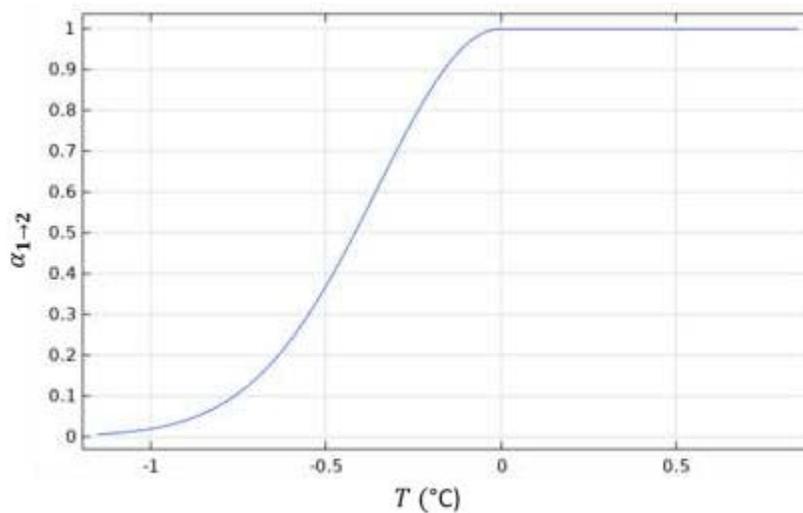


Figure 3.7 Phase change temperature function. The x-axis indicates the temperature inside the pile and the y-axis indicates the phase transition.

3.4.3.8 Ground temperature, initial temperature and bottom boundary condition of SMPs

Figure 3.8 illustrates the typical evolution of temperature at the interface between SMPs and the ground at the beginning of the melting process, which occurs from the end of March to mid-May (further discussed in Chapter 4). According to the figure, the initial temperature of the SMPs was approximately -4.5°C , which rose to -0.1°C after six days.

The blue line in the diagram represents the regression used to define the equation in the software. The defined equation is used as bottom boundary condition:

$$\begin{cases} D \leq 6: T = 0.6357 * D - 4.5 \\ D > 6: T = -0.1 \end{cases} \quad (3.3)$$

According to field data, the initial internal temperature of the SMPs was set to -5°C .

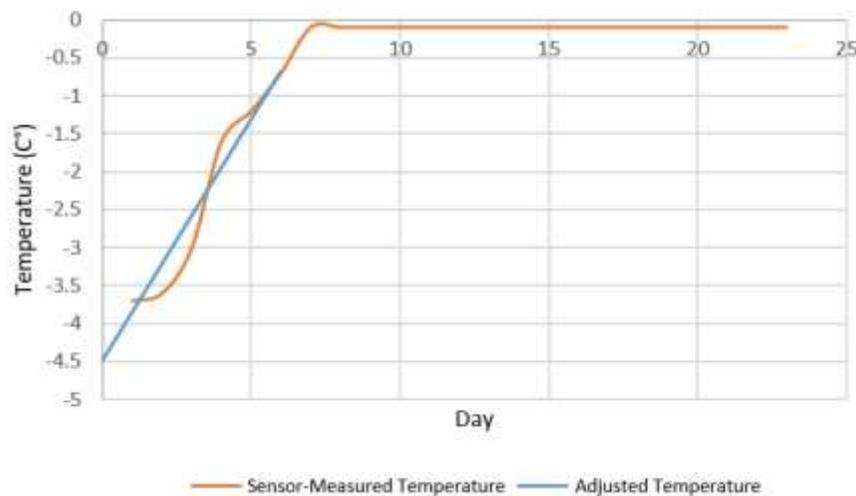


Figure 3.8 Evolution of the temperature at the SMP-ground interface in 2023.

3.4.3.9 Calibration of a snow-surface temperature function based on measured air temperature and establishment of the SMP surface boundary condition

Because air temperature fluctuates significantly from hour-to-hour and day-to-day during snowmelt, a calibrated surface boundary condition had to be developed to ensure numerical stability and convergence. The data from 2023 at Kirkland ECC station were first used to assess the best potential option to establish such boundary conditions. Such an approach came down to fit a polynomial curve representing the 100 days of snowmelt (more details in Chapter 4). Doing so resulted in the development of a site- and time-specific boundary condition that represented well the melting behavior of the tested SMPs and that could also be used to test different SMP sizes and configurations exposed to the 2023 Kirkland Lake climatic conditions. The same approach was then applied to the 2022 tested SMPs, using the Val D'Or station air temperature data (more details in Chapter 4). The 2022 climatic

conditions were used as ‘typical spring conditions’ in the modeling work that was done to extend the understanding of the melting behavior of SMPs in general (other sizes and configurations) whereas the 2023 climatic conditions were deemed representative of a rapid snowmelt.

CHAPTER 4 FIELD RESULTS AND MODEL CALIBRATION

4.1 General approach

This section presents the comprehensive field results gathered from the study, covering various aspects including temperature, precipitation, snow thickness, and their impact on SMPs. The data on temperature, precipitation, and snow thickness is analyzed to understand their effects on the study sites, including seasonal variations and their implications for the SMPs' performance. The observed snowmelt patterns of the SMPs are highlighted, showing differences in melting rates under various conditions. An assessment of snow density and its impact on the melting process is conducted, including measurements during different periods and their correlation with temperature changes. The effect of the slope on the performance of SMPs is examined. A comparison of the size parameters of SMPs is presented, detailing how size variations affect their performance. The efficiency of various sizes and shapes of SMPs is evaluated, providing a clear picture of which configurations yield the best results in terms of melting efficiency and stability. The relationship between temperature variations and the melting behavior of SMPs is explored, analyzing how different temperature profiles impact the rate and extent of snowmelt. The numerical modeling results are presented, showcasing the calibration and validation of the models used in the study. The results from field-tested SMPs are analyzed and compared with the numerical model predictions, helping to validate the accuracy of the models and providing insights into any discrepancies. Finally, a detailed comparison of the numerical modeling results and actual field results is provided, highlighting the strengths and limitations of the models and offering a comprehensive understanding of their reliability and accuracy in predicting the behavior of SMPs under various conditions.

4.2 Field results

The following sections will present the field results data.

4.2.1 Temperature, precipitation, and snow height

The temporal evolution of the average air temperature, precipitation and the thickness of the snow on the ground is provided at Figure 4.1 for 2022 (ECC-MS VAL D'OR station)

and at Figure 4.2 for 2023 (ECCC KIRKLAND LAKE and ECCC-MSV VAL D'OR stations).

In 2022, the average daily temperatures during the monitoring period ranged from -22°C to 23°C . The average air temperature fluctuated above and below 0°C . Notably, on February 26, 2022, the average temperature rose above 0°C for the first time. During this time, the thickness of natural snow on the ground varied slightly until April 23. Initially, the snow depth decreased until March 25, then increased until March 30. After March 30, the snow depth began to decline, and by April 24, all-natural snow had melted. During this melting period, the air temperature rose from -15 to 6°C . This indicates that natural snow was present from the start of the monitoring period until April 24. Ultimately snowmelt occurred for 2 weeks. Figure 4.1 shows that rising air temperatures significantly influenced snow melting. Conversely, when temperatures were below zero, snow melting slowed or halted. Additionally, increased rainfall contributed to snow melting. For instance, snowfall on March 24 increased the snow depth, while up to 15 mm of rain at the end of April accelerated the melting process.

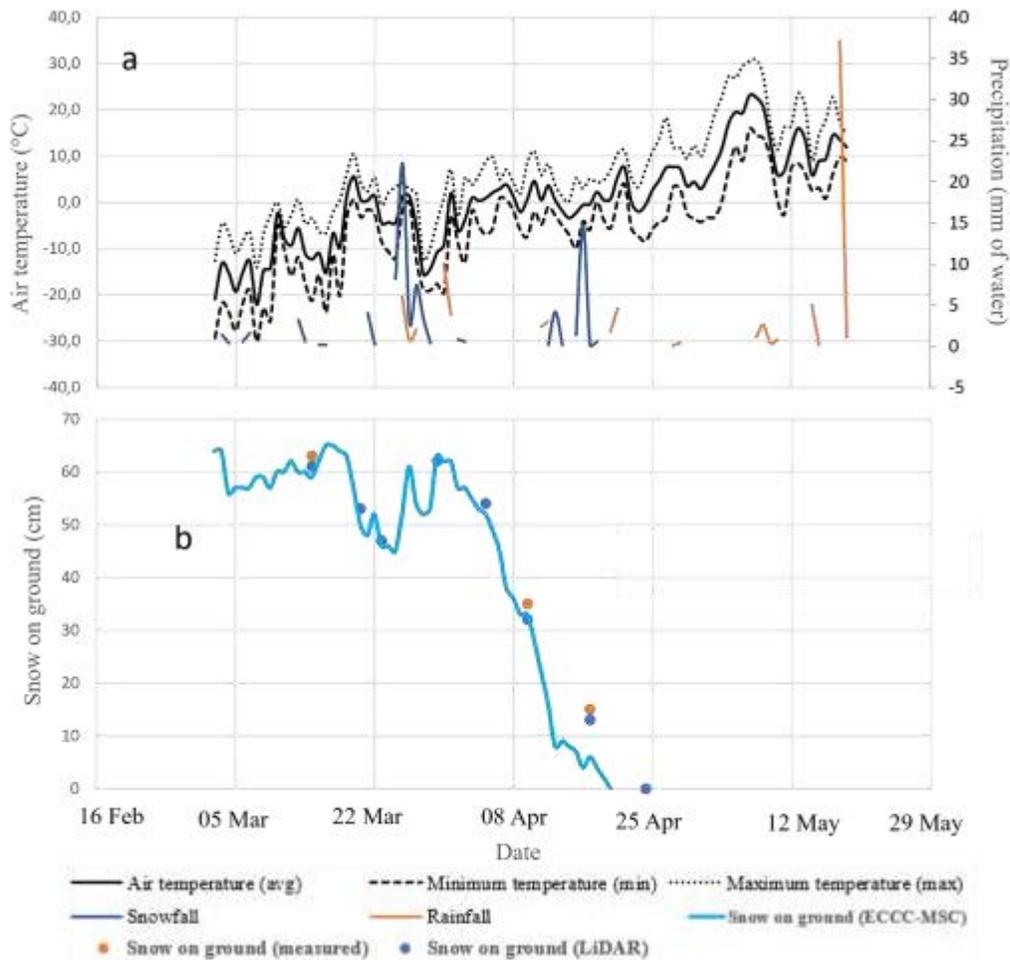


Figure 4.1 (a) Daily climatic parameters recorded at the ECCC Val d'Or weather station, and (b) comparison of the snow on the ground measured at the ECCC-MSC Val d'Or with field measurements and LiDAR surveys.

In 2023, the average temperatures during the monitoring period ranged from a high of 12°C to a low of -12°C. The average air temperature has been above 0°C from 6 April. Unlike 2022, the average air temperature in 2023 did not fluctuate above and below 0°C. Notably, on April 6, 2023, the average temperature rose above 0°C for the first time. During this time, the thickness of natural snow on the ground varied. Initially, the snow depth decreased to 60cm until March 31, then increased to 70cm until April 5. After April 6, the snow depth began to decline, and by April 14, all-natural snow had melted. The duration of snowmelt was 5 days. In 2023, one of the significant observations was the rapid snowmelt. Temperatures soared to over 20°C, causing the snow to melt almost entirely and very quickly. This indicates that natural snow was present from the start of the monitoring

period until April 14. Figure 4.1 and 4.2 show that rising air temperatures significantly influenced snow melting. Conversely, when temperatures were below zero, snow melting slowed or halted. Snowfall at the end of March increased the snow depth. Since mid-April, the snowfall has transitioned to rain due to rising temperatures.

The evolution of snow thickness over time, as monitored by the ECCC weather station, manual measurement techniques, and LiDAR surveys at both 2022 and 2023, is depicted in Figure 4.1b and 4.2b. Notably, all measurement methods yielded comparable results for snow thickness, suggesting their reliability and consistency. Consequently, the ECCC's snow-on-ground curve can serve as an effective representation of site conditions.

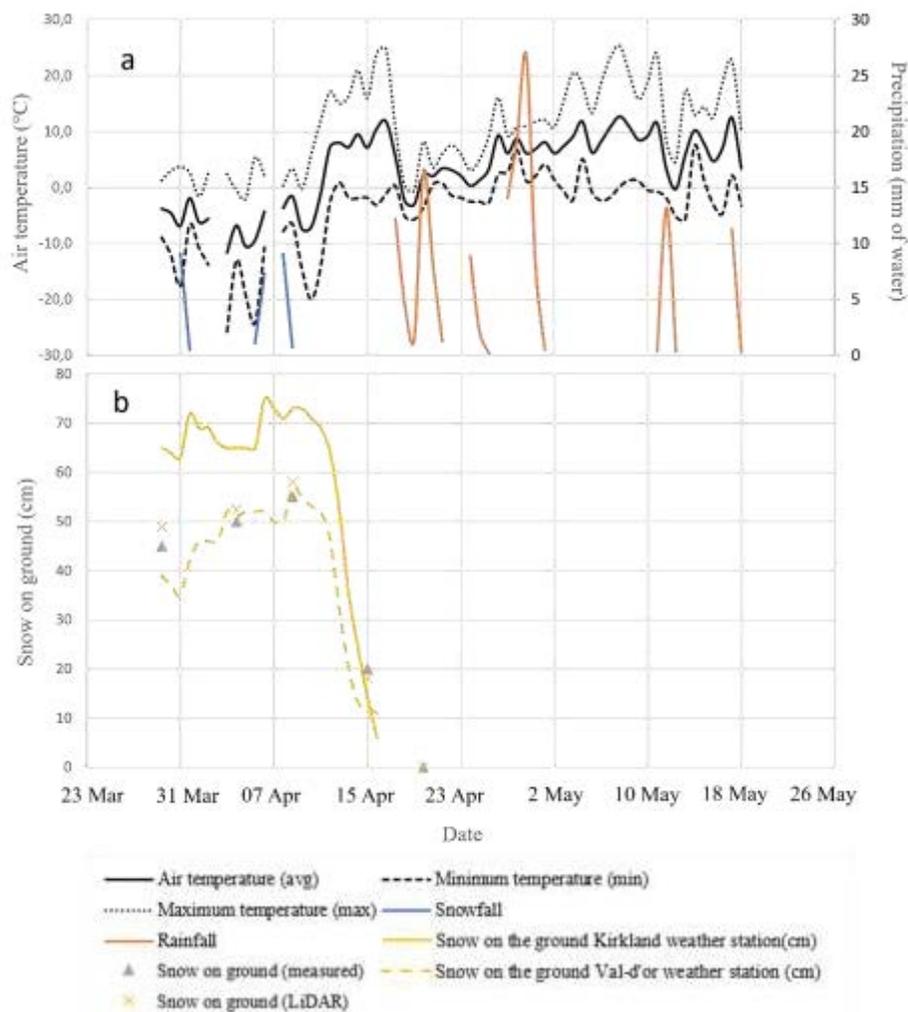


Figure 4.2 (a) Daily climatic parameters recorded at the ECCC Kirkland weather station, and (b) comparison of the snow on the ground measured at the ECCC-MSK Kirkland and Val d'Or weather station with field measurements and LiDAR surveys.

4.2.2 Snowmelt of SMPs

Figure 4.3a depicts the volume changes for each of the SMP constructed in 2022 using both Lidar and SfM photogrammetry. The SMPs were constructed by March 11, 2022. The initial average volumes for the ridge-shaped, cubic, and cone SMPs were 2565 m³, 2275 m³, and 1355 m³, respectively. Despite its smaller volume, the cone SMP took the longest to melt. In general, the reduction of pile volumes follows a same pattern. As mid-May approaches, the reduction rate of ridge-shaped and cubic piles accelerates, diverging from the behavior of the cone pile. On May 15, the cone pile's volume, previously lower than the others, surpasses theirs. The cubic pile volume reaches 0 m³ first on May 15, followed by the ridge-shaped pile, with the cone pile reaching 0 m³ on May 24. The discrepancy between LiDAR and SfM data measurements for the cone pile was smaller compared to the other two piles. The difference ranged from 50 to 100 m³ for the cone pile, whereas for the cubic and Ridge piles, the minimum difference was 350 m³, with the minimum error at the end of the period being 60 m³.

Figure 4.3b illustrates the changes in footprint size for each SMP in 2022. Initially, the footprints for the ridge-shaped SMP, cubic SMP, and cone SMP were 1150 m², 965 m², and 665 m², respectively. Initially, the ridge-shaped pile had a larger footprint compared to the other piles. However, over time, the volume reduction rate of the ridge-shaped pile accelerated. By May 9, the footprint of the two ridge-shaped and cubic piles reached 600m², after which they followed the same decreasing trend. The footprint of these two piles continued to diminish after May 9. Meanwhile, the cone pile experienced a consistent reduction in footprint without fluctuations. Although it started with a smaller footprint, by May 15, the footprint of the cone pile exceeded that of the other piles.

Figure 4.3c shows the heights of each SMP. The initial heights for the cone SMP, ridge-shaped SMP, and cubic SMP were 7.32 m, 3.52 m, and 3.49 m, respectively. Initially, the cone pile was taller than the other piles. The height reduction process follows a consistent pattern. The height changes of the cubic and ridge-shaped piles were almost identical. On May 15, the heights of both the ridge-shaped and cubic piles reached 0m, while this occurred for the cone pile on May 24. The height reduction of the cone pile showed an increase on May 9.

The green line in Figure 4.3 illustrates that all-natural snow on the ground had melted by April 25th. This suggests that the creation of SMPs postponed the snowmelt by 2 to 5 weeks.

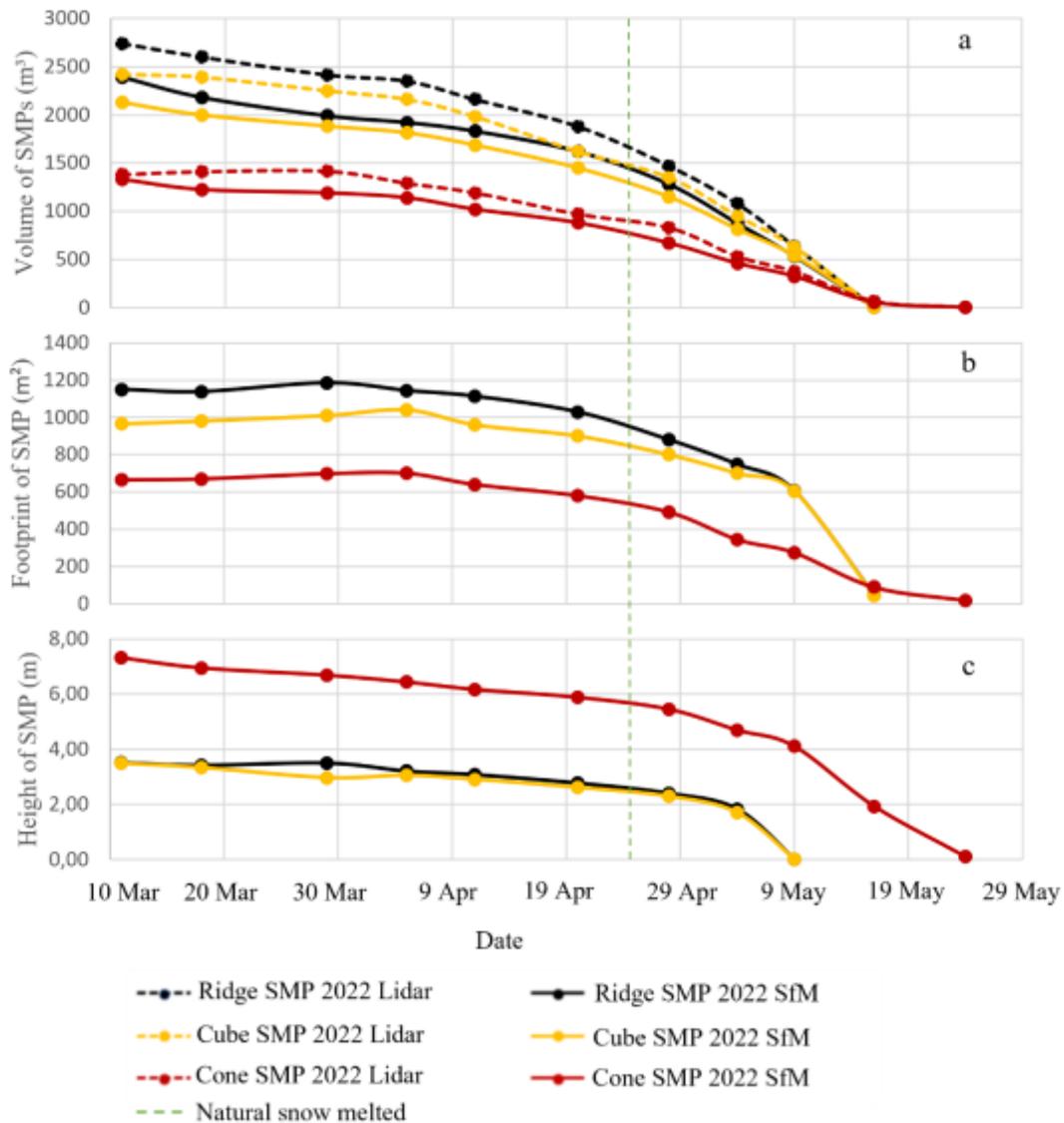


Figure 4.3 (a) Volume, (b) footprint, and (c) height measured for the SMPs throughout the monitoring period as determined by LiDAR and SfM photogrammetry in 2022.

Boulanger-Martel et al. (2022) noted that the absolute volume obtained for each SMP at any given time varied slightly depending on the measurement method. While the measured heights and footprints of SMPs were similar, the overall volumes measured by LiDAR

were generally greater than those computed using SfM photogrammetry. These discrepancies are likely due to the limitations of LiDAR and SfM photogrammetry in capturing and representing all features and snow conditions associated with snowmelt. For instance, LiDAR may have poor signal returns when water is present, and SfM photogrammetry may struggle with over-saturated snow-covered zones (Boulanger-Martel et al., 2022). Despite these differences, the trends in the volumetric decreases of SMPs were consistent.

In 2023, the construction of the SMPs was completed on March 23. The average initial volumes for the big cone, small cone, and ramped-shaped SMPs were 3628 m³, 2213 m³, and 1608 m³, respectively. Notably, the big cone SMP melted later than the other SMPs (Figure 4.4a). The volume discrepancy measured by LiDAR and SfM for the ramp-shaped pile started at 500 m³ and decreased to 50 m³ over time. This trend was similar for both the big cone and small cone piles. For the big cone and small cone piles, the maximum difference was 450 m³, while the minimum difference was 15 m³. The melting process of all three piles follows a consistent pattern, with fluctuations occurring on April 25. The volume of the ramp-shaped pile reached 0 m³ on May 4, followed by the small cone pile on May 11 and the big cone pile on May 19.

Figure 4.4b illustrates the initial footprints for the big cone, small cone, and ramped-shaped SMPs were 1950 m², 1343 m², and 946 m², respectively. Like the volume change, the footprint change for all three piles follows a consistent pattern. The footprint of the ramp-shaped pile reached 0 m² on May 4. The small cone's footprint dropped to 0 m² on May 11, followed by the big cone on May 19.

Figure 4.4c illustrates the height of each SMP, with the initial heights being 7.6 m for the big cone, 5.80 m for the ramped-shaped, and 5.58 m for the small cone. The height reduction process for all three piles follows a similar pattern. Interestingly, the small cone pile initially had a lower height compared to the other piles, but after April 9, its height decreased more slowly than the ramp pile. This indicates that the ramp-shaped pile's height decreased at a faster rate. Ultimately, the height of the ramp-shaped pile reached 0 m on May 4, the small cone on May 11, and the big cone on May 19.

The green line in Figure 4.4 illustrates that all-natural snow on the ground had melted by April 20th. This suggests that the creation of SMPs postponed the snowmelt by 4 to 8 weeks.

Differences in absolute volume measurements between SfM and Lidar similar to that of 2022 were observed in 2023. Because the trends are similar, an average of both measurement methods will be used from now on to push the interpretation further.

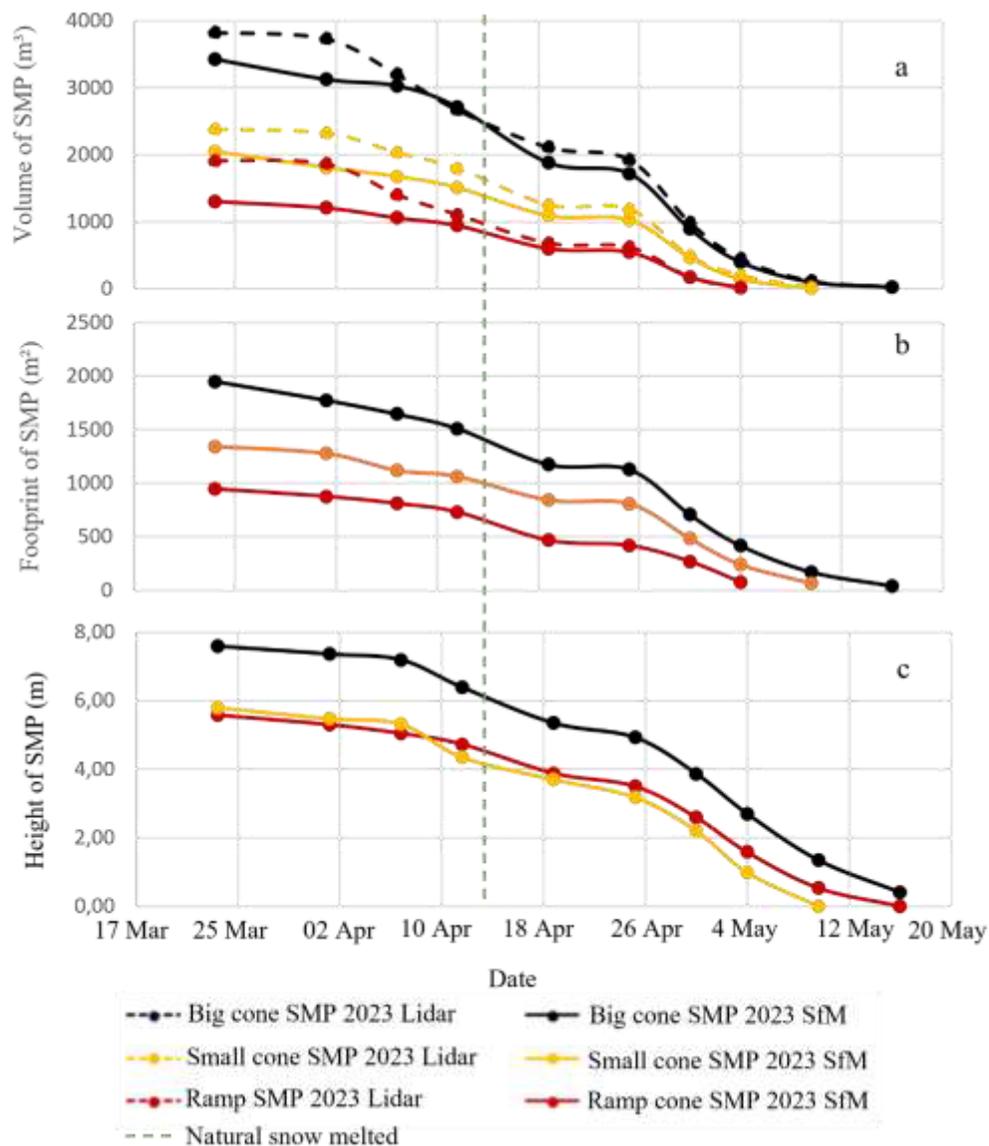


Figure 4.4 (a) Volume, (b) footprint, and (c) height measured for the SMPs throughout the monitoring period as determined by LiDAR and SfM photogrammetry in 2023.

4.2.3 Assessment of snow density

Throughout the entire duration spanning from the initiation of SMP construction until its eventual melting, there are fluctuations in the density of the snow. Figure 8c is segmented into three parts to illustrate distinct phases of snow density changes. In Part A, 23 snow density samples are presented from undisturbed ground conditions. Part B showcases density samples collected during SMP construction, while Part C depicts density measurements post-construction up to the onset of melting. Notably, there's a discernible increase in snow density from 250 kg m^{-3} to 600 kg m^{-3} , indicating that SMP construction led to densification by reducing air voids within the snow structure through compaction.

Further analysis in Part C reveals a subsequent rise in snow density, climbing from 600 kg m^{-3} to approximately 700 kg m^{-3} between late March and May, attributed to rising temperatures, and finally reached to 900 kg m^{-3} at the end of May. This heightened density is attributed to snowmelt and the consequent formation of water within the SMP.

As spring arrived, SMPs contained a mixture of snow, ice, and liquid water (Figure 4.5b). Meltwater and rainwater percolated to the bottom, increasing the snow's density, and creating more distinct layers. At the base, where the SMP met the tailings, there was an ice layer 10 to 20 cm thick with a density of approximately 910 kg m^{-3} . Above this ice layer, a 10 cm thick capillary fringe had an average density of 850 kg m^{-3} . The density decreased with height, averaging 600 kg m^{-3} at heights of 50 cm or more. Figure 4.5a illustrates this depth profile. The black-highlighted area indicates samples taken during the spring, while samples outside this area were collected in winter. These observations also show that a 20 cm thick ice layer forms within the SMP after the melting process.

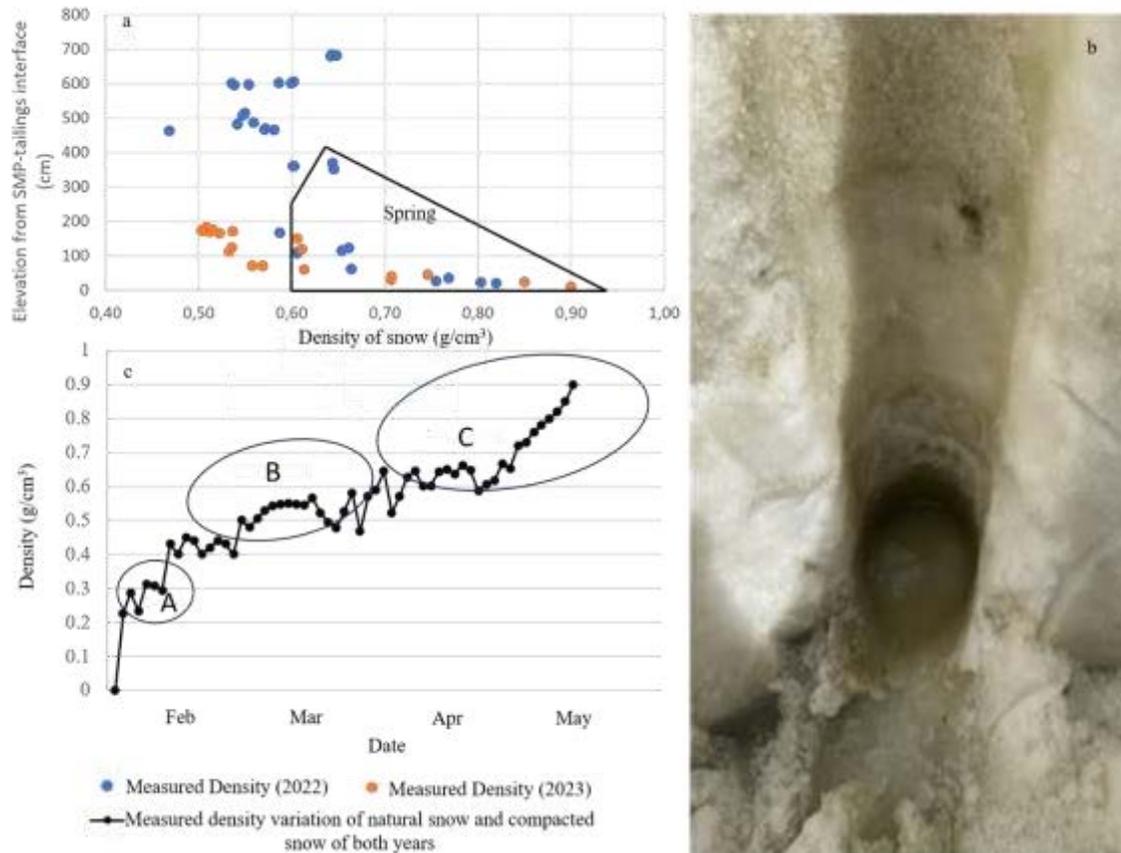


Figure 4.5 (a) The relationship between snow specific gravity at various elevations from the interface of SMP-tailings in 2022 and 2023, (b) The system involving snow, liquid water, and ice that formed within the SMP, and (c) Measured density variation of natural snow and compacted snow of both years

4.2.4 Effect of SMP's slope angle

Utilizing varying equipment during the construction of SMPs results in different side slopes. Illustrated in Figure 4.6 are the slopes of six distinct SMPs erected in 2023 (Figure 4.6b) and 2022 (Figure 4.6a). Notably, the slopes of SMPs in 2023 are softer compared to those built in 2022. This is essentially attributed to the construction methods; Utilizing a groomer yields to slopes much softer sloped than when loaders and bulldozers are used. Additionally, the variations in slope could be influenced by the contrasting sizes of the SMPs between the 2022 and 2023. Enlarging the SMP footprint may contribute to mitigating slope steepness.

Among the six SMPs constructed, the conical SMPs in 2022, exhibited the steepest slope while the most gradual incline was observed in the small cone in 2023.

Furthermore, it is important to note that a minimal slope on the SMPs can facilitate uniform melting of snow across all its sections. For instance, in 2023, SMPs have gradually attained slopes of less than 3 degrees over time, indicating a consistent decrease in SMP height corresponding to the reduction in footprint. This uniform slope contributes to an even melting process, ensuring that all sections of the piles melt at a similar rate.

Conversely, in 2022, the slope of the SMPs remained steep for a longer period, not decreasing to less than ten degrees until the final stages of melting. This suggests that the rate of height reduction was not uniform, with steeper sections of the piles storing more snow per footprint unit, thereby melting at a different rate compared to flatter sections. The gradual decrease in slope angle throughout 2022 led to an uneven melting process, with sections of the piles melting at different rates.

In contrast, the more drastic drop in slope observed in 2023 allowed for a more consistent melting pattern. The SMPs started with a steeper slope but quickly transitioned to a flatter angle, promoting uniformity in the melting process, and reducing the disparity in height reduction rates. This indicates that managing the slope of SMPs can significantly influence the melting behavior, with steeper slopes initially storing more snow per footprint unit but requiring more time to reach a uniform melting state.

Thus, the management of slope angles in snow piles is crucial for ensuring an efficient and uniform melting process. The observed patterns in 2022 and 2023 illustrate how changes in slope can impact the melting dynamics and the overall reduction in snow pile volume and height.

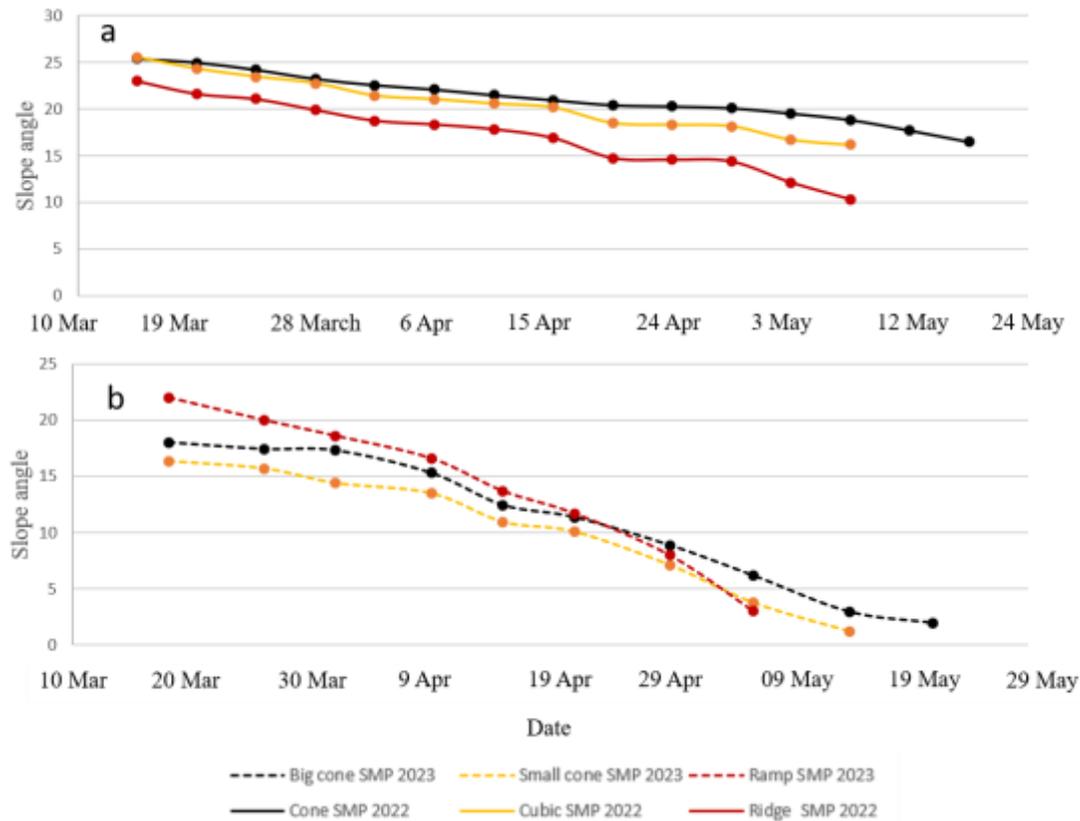


Figure 4.6 Slope of SMPs built in (a) 2022 and (b) 2023.

4.2.5 Effect of configuration and climate on melting behaviour

To enable comparison of SMP effectiveness in managing snowmelt in the two different climatic contexts (of 2022 and 2023), the evolution of the fraction of key SMP metrics is represented for the time from the beginning of the snowmelt (Figure 4.7). In Figure 4.7a, it is evident that volume reduction in SMPs in 2022 exhibits a consistent pattern, whereas, in 2023, this trend occurs in a staircase process. Notably, in early April, there is a notable observation that initially, the small cone SMP experiences a greater volume loss compared to the ramped-shaped SMP, but by the third week of April, this pattern reverses, with the ramped-shaped SMP melting earlier than the cone SMP.

Figure 4.7b illustrates that the reduction in footprint in both years. In 2023, SMPs follows a similar trend until mid-April, after which the rate of reduction accelerates notably for the ramped-shape SMP. Conversely, in 2022, the cone SMP exhibits a faster decrease in

footprint area compared to the ridge shaped and cubic SMPs. Notably, the ratio of SMP footprint changes in 2023 consistently surpasses that in 2022.

Examining Figure 4.7c reveals that the rate of height change in all SMPs follows a similar trajectory. Ramped-shaped SMP in 2023 and cubic SMP in 2022 reach zero height earlier than other SMPs. Despite the ramped-shape of the SMP in 2023 having greater height compared to the small cone SMP in 2023, the ridge shape SMP and cubic SMP in 2022, its dimensional changes diminish more rapidly, leading to an earlier melting. This underscores that height isn't the sole determinant influencing SMP melting; other factors such as volume play crucial roles as well.

To explore how air temperature influences SMP temperature, thermal sensors were positioned within the ridge SMP at a 4.3 m height. Figure 4.7 illustrates the month-long fluctuations in both air temperature and SMP temperature in 2023. Throughout the month, air temperature displayed significant variation, predominantly below freezing, with sporadic periods above zero. The lowest recorded air temperature was approximately -12°C , while the highest reached around 11°C . In contrast, SMP temperature remained relatively stable, consistently above freezing. However, it exhibited slight fluctuations correlating with changes in air temperature. The snow cover provided an insulating layer, which helped to buffer the SMP temperature against the more extreme fluctuations in air temperature. This insulation effect means that the SMP temperature did not drop as low as the air temperature during cold periods. The SMP exhibited a degree of thermal inertia, meaning it responded more slowly to changes in air temperature. This delayed response helped maintain a more stable temperature within the SMP. When the air temperature decreased, the SMP temperature also decreased but to a lesser extent. Similarly, when the air temperature increased, the SMP temperature rose, but not as dramatically.

The lowest SMP temperature recorded was around -1°C and the highest was approximately 1°C . The data suggests a relationship between air temperature and SMP temperature, although not identical. When air temperature decreased, SMP temperature followed suit but to a lesser extent. Conversely, when air temperature increased, so did SMP temperature, albeit less dramatically. This indicates some insulation effect, likely due to snow cover or water depth, and a degree of thermal inertia, resulting in delayed heating or cooling. The

important key is that in 2022, natural snow melted 46 days after the start of the monitoring period, whereas in 2023, it melted much faster, taking only 29 days.

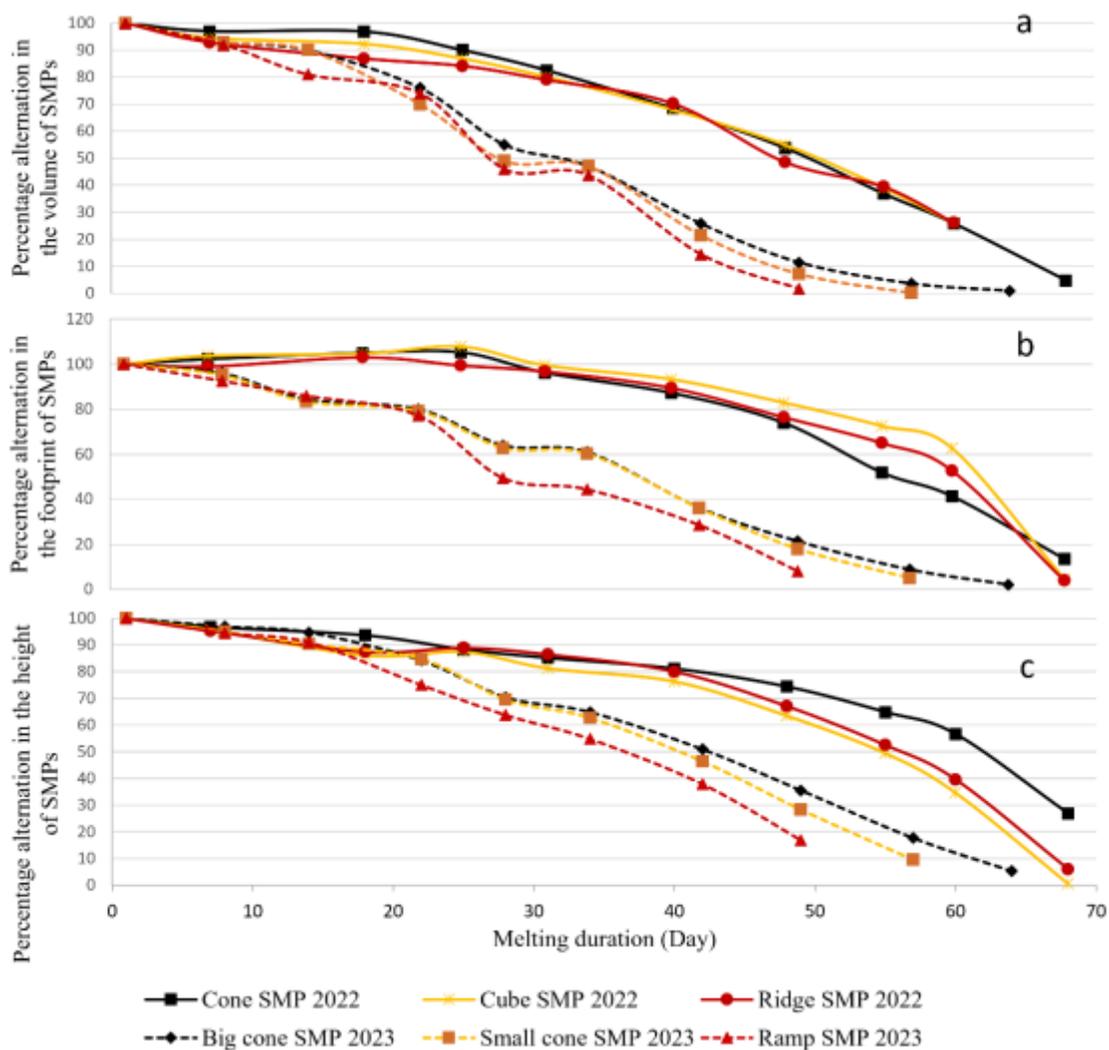


Figure 4.7 Assessment of changes in the percentage of (a) volume, (b) footprint, and (c) height of SMPs.

To further examine the impact of size and shape, we plotted the average volume of melted snow (measured in m^3) per m^2 of SMP footprint per day (Figure 4.8). The data was then converted to density to represent the snowmelt as meltwater. The data reveals a noteworthy disparity in that the amount of melted snow in 2023 SMPs surpasses that in 2022 SMPs. This discrepancy suggests that air temperature variations in 2023 were more pronounced,

exerting a substantial impact on snow melting dynamics. Particularly, the largest volume of melted snow is attributed to the big cone in 2023.

In 2022, the air temperature in the region showed less variation compared to 2023. This conclusion is based on the observation that the volume of melted snow in the fluctuated only twice in 2022, whereas in 2023, the volume of melted snow fluctuated four times. Essentially, the more frequent fluctuations in 2023 indicate greater variability in air temperature, leading to more frequent changes in the amount of snow melting.

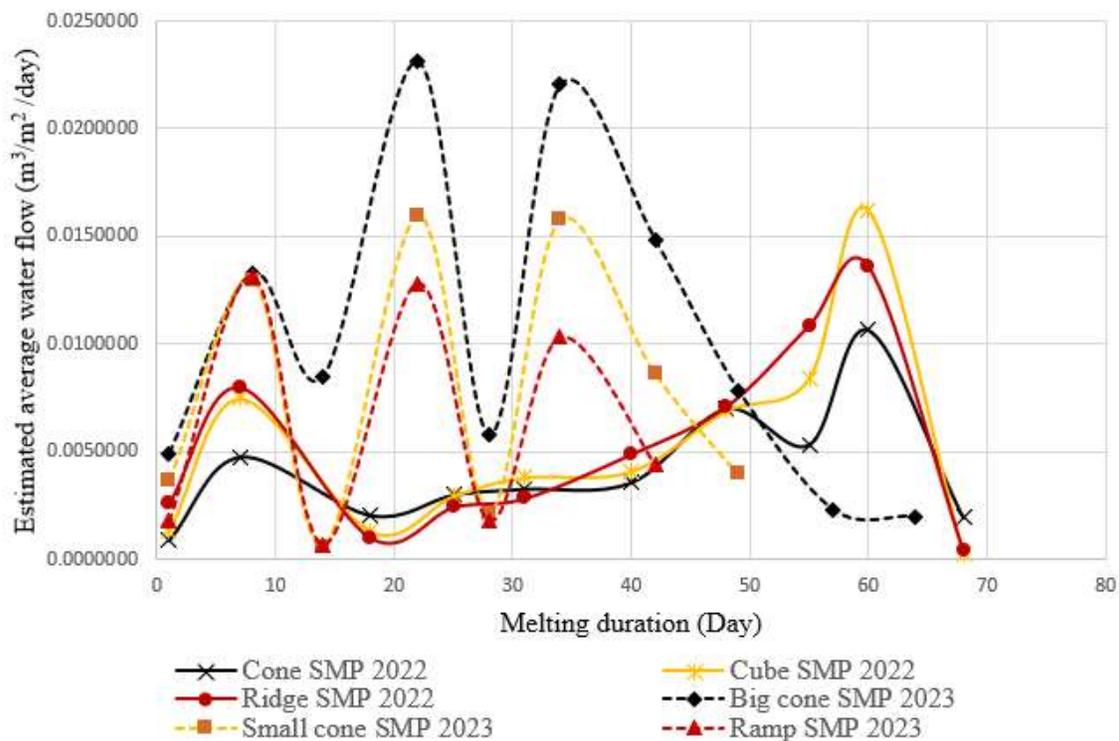


Figure 4.8 Variations of melted volume of snow between two consecutive surveys for the 2022 and 2023 SMPs.

To further explore the influence of air temperature on SMP melting, the degree-days of melting (DD) over the entire melting period (M) for each SMP has been calculated (Figure 4.9a). DD is calculated according to the ICCM and represents the total average daily air temperature above 0°C. During the 64-day melting period, the big cone SMP recorded the highest DD value at 304°C-days, while the ramped-shaped SMP had the lowest DD value at 189.6°C-days. Among the 2022 SMPs, the highest DD value during the 70-day melting

period was observed in the cone SMP at 278.3°C-days, whereas the ridge-shaped SMP had the lowest DD value at 240.3°C-days over a 66-day melting period.

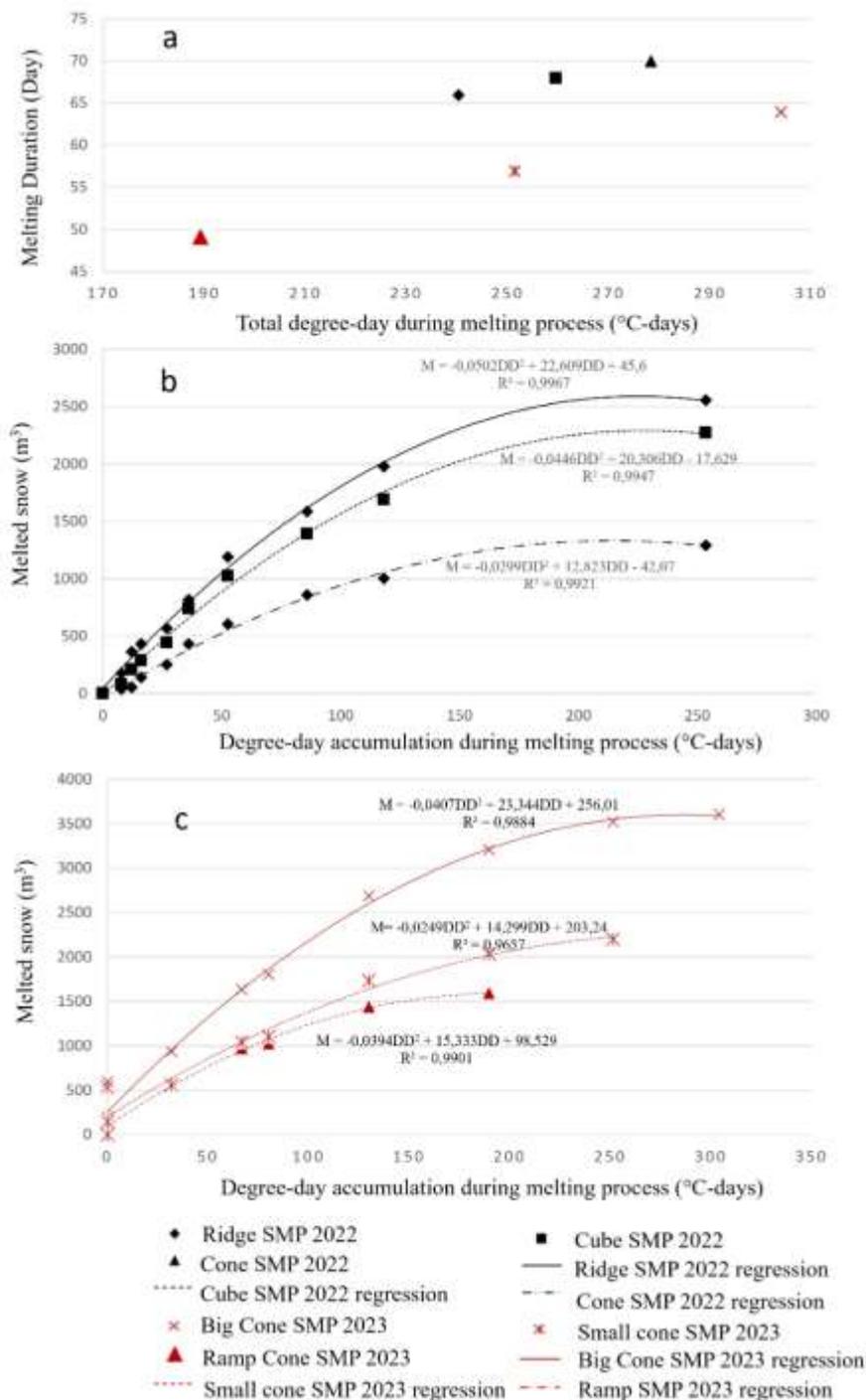


Figure 4.9 (a) Total degree- day during melting process for each SMP, (b) comparison of cumulative degree- day and melting period in 2022, and (c) 2023.

Figure 4.9b illustrates the cumulative DD for the melted snow in 2022. Additionally, this figure presents the behavioral regression equation for each snow SMP, demonstrating the relationship between the amount of melted snow and DD. By rearranging the equation, equations 4.1, 4.2, and 4.3 can be derived for the cone, cubic, and ridge-shaped SMPs in 2022.

$$M = -0,0502DD^2 + 22,609DD + 45,6 \quad (4.1)$$

$$M = -0,0446DD^2 + 20,306DD - 17,629 \quad (4.2)$$

$$M = -0,0299DD^2 + 12,823DD - 42,07 \quad (4.3)$$

Figure 4.9C also illustrates the cumulative DD for the melted snow in 2023. Additionally, this figure presents the behavioral regression equation for each SMP, demonstrating the relationship between the amount of melted snow and DD. By rearranging the equation, equations 4.4, 4.5, and 4.6 can be derived for the ramped-shaped, small cone, and big cone in 2023.

$$M = -0,0407DD^2 + 23,344DD + 256,01 \quad (4.4)$$

$$M = -0,0249DD^2 + 14,299DD + 203,24 \quad (4.5)$$

$$M = -0,0394DD^2 + 15,333DD + 98,529 \quad (4.6)$$

Utilizing the provided equations allows for the prediction of SMP melting based on DD, facilitating effective runoff management planning.

The robustness of these equations in space and time can be assessed based on their ability to predict the melting of snow in different shapes and conditions over multiple years. Here are some key points:

The equations are derived for different shapes of SMPs (cone, cubic, ridge, ramped-shaped, small cone, and big cone) in both 2022 and 2023. This indicates that the equations are adaptable to various geometries, suggesting spatial robustness. The ability to apply these equations to different shapes means they can be used in diverse physical settings.

The equations are based on data from two different years. The consistency in the form of the equations across these years suggests that they can reliably predict snow melting over

time. The equations account for the cumulative degree days, which is a measure of accumulated temperature over time, further supporting their temporal robustness.

The equations demonstrate a clear relationship between the amount of melted snow and the cumulative degree days. This relationship is captured through behavioral regression equations, which have been validated by the data from two consecutive years. The ability to rearrange and derive specific equations for different SMP shapes and years indicates a strong predictive capability.

These equations' use for predicting SMP melting based on degree days facilitates effective runoff management planning. This practical application underscores their robustness, as they provide actionable insights for managing snowmelt and associated water resources.

Overall, the equations appear to be robust both spatially and temporally, given their adaptability to different shapes and consistent performance over multiple years. They provide a reliable tool for predicting snow melting and effectively managing runoff.

4.3 Numerical modeling results

In the following sections, the numerical modeling results and their validation will be discussed.

4.3.1 Calibration of air temperature function

Figure 4.10 displays the adapted air temperature functions derived from Val d'Or and Kirkland station weather data. Both graphs illustrate the construction of two different functions from meteorological data. In 2022, equation 4-7 covers the melting period;

$$(T = -5E - 05 * D^3 + 0.0091 * D^2 - 0.1673 * D - 7) \quad (4.7)$$

The purpose of having a temperature function is first to analyze the melting behavior of the pile and compare it with actual samples, and then to predict the melting of piles with different dimensions throughout 70 to 100 days. This last aspect will be discussed in Chapter 5. Similarly, for the 2023, equation 4-8 covers the melting period;

$$(T = 6E - 07 * D^4 - 0.0001 * D^3 + 0.0059 * D^2 + 0.1956 * D - 5) \quad (4.8)$$

This approach aims to reduce errors in predicting the long-term melting of snow piles.

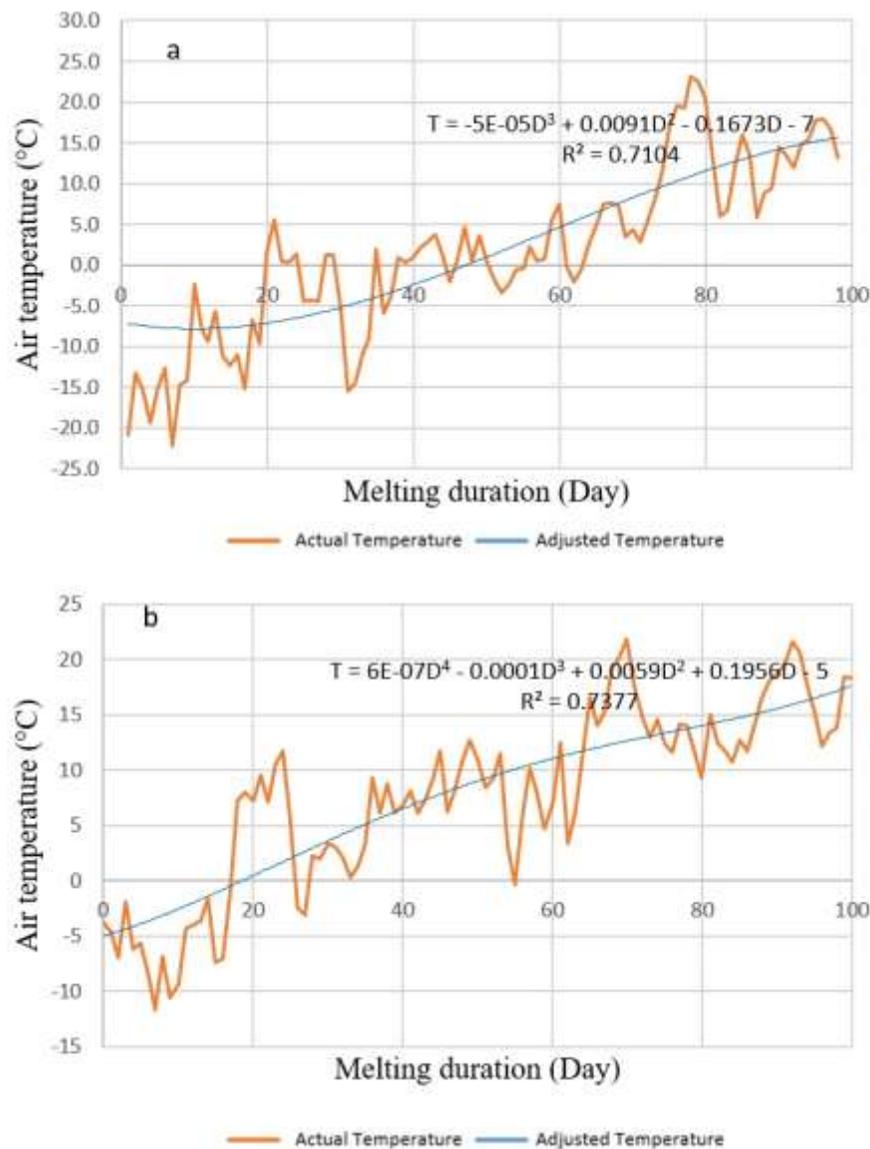


Figure 4.10 (a) The adapted air temperature functions derived from Val d'Or, and (b) Kirkland station weather data.

4.3.2 Numerical modelling of field-tested SMPs

Figure 4.10 illustrates that the Ridge-shaped SMP in 2022 and Big cone SMP in 2023 have significantly more snow than other SMPs. Initially, the snow volumes in 2022 were 1547.4 m³ for the cone SMP, 2223.4 m³ for the cubic SMP, and 2552.1 m³ for the ridge-shaped SMP (Figure 4.11a). In 2023, the initial volumes were 1827 m³ for the ramp-shaped SMP, 2400.3 m³ for the small cone SMP, and 4142.7 m³ for the big cone SMP (Figure 4.11b).

During the snowmelt period in 2022, the ridge-shaped and cubic SMP volumes decreased more rapidly than the cone SMP. The melting durations were 76 days for the cone SMP, 65 days for the cubic SMP, and 70 days for the ridge-shaped SMP. Notably, the initial volume of the ridge-shaped SMP was about 1.7 times that of the cone SMP.

In 2023, the small cone SMP melted faster than the ramp-shaped SMP after 30 days. The melting periods were 58 days for the ramp-shaped SMP, 53 days for the small cone SMP, and 70 days for the big cone SMP. Interestingly, although the small cone SMP had a larger initial volume than the ridge-shaped SMP, its height was lower.

An additional crucial factor to consider is the impact of air temperature on SMP melting. Despite the two cone SMPs in 2022 and 2023 having identical heights, the snow volume in the 2022 cone SMP is roughly one-third of that of the 2023 cone SMP. Interestingly, the melting duration for in the 2022 cone SMP is five days longer than that in 2023. This observation underscores the importance of forecasting the air temperature when designing an optimal snow pile for a mining operation.

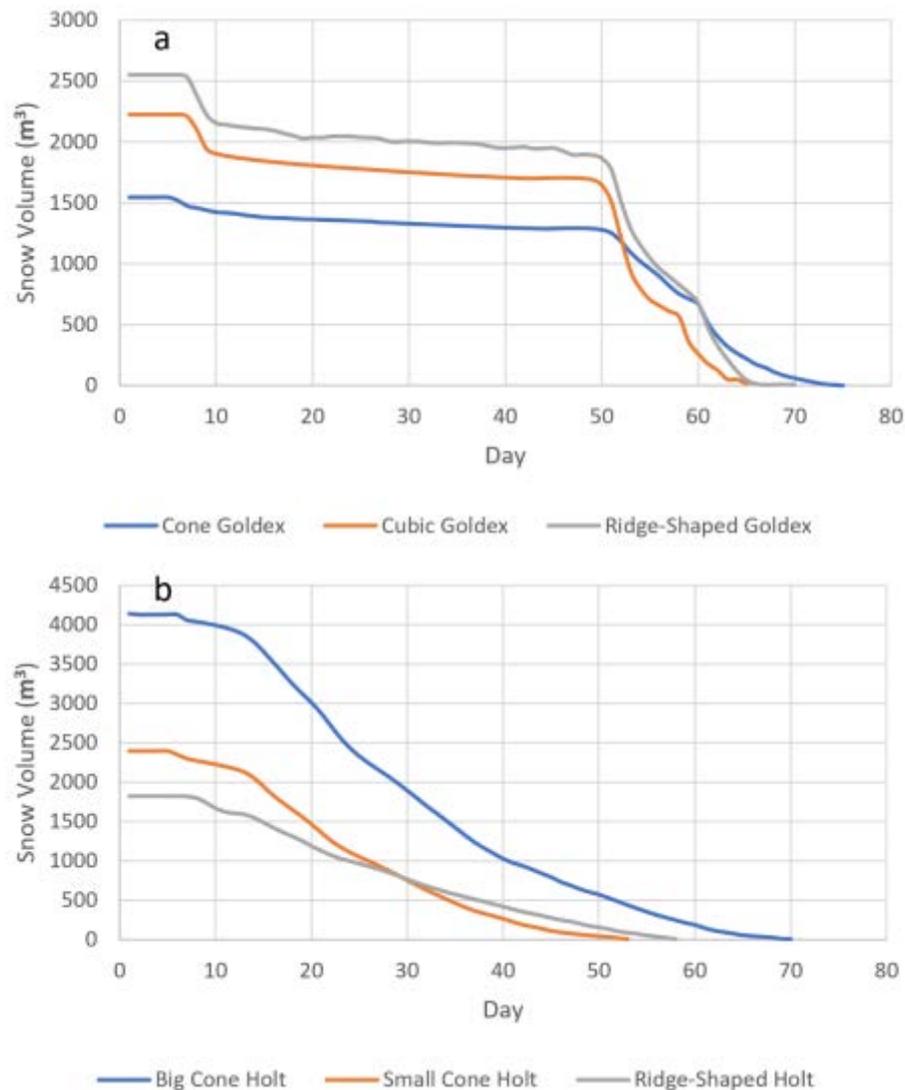


Figure 4.11 (a) Numerical Modeling of SMPs in 2022, and (b) in 2023.

4.3.3 Calibration of numerical modeling results and actual results

Figure 4.12 presents the results of numerical modeling alongside actual data for various SMPs in 2022 and 2023. Figure 4.12a shows the cone SMP in 2022. This will be further investigated by comparing the measured and modeled SMP snowmelt behaviours. The melting duration was 73 days, while the model predicted 76 days, resulting in a 3-day overestimation and a 3.94% error. The average error for predicting the melting process was 7.6%. Also, Figure 4.12b illustrates the cubic SMP in 2022. The actual melting duration

was 66 days, compared to the model's 65 days, leading to a 1-day underestimation and a 1.5% error. The average error for the melting process of that SMP was 7.2%. In Figure 4.12c, the ridge-shaped SMP in 2022 is depicted. The actual melting duration was 70 days, while the model predicted 69 days, resulting in a 1-day underestimation and a 1.42% error. The average error for the melting process was 4.64%. Figure 4.12d shows the big cone SMP in 2023. The actual melting duration was 67 days, compared to the model's 70 days, leading to a 3-day overestimation and a 4.47% error. The average error for the melting process was 4.86%. Figure 4.12e presents the small cone SMP in 2023. The actual melting duration was 59 days, while the model predicted 58 days, resulting in a 1-day underestimation and a 1.69% error. The average error for the melting process was 11.5%. Finally, Figure 4.12f illustrates the ramp-shaped SMP in 2023. The actual melting duration was 53 days, compared to the model's 58 days, leading to a 5-day overestimation and a 9.4% error. The average error for the melting process was 4.73%.

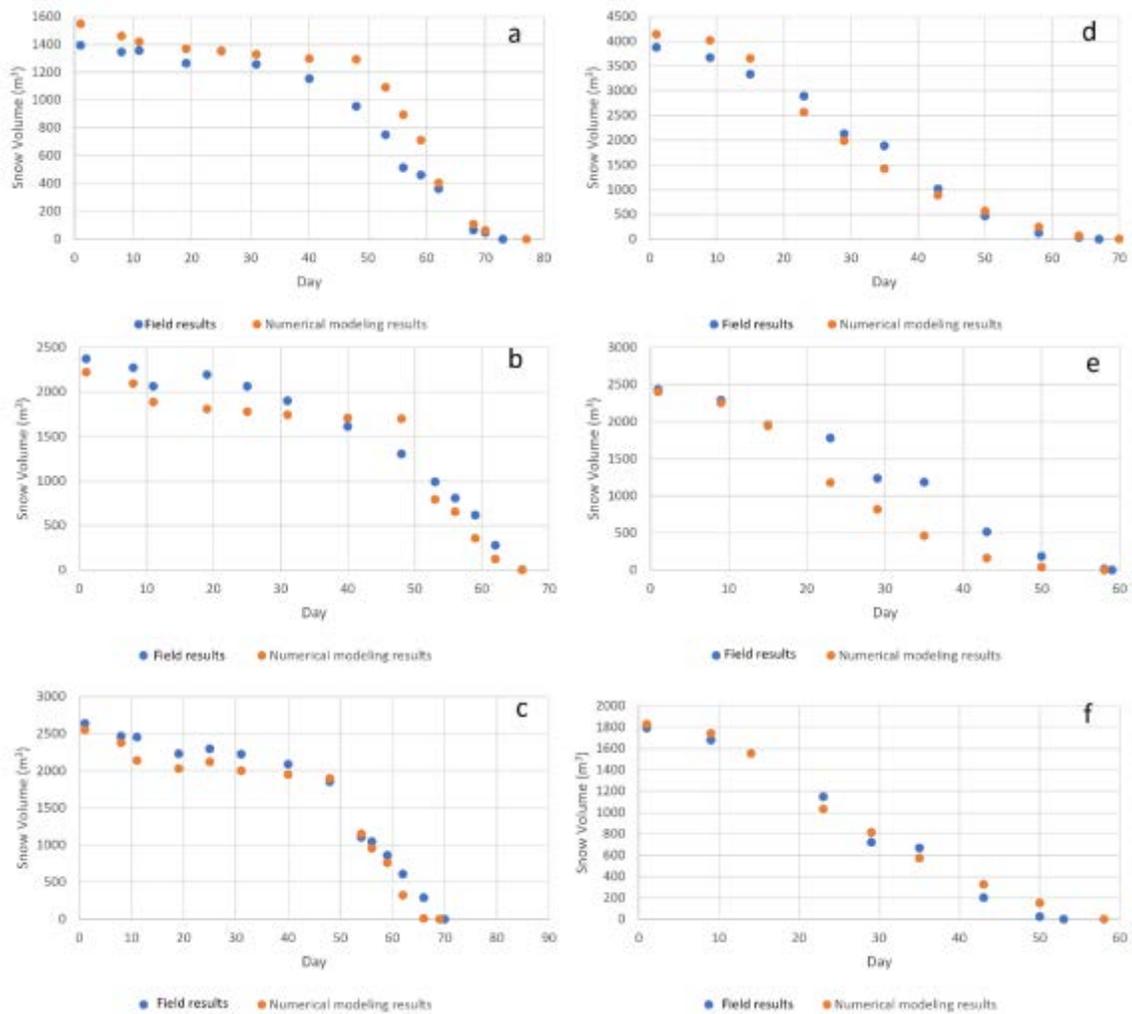


Figure 4.12 (a), (b), and (c) numerical modeling VS actual results of cone, cubic, and ridge-shaped SMPS in 2022, and (d), (e), and (f) numerical modeling VS actual results of big cone, small cone, and ramp-shaped SMPs in 2023.

Overall, the numerical modeling showed an average error of 3.73% for predicting the melting duration and 6.75% for the melting process. It should be noted that the error range for predicting the melting process of piles varies between 2% and 25%, with the maximum error typically occurring in the middle of the melting process. The reasons for this error in the melting process are discussed below. These results demonstrate accuracy for predicting the SMP melting behaviour. This approach will be used in Chapter 5 to further optimize SMPs at controlling snowmelt in TSFs.

The discrepancies observed between numerical modeling and fieldwork can be attributed to several factors:

- **Temperature Variability:** The numerical model uses average daily temperatures to simulate snow melting. However, air temperatures fluctuate throughout the day, impacting the melting process in ways that the model does not account for.
- **Precipitation Effects:** In the real world, snowfall and rain affect the snow pile's volume and influence its melting rate like the phenomenon in 2023. This phenomenon is often excluded from the numerical model, leading to inaccuracies.
- **Water Movement:** The presence and movement of water within the snow pile significantly affect the melting process. The numerical model ignores these dynamics, resulting in errors.
- **Measurement Techniques:** Errors can also stem from the methods used to measure the snow pile's volume, such as Lidar scanning and photogrammetry. These techniques, while advanced, can introduce inaccuracies that affect the overall modeling results.

Considering these factors helps to better understand the limitations of numerical modeling and work towards improving the accuracy of predictions in future studies.

CHAPTER 5 GENERAL DISCUSSION

In the earlier sections, a comprehensive description of the field data was provided, followed by the presentation of modeling results and their validation. The study modeled snow under three-dimensional conditions of varying dimensions using two distinct temperature functions. This section aims to further assess the impact of climate on the capacity of SMPs to control snowmelt. Thus, the snowmelt behavior of different SMP configurations under the climatic conditions of 2022 and 2023 were analysed by performing additional numerical analyses assessing the impact of height, volume, and air temperature functions on the melting duration. By comparing these factors, a comprehensive understanding of the snowmelt process for different SMP configurations is achieved. The relationship between the height of SMPs and their melting duration is examined further, revealing insights into how height affects snowmelt behavior under different climatic conditions. The impact of SMP volume on melting duration is also explored, highlighting significant correlations between volume, and melting rates. The effects of the two different air temperature functions on the melting duration of SMPs are analyzed, showcasing the sensitivity of SMPs to temperature variations. Additionally, the optimization of construction methods is discussed, providing recommendations for improving efficiency and effectiveness in real-world applications. Finally, the key findings and lessons learned from this study are summarized, offering valuable insights for future research and practical applications.

5.1 Prediction of the snowmelt behavior of SMP configurations under the 2022 and 2023 climatic conditions

This section presents the comprehensive modeling results of 70 distinct combinations of SMPs configurations and climatic conditions. The analysis covers several key aspects:

- **Height and Melting Duration:** The relationship between the height of the SMPs and the duration of their melting periods is explored, providing insights into how these two variables interact. The height of the piles for the cone SMP ranges from 3 to 10 m; for the ramp-shaped SMP, from 3 to 10 m; for the ridge-shaped SMP, from 3.5 to 9.5 m; and for the cube SMP, from 3.5 to 9.5 m.

- Volume and Melting Duration: The correlation between the volume of the SMPs and the time it takes for them to melt completely is examined. The volume of the piles for the cone SMP ranges from 509 to 5618 m³; for the ramp-shaped SMP, from 330 to 7350 m³; for the ridge-shaped SMP, from 2552 to 16204 m³; and for the cube SMP, from 2223 to 14985 m³.
- Temperature function: The impact of varying the temperature function considered as a boundary condition for melting SMPs with identical shapes and dimensions is studied to provide a detailed understanding of how temperature influences the melting process. The 2022 temperature function is considered representative of typical snowmelt, while the 2023 temperature function represents rapid snowmelt.

Empirical equations are presented to calculate both the height and the volume of SMPs based on their melting duration. This information is particularly useful for predicting and managing snow pile behavior in various conditions. Appendix D presents the geometric properties of the 70 modeled SMPs. Additionally, Appendix E provides detailed results for each SMP.

5.1.1 Impact of height and volume on the duration of SMP snowmelt within their respective climatic conditions

Generally, Figure 5.1 illustrates the relationship between the height of SMPs and the duration of their melting periods. The figure includes equations derived from the regression analysis of the modeling results, providing a clear visual representation of this relationship. To better identify the piles built in 2022 and 2023 (field-tested configuration), red circles are drawn around the respective piles in Figure 5.1.

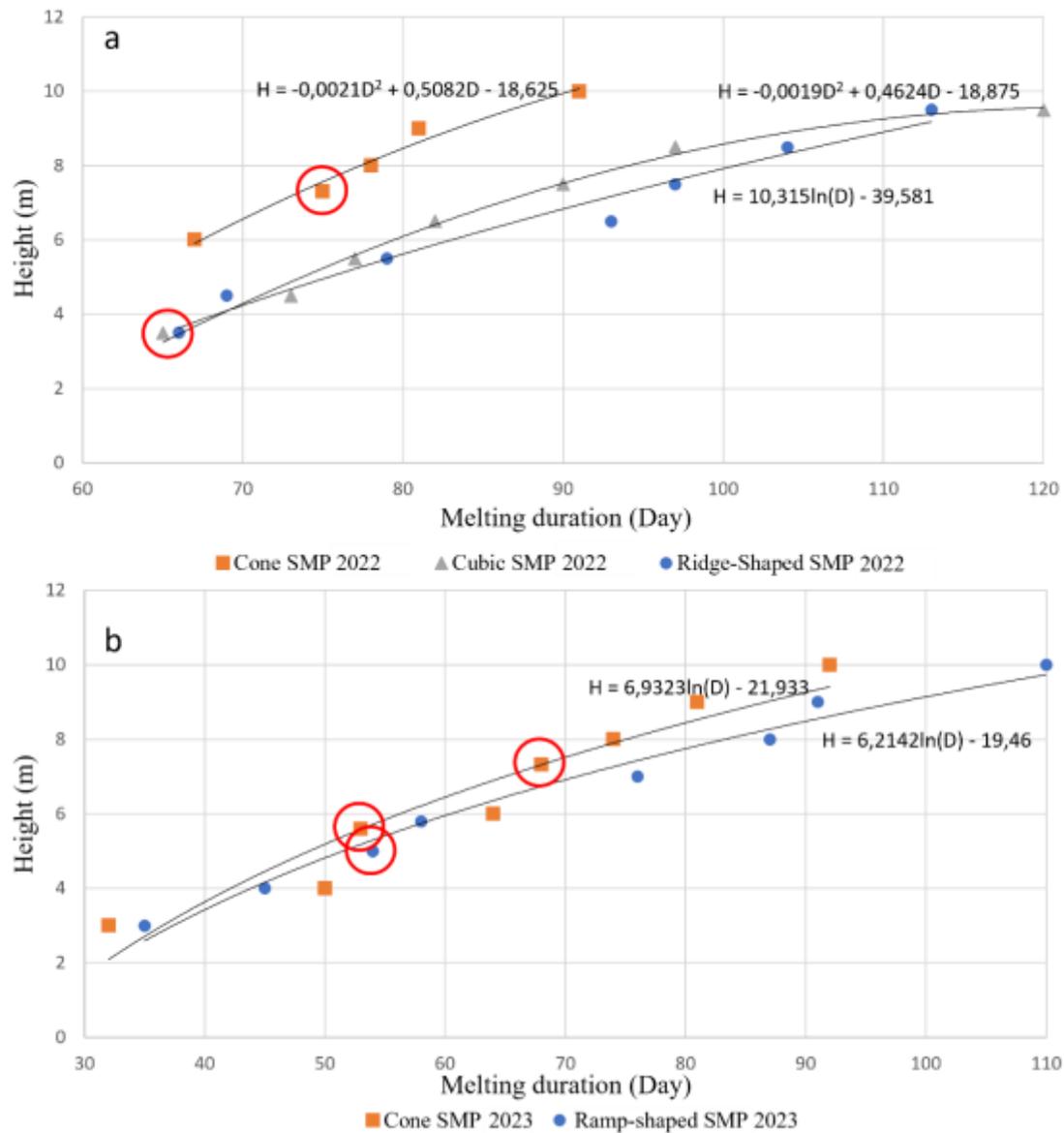


Figure 5.1 (a) Relationship between height and melting duration in 2022, and (b) in 2023.

Figure 5.1 reveals that the cone SMP, despite its greater height than other piles, experienced a shorter melting period. This anomaly can likely be attributed to its smaller volume, a factor that will be examined in more detail in the subsequent section. The cubic and ridge-shaped SMPs demonstrated nearly identical melting behaviors up to a height of 5.5 meters. Beyond this height, up to 9 meters, the ridge-shaped SMP exhibited a longer melting period

than the cubic SMP. Interestingly, this trend reversed beyond the 9-meter mark, with the cubic SMP taking longer to melt than the ridge-shaped SMP.

Equations 5.1, 5.2, and 5.3 illustrate the relationships between the height and melting period for cone, cubic, and ridge-shaped SMPs in 2022. Additionally, equations 5.4 and 5.5 depict the relationships between height and melting period specifically for cone-and ramp-shaped SMPs. These equations provide a mathematical framework for understanding how the height of different SMP geometries influences their melting durations, offering valuable insights for managing snow accumulation and melt in mining operations.

$$H = -0,0021D^2 + 0,5082D - 18,625 \quad (5.1)$$

$$H = -0,0019D^2 + 0,4624D - 18,875 \quad (5.2)$$

$$H = 10,315\ln(D) - 39,581 \quad (5.3)$$

$$H = 6,9323\ln(D) - 21,933 \quad (5.4)$$

$$H = 6,2142\ln(D) - 19,46 \quad (5.5)$$

Where H (m) is the height of SMP, and D (Day) is the melting duration.

These observations suggest that the melting dynamics of SMPs are influenced by their height, volume, and shape, highlighting the complex interplay of these factors. The forthcoming sections will delve deeper into these relationships, comprehensively analyzing the melting behaviors of different snow pile geometries.

Similar to Figure 5.1, Figure 5.2 illustrates the relationship between the volume of SMPs and the duration of their melting periods. The figure includes equations derived from the regression analysis of the modeling results, providing a clear visual representation of this relationship.

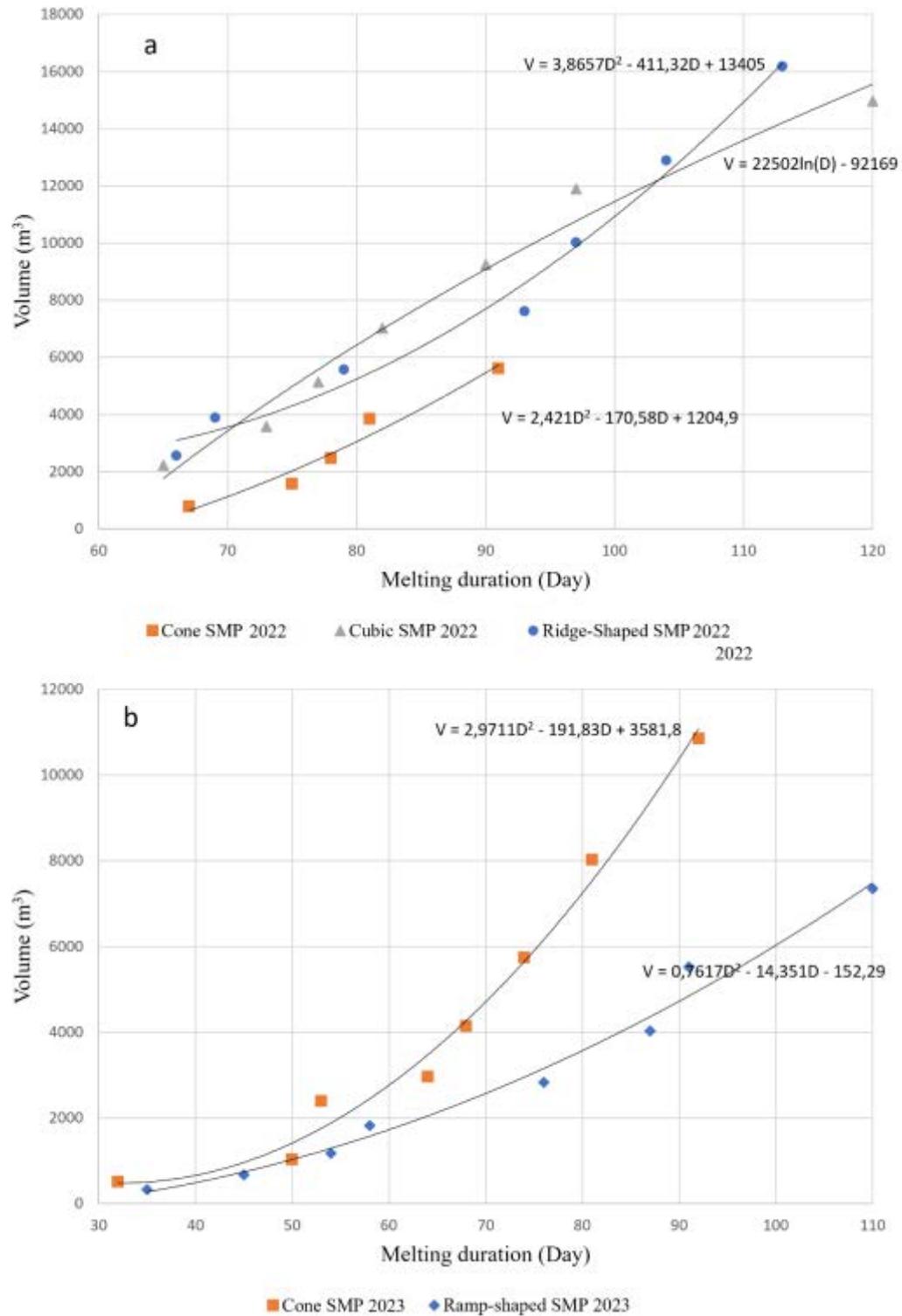


Figure 5.2 (a) Relationship between volume and melting duration in 2022, and (b) In 2023.

The shorter melting period of the cone SMP in 2022 is attributed to its smaller volume. Figure 5.2a illustrates that, despite the nearly equal volumes of all three SMPs in 2022, the cone SMP exhibits a longer melting period compared to the other shapes when volumes are considered. For instance, within the volume range of 2000 to 6000 m³, the cone SMP has a longer melting period than both the cubic and ridge-shaped SMPs.

Furthermore, assuming a volume of 15,000 m³ for the cone SMP, the melting period is calculated to be 119 days based on the derived equation. This duration is almost equivalent to the melting period of a cubic SMP with the same volume and exceeds the melting period of a ridge-shaped SMP with a larger volume.

Figure 5.2b depicts the relationship between volume and melting duration in 2023. The figure reveals an interesting phenomenon: despite having a larger volume than the ramp-shaped SMP, the cone SMP has a shorter melting period. Specifically, for volumes of 4000 m³ and above, the melting period of the cone-shaped pile is shorter than that of the ridge-shaped pile, whereas, for volumes below this threshold, the cone SMP had a longer melting period.

Equations 5.6, 5.7, and 5.8 illustrate the relationships between the volume and melting period for cone, cubic, and ridge-shaped SMPs in 2022. Additionally, equations 5.9 and 5.10 depict the relationships between volume and melting period specifically for cone and ramp-shaped SMPs in 2023. These equations provide a mathematical framework for understanding how the volume of different SMP geometries influences their melting durations, offering valuable insights for managing snow accumulation and melt in mining operations.

$$V = 2,421D^2 - 170,58D + 1204,9 \quad (5.6)$$

$$V = 22502\ln(D) - 92169 \quad (5.7)$$

$$V = 3,8657D^2 - 411,32D + 13405 \quad (5.8)$$

$$V = 2,9711D^2 - 191,83D + 3581,8 \quad (5.9)$$

$$V = 0,7617D^2 - 14,351D - 152,29 \quad (5.10)$$

Observations indicate that cone SMPs exhibited different melting behaviors in 2022 and 2023. In 2022, the cone SMP, despite its smaller volume, had a longer melting period compared to other SMPs. Conversely, in 2023, the cone SMP, even with a larger volume, had a shorter melting period than the ramp-shaped SMP.

This suggests that when air temperatures are moderate, the cone shape is the optimal form for extended melting periods, as shown in Figure 5.2a. However, under higher temperatures, the cone shape is less effective, resulting in a shorter melting period, as illustrated in Figure 5.2b. This difference in melting behavior could be attributed to the shape's surface area exposure and heat absorption dynamics, which vary under different temperature conditions.

5.1.2 Impact of height and volume on the duration of SMP snowmelt with in typical and rapid snowmelt conditions

To thoroughly examine the impact of temperature variations on the melting process of SMPs, a detailed study has been conducted. This study involves re-modeling SMPs with the two temperature functions defined earlier. SMPs originally modeled using the 2022 temperature function were re-modeled using the 2023 temperature function, and vice-versa. This was done to test the melting behaviour of the SMP configurations in typical (2022) and rapid (2023) snowmelt conditions.

This comprehensive approach will generate five sets of outputs, as shown in Figure 5.3, enabling a comparative analysis of how the two distinct temperature functions influence the melting behavior of the SMPs volume. Similar to Figure 5.3, Figure 5.4 shows a comparative analysis of how the two distinct temperature functions influence the melting behavior of the SMPs volume height.

This investigation aims to provide deeper insights into the thermal dynamics and melting patterns under varying temperature conditions.

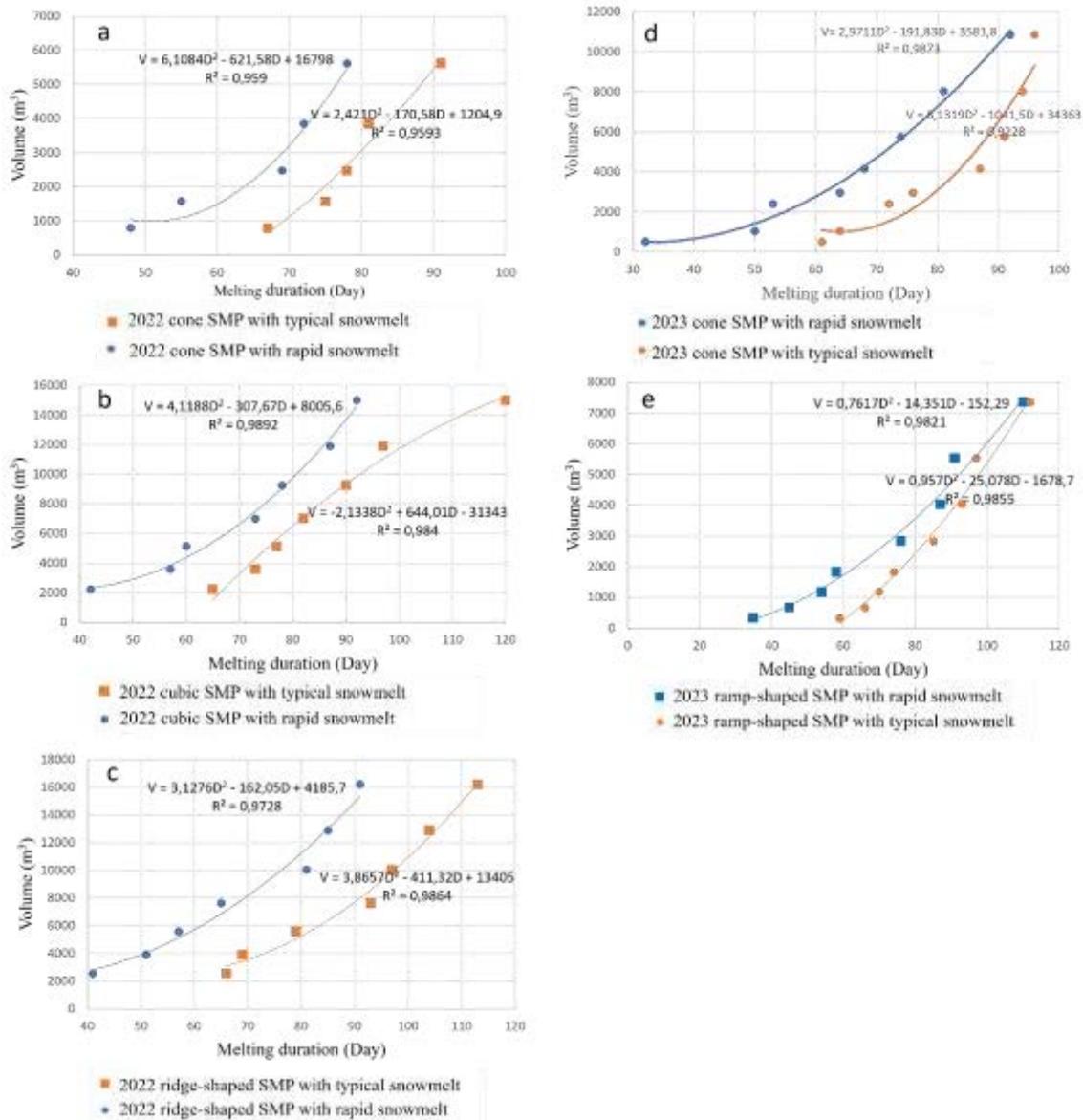


Figure 5.3 Impact of two temperature functions on volume change of (a) 2022 cone SMPs, (b) 2022 cubic SMPs, (c) 2022 ridge-shaped SMPs, (d) 2023 cone SMPs, and (e) 2023 ramp-shaped SMPs volume.

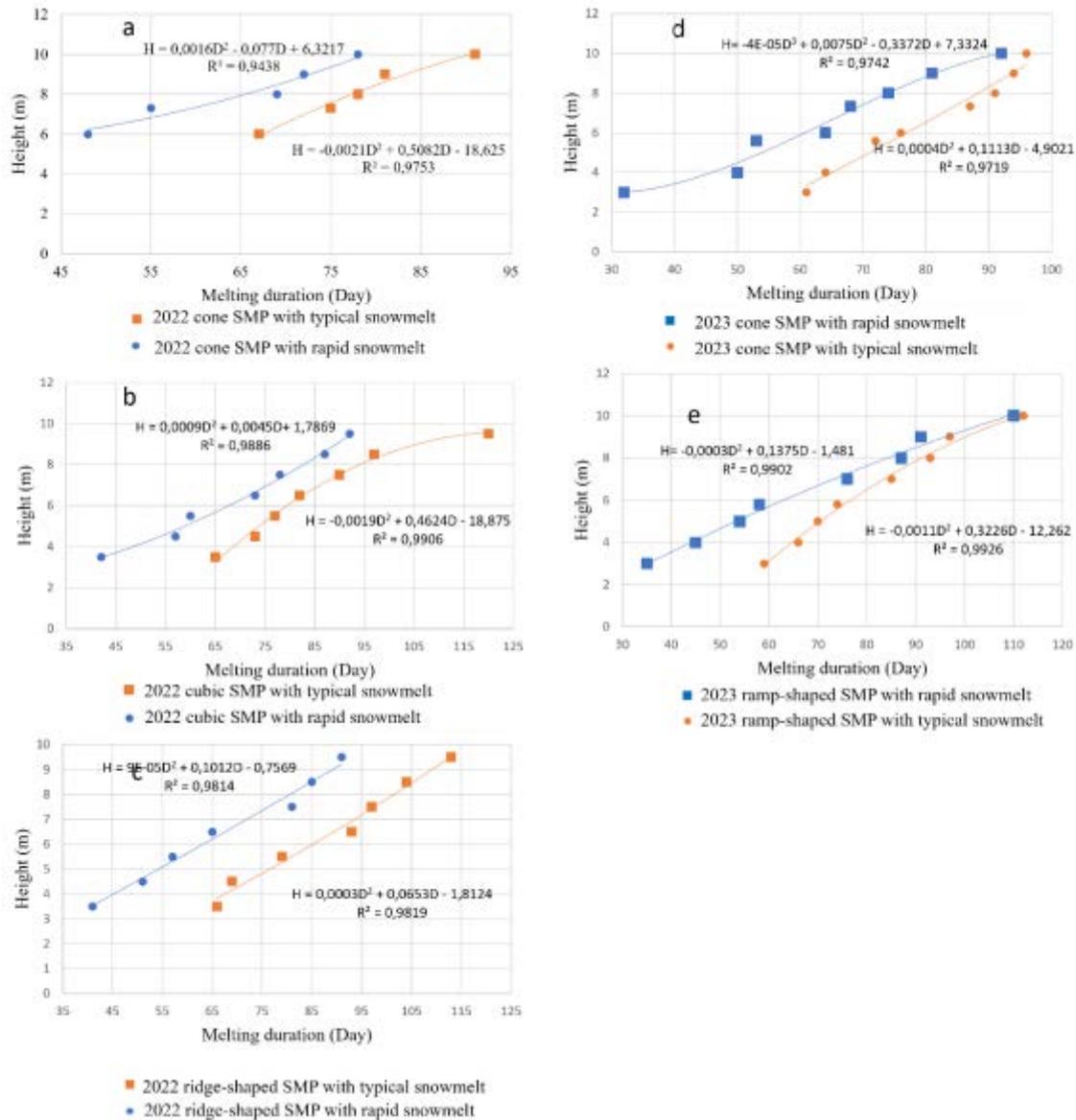


Figure 5.4 Impact of two temperature functions on height change of (a) 2022 cone SMPs, (b) 2022 cubic SMPs, (c) 2022 ridge-shaped SMPs, (d) 2023 cone SMPs, and (e) 2023 ramp-shaped SMPs volume.

Overall, the modeling results using the 2022 temperature data show a delay in the melting of SMPs, ranging from 30 days to 3 days. This underscores the crucial role of accurately predicting air temperatures in the proper design of SMPs. Figure 5.3a and 5.4a present the modeling results for the cone SMPs at Goldex mine, using the temperature functions of 2022 and 2023. The variation in these temperature functions indicates that the melting period of the pile decreases from 30 days to 20 days as the air temperature rises. Figure

5.3b and 5.4b present the modeling results for the cubic SMPs at Goldex mine, using the temperature functions of 2022 and 2023. The variation in these temperature functions indicates that the melting period of the pile decreases from 25 days to 10 days as the air temperature rises. Finally Figure 5.3c and 5.4c present the modeling results for the ridge-shaped SMPs at Goldex mine, using the temperature functions of 2022 and 2023. The variation in these temperature functions indicates that the melting period of the pile decreases from 25 days to 20 days as the air temperature rises. Figure 5.3d and 5.4d illustrates the modeling results for the cone SMP at Holt mine, modeled under the temperature functions of 2022 and 2023. The variation in temperature functions reveals that the melting period of the pile shortens from 30 days to 5 days as the air temperature increases. Figure 5.3e and 5.4e presents the modeling results for the ramp-shaped SMP at Holt mine, using the temperature functions of 2022 and 2023. The variation in these temperature functions indicates that the melting period of the pile decreases from 25 days to 3 days as the air temperature rises. This figure is less sensitive to changes in air temperature compared to other SMP shapes.

In summary, for a typical winter with an average temperature between 0 and 1°C during the SMP melting period, the cone SMP's estimated volume and height can be calculated using equations 5.1 and 5.6. By inputting the desired melting duration into these equations, the estimated height and volume values can be obtained. Similarly, for cubic or ridge-shaped SMPs under the same conditions, equations 5.2 and 5.7, as well as 5.3 and 5.8, are useful for determining height and volume.

In contrast, during winters with higher average temperatures (between 3 and 4°C) during the melting period, equations 5.4 and 5.9 for cone SMP, and equations 5.5 and 5.10 for ramp-shaped SMP, are effective for calculating the height and volume. These equations allow for predictions and management of SMP behavior under varying temperature conditions.

5.2 Optimisation of Construction Methods

The goal of this section is to compare the advantages and disadvantages of civil and specialized equipment. When evaluating these types of equipment for snow management,

several key differences and advantages emerge, each influencing their suitability for various tasks.

Civil equipment is characterized by its lower efficiency and relatively high ground pressure. This type of equipment is easily accessible and versatile, making it suitable for a wide range of applications beyond snow management. However, the lower efficiency means that it takes longer to cover a given area, which can be a significant drawback in time-sensitive operations. The higher ground pressure can also be a concern, particularly in environments where soil compaction or damage to underlying surfaces is an issue (Table 5.1).

In contrast, specialized equipment demonstrates significantly higher efficiency. This high efficiency makes it ideal for large-scale snow management tasks where speed and productivity are critical. Specialized equipment also exerts low ground pressure, reducing the risk of soil compaction and damage to surfaces, which is particularly beneficial in sensitive environments. However, this equipment is dedicated to specific tasks, meaning it may not be as versatile as civil equipment. Additionally, while the cost analysis is still in progress, specialized equipment typically involves higher initial investment and maintenance costs (Table 5.1).

The primary advantage of civil equipment lies in its accessibility and versatility. It can be used for various tasks, making it a practical choice for operations that require flexibility. However, its lower efficiency and higher ground pressure can limit its effectiveness in large-scale or sensitive projects.

On the other hand, specialized equipment excels in efficiency and minimal ground impact. Its ability to cover large areas quickly and with less environmental disturbance makes it ideal for extensive snow management operations. A detailed cost and operation analysis could provide further insights into the financial implications of using specialized equipment, but it is believed that the higher efficiency and lower ground pressure can justify the initial costs in many scenarios.

The choice between civil and specialized equipment depends largely on the specific requirements of the project. For tasks requiring versatility and accessibility, civil

equipment is advantageous. However, for large-scale operations where efficiency and minimal ground impact are paramount, specialized equipment is the superior choice.

Table 5.1 Optimization of construction methods.

Civil equipment	Specialized equipment
Lower efficiency	High efficiency
Relatively high ground pressure	Low ground pressure
Easily accessible	Dedicated equipment
Various uses	Cost analysis in progress

5.3 Lessons learned

At the outset of the project, it was assumed that modeling snow in the software would be a straightforward task. The initial plan was to utilize the physics of water flow in COMSOL software, along with the physics of phase change and heat transfer in porous media, to simulate snow melting. The project began with one-dimensional modeling, and the promising results suggested that an accurate model of snow pile melting could indeed be developed in COMSOL.

Upon completing the one-dimensional phase, the project progressed to two-dimensional modeling, which was intended to be the final goal. Initially, the physics of heat transfer in a porous medium, phase change, and Richard's equations were employed. However, contrary to expectations, the software failed to accurately predict snow melting. Specifically, it could not correctly simulate the movement of water within the model. This issue became apparent when the model was unable to effectively transfer water from the SMP to the lower sections and eventually remove it from the system. Consequently, water retention within the SMP hindered the proper transfer of thermal energy to the lower snow layers, leaving the bottom layers unchanged and trapping water inside the pile. This problem ultimately caused the software to halt the modeling process.

In response, the physics used in the water transfer section was modified. Darcy's law was introduced to simplify the water movement in the model. Although this change resulted in

slight improvements, the software still could not accurately model water movement, and the initial problem persisted.

Further investigation suggested that improper meshing dimensions might be causing the error and preventing the model from effectively moving and expelling water. Consequently, a thorough review of meshing was undertaken. Despite testing over 30 different meshing configurations, the software error continued. Additionally, fine meshing (with dimensions smaller than 0.2 m) significantly prolonged the modeling process.

Ultimately, it was decided to simplify the approach further. Instead of modeling the phase change from snow to water and its subsequent removal from the model, a material with high thermal conductivity was used to simulate water movement. This entire process was the start of SMPs behavior numerical modeling which is useful to predict the volume of snowmelt and meltwater. The starting simple can still provide insight full results despite the downfalls.

Preliminary 2D modeling brought-up the challenges of comparing modeling and field results. As a result, it was decided to proceed with three-dimensional modeling to enable a more accurate comparison of snow volume changes between the model and reality.

During the initial phase of three-dimensional modeling, it was assumed that the average air temperature over the entire period could be used as a constant boundary condition. This assumption led to an average error of about 30% in predicting snowmelt between real data and the model. To address this, the temperature functions presented in this chapter were defined based on real meteorological data, significantly improve numerical results.

Next, the effect of solar radiation was investigated using the physics of an external radiation source. This attempt aimed to measure the impact of sunlight on the walls of snow piles and determine the optimal slope for each shape. Despite extensive efforts, this modeling process was unsuccessful, leading to the removal of this part of the work from the project.

Additionally, an attempt was made to model the impact of rainfall using the Physics of Transport of Diluted Species Module. This was done before the secondary water change. Like the previous issue, water was not correctly added to the model, only causing a decrease in ambient temperature on the pile's surface and being used for heating the water.

Due to the complexity and lack of success, this process was also removed from the modeling.

In conclusion, the project faced numerous challenges and required several adjustments to the initial approach. The experience highlighted the importance of flexibility and the willingness to simplify models when necessary to achieve accurate and practical results.

CHAPTER 6 CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

A comprehensive review of studies on snow properties and heat transfer in snow provides valuable insights into the challenges and management strategies for snowmelt. This review evaluates various approaches to modeling heat transfer in snow, comparing the advantages and disadvantages of different models. It discusses the challenges associated with snow modeling and provides an overview of the current state of snow heat transfer modeling. Additionally, the review highlights the use of COMSOL software to model heat transfer in snow, explaining the necessary physics and key parameters that must be defined in the software.

The main objective of this research was to evaluate the effectiveness of SMPs in regulating the winter water balance of TSFs. Specifically, the study aimed to assess how SMPs can moderate snowmelt rates, reduce peak meltwater flows, and stagger spring runoff. To achieve this, three pilot-scale SMPs were constructed at the Holt mine in Kirkland, Ontario, 2023 using a Prinoth groomer, and another three at the Goldex mine in Val d'Or, Quebec, 2022 using a loader and bulldozer.

In 2022, the SMPs were designed in three shapes: a cone with an initial volume of 1135 m³, a footprint of 665 m², and a height of 7.3 m; a cube with an initial volume of 2275 m³, a footprint of 965 m², and a height of 3.5 m; and a ridge shape with an initial volume of 2565 m³, a footprint of 1150 m², and a height of 3.5 m. The cone SMP melted in 70 days, the cubic SMP in 68 days, and the ridge-shaped SMP also in 68 days. In contrast, natural snow melted in 46 days from the start of the monitoring period, indicating that the SMPs delayed snowmelt by 3 to 4 weeks.

In 2023, the SMPs were redesigned with different shapes and sizes: a large cone with an initial volume of 4130 m³, a footprint of 1950 m², and a height of 7.33 m; a ramp shape with an initial volume of 2650 m³, a footprint of 1343 m², and a height of 5.5 m; and a small cone with an initial volume of 1600 m³, a footprint of 946 m², and a height of 5.6 m. The large cone SMP melted in 64 days, the ramp-shaped SMP in 49 days, and the small cone in 57 days. Natural snow melted in 29 days from the start of the monitoring period,

showing that the SMPs delayed snowmelt by 3 to 5 weeks. These designs were used to investigate the impact of size and shape on snowmelt dynamics.

Changes in the SMPs, including volume, height, and footprint, were monitored using LiDAR and SfM photogrammetry techniques over ten weeks, with data collected between eight and eighteen times. Meteorological data revealed two distinct patterns of behavior in 2022 and 2023. In 2022, winter conditions were typical, resulting in natural snow melting over 46 days. Conversely, in 2023, warmer temperatures led to a much quicker snowmelt, taking only 29 days. Snow density measurements were also obtained through core sampling at different intervals during the observation period. The results indicated that SMPs effectively increased the duration of snowmelt, prolonging the process by approximately four to six weeks. The volume and height of SMPs emerged as critical factors influencing their ability to stagger snowmelt.

The modeling efforts, including both the unsuccessful attempts and the final successful model, were discussed in detail. These efforts aimed to simplify the process and reduce model error. The results showed that the prediction of snow melting behavior during the melting period had an average error of 6.75%, while the error rate for predicting the entire length of the snow melting period was less than 4%. Based on these modeling results, snow melting prediction charts were developed, considering the dimensions, shape, and cost of snow pile construction. These charts assist miners in reducing the geotechnical hazards of tailings dams by managing spring snowmelt.

To derive equations for the height and volume of SMPs with the required melting period, 70 piles were modeled, and the relevant equations were determined. It was found that cone-shaped SMPs are highly sensitive to temperature changes, while ridge-shaped SMPs are less sensitive and exhibit consistent performance across different temperatures. In another section, a comparison was made between the use of construction and specialized equipment, detailing the benefits and drawbacks of each. Furthermore, the study concluded that SMPs can help mitigate environmental and geotechnical risks associated with rapid snowmelt, potentially reducing the need for additional storage and treatment facilities during extreme events. This is particularly important in the context of climate change, where predicting future weather patterns is becoming increasingly challenging.

6.2 Recommendations

Here are some recommendations for future snow management and modeling projects:

- SMPs can be highly effective in mitigating the impacts of freshet on tailings dams and water management infrastructures. Implementing these practices helps manage the sudden influx of water during snowmelt periods, reducing potential damage and improving overall water management.
- There is a need for more research to develop and refine adaptive and autonomous monitoring tools. These tools can provide real-time data, enhancing the accuracy and responsiveness of snow management systems.
- Advancement in Snowmelt Process Modeling: Further research is essential to advance the modeling of snowmelt processes (SMP melting). This includes developing more accurate physics-based models that can better predict the dynamics of snowmelt, leading to improved management strategies.
- Utilize Real-Time Meteorological Data: Incorporate current meteorological data into your models to ensure that simulations reflect real-world conditions accurately.

By following these recommendations, future projects can achieve more precise and reliable results in snow management and modeling.

References

- Abbott, M. B., Bathurst, J. C., Cunge, J. A., O'Connell, P. E., & Rasmussen, J. (1986). An introduction to the European Hydrological System—Systeme Hydrologique Europeen, “SHE”, 2: Structure of a physically-based, distributed modelling system. *Journal of hydrology*, 87(1-2), 61-77.
- Abegg, B., Agrawala, S., Crick, F., and de Montfalcon, A. (2007). “Climate change impacts and adaptation in winter tourism,” in *Climate Change in the European Alps: Adapting Winter Tourism and Natural Hazards Management*, ed S. Agrawala (Paris: OECD Publishing), 25–60.
- Abele, G., & Gow, A. J. (1975). Compressibility characteristics of undisturbed snow (Vol. 336). US Army Cold Regions Research and Engineering Laboratory.
- Abels, H. F. (1892). Beobachtungen der täglichen Periode der Temperatur im Schnee und Bestimmung des Wärmeleistungsvermögens des Schnees als Function seiner Dichtigkeit.
- Acar, R., Elik, S., Enocak, S. (2015). Modelling Snowmelt Runoff Using an Artificial Neural Network ANN Approach. In *Proceedings of the 3rd International Conference on Advances in Civil, Structural and Mechanical Engineering (ACSM)*, Bangkok, Thailand, 28–29.
- Akitaya, E. (1974). Studies on depth hoar. *Contributions from the Institute of Low Temperature Science*, 26, 1-67.
- Albert M, Perron F (2000) Ice layer and surface crust permeability in a seasonal snowpack. *Hydrological Processes* 14:3207–3214
- Albert M, Schultz E, Perron F (2000) Snow and firn permeability at Siple Dome, Antarctica. *Annals of Glaciology* 31:353–356
- Albert, M. R., & Perron Jr, F. E. (2000). Ice layer and surface crust permeability in a seasonal snowpack. *Hydrological Processes*, 14(18), 3207-3214.
- Albert, M. R., Shultz, E. F., & Perron, F. E. (2000). Snow and firn permeability at Siple Dome, Antarctica. *Annals of Glaciology*, 31, 353-356.

- Alford, D. L. (1974). *Snow*: Methuen & Company, Limited
- Alizadeh, O. (2022). Advances and challenges in climate modeling. *Climatic Change*, 170(1), 18.
- Allan, J. D., and Castillo, M. M. (2007). *Stream Ecology: Structure and Function of Running Waters*, 2nd Edn. New York, NY: Chapman and Hall.
- Alley, R. B. (1987). Firn densification by grain-boundary sliding: a first model. *Le Journal de Physique Colloques*, 48(C1), C1-249.
- Alley, R. B. (1987). Texture of polar firn for remote sensing. *Annals of Glaciology*, 9, 1-4.
- Amiri, A., & Vafai, K. (1998). Transient analysis of incompressible flow through a packed bed. *International Journal of Heat and Mass Transfer*, 41(24), 4259-4279.
- Andersland, O., & Anderson, D. (1978). *Geotechnical engineering for cold regions*
- Anderson, E. A. (1973). National Weather Service River forecast system: Snow accumulation and ablation model (Vol. 17). US Department of Commerce, National Oceanic and Atmospheric Administration, National Weather Service.
- Anderson, E. A. (1976). A point energy and mass balance model of a snow cover. Stanford University.
- Anderson, S., & Tinkler, T. (2021). *Developing Integrated Water Management Models to Address Water Related Risks and Provide Resilience in the Mining Industry*.
- Aoki, T., Hachikubo, A. & Hori, M. (2003) Effects of snow physical parameters on shortwave broadband albedos, *J. Geophys.Res.* 108(D19), 4616.
- Arakawa, H., Izumi, K., Kawashima, K., & Kawamura, T. (2009). Study on quantitative classification of seasonal snow using specific surface area and intrinsic permeability. *Cold Regions Science and Technology*, 59(2), 163-168.
- Araya, S. N., & Ghezzehei, T. A. (2019). Using machine learning for prediction of saturated hydraulic conductivity and its sensitivity to soil structural perturbations. *Water Resources Research*, 55(7), 5715-5737.

- Arnaud, L., Gay, M., Barnola, J. M., & Duval, P. (1998). Imaging of firn and bubbly ice in coaxial reflected light: a new technique for the characterization of these porous media. *Journal of Glaciology*, 44(147), 326-332.
- Arnold, J. G., Srinivasan, R., Muttiah, R. S., & Williams, J. R. (1998). Large area hydrologic modeling and assessment part I: model development 1. *JAWRA Journal of the American Water Resources Association*, 34(1), 73-89.
- Arriagada, P., Karelovic, B., & Link, O. (2021). Automatic gap-filling of daily streamflow time series in data-scarce regions using a machine learning algorithm. *Journal of Hydrology*, 598, 126454.
- Ashton, G. D. (2011). River and lake ice thickening, thinning, and snow ice formation. *Cold Regions Science and Technology*, 68(1-2), 3-19.
- Aufdemberge, T. P. (1971). Energy balance studies over glacier and tundra surfaces, summer, 1969. University of Michigan.
- Azam, S. & Li, Q. (2010). Tailings Dam Failures: A Review of the Last 100 Years, *Waste Geotechnics*. *Geotechnical News*: 50-53.
- Baba, M. W., Gascoin, S., & Hanich, L. (2018). Assimilation of Sentinel-2 data into a snowpack model in the High Atlas of Morocco. *Remote Sensing*, 10(12), 1982.
- Bader, H. (1939). *Der schnee und seine metamorphose*. Kommissionsverlag Kummerly & Frey, Druck von Aschmann & Scheller a.-g., Zurich.
- Bader, H. (1939). Mineralogische und Strukturelle Charakterisierung des Schnees und seiner Metamorphose. *Beitrage zur Geologie der Schweiz, Geotechn. Ser. Hydrol*, 3(1)
- Bair, E. H., Abreu Calfa, A., Rittger, K., & Dozier, J. (2018). Using machine learning for real-time estimates of snow water equivalent in the watersheds of Afghanistan. *The Cryosphere*, 12(5), 1579-1594.
- Bales, R. C., Molotch, N. P., Painter, T. H., Dettinger, M. D., Rice, R., & Dozier, J. (2006). Mountain hydrology of the western United States. *Water Resources Research*, 42(8).

- Balland, V., & Arp, P. A. (2005). Modeling soil thermal conductivities over a wide range of conditions. *Journal of Environmental Engineering and Science*, 4(6), 549-558.
- Bansal, A., & Suthar, O. P. (2024). Temperature modulation effects on chaos and heat transfer in Darcy–Bénard convection using a local thermal non-equilibrium model. *Nonlinear Dynamics*, 1-19.
- Barnett, T. P., Adam, J. C., and Lettenmaier, D. P. (2005). Potential impacts of a warming climate on water availability in snow-dominated regions. *Nature* 438, 303–309.
- Bartelt, P., & Lehning, M. (2002). A physical SNOWPACK model for the Swiss avalanche warning: Part I: numerical model. *Cold Regions Science and Technology*, 35(3), 123-145.
- Bavay, M., Grünewald, T., & Lehning, M. (2013). Response of snow cover and runoff to climate change in high Alpine catchments of Eastern Switzerland. *Advances in water resources*, 55, 4-16.
- Bear, J. (2012). *Hydraulics of groundwater*. Courier Corporation.
- Bear, J. (2013). *Dynamics of fluids in porous media*. Courier Corporation
- Bear, J., & Braester, C. (1972). On the flow of two immiscible fluids in fractured porous media. In *Developments in soil science* (Vol. 2, pp. 177-202). Elsevier.
- Bejan, A. (2013). *Convection heat transfer*. John Wiley & Sons.
- Bender, J. A. (1957). Air permeability of snow, SIPRE research report 37, U.S. Army corps of engineers, Snow Ice and Permafrost Research Establishment, November 1957, 27 pp.
- Beniston, M. (2012). Is snow in the Alps receding or disappearing? *WIREs Climate Change* 3, 349–358.
- Benson, C. (1962). Stratigraphic studies in the snow and firn of the Greenland Icesheet, Cold Regions Research and Engineering Laboratory–Research Report 70. US Army Snow, Ice, and Permafrost Research Establishment, Engineer Research and Development Center (US).

- Bergström, S. (1995). The HBV models. *Computer models of watershed hydrology*, 443-476.
- Bernhardt, M., Zängl, G., Liston, G. E., Strasser, U., & Mauser, W. (2009). Using wind fields from a high-resolution atmospheric model for simulating snow dynamics in mountainous terrain. *Hydrological Processes: An International Journal*, 23(7), 1064-1075.
- Berris, S. N., & Harr, R. D. (1987). Comparative snow accumulation and melt during rainfall in forested and clear-cut plots in the western Cascades of Oregon. *Water Resources Research*, 23(1), 135-142.
- Bieniek, P. A., Bhatt, U. S., Walsh, J. E., Lader, R., Griffith, B., Roach, J. K., & Thoman, R. L. (2018). Assessment of Alaska rain-on-snow events using dynamical downscaling. *Journal of Applied Meteorology and Climatology*, 57(8), 1847-1863.
- Bishop, M. P., Björnsson, H., Haeberli, W., Oerlemans, J., Shroder, J. F., & Tranter, M. (2011). *Encyclopedia of snow, ice, and glaciers*. Springer Science & Business Media.
- Blackwell, J. (1954). A transient-flow method for determination of thermal constants of insulating materials in bulk part I—Theory. *Journal of applied physics*, 25(2), 137-144.
- Blöschl, G. (1999). Scaling issues in snow hydrology. *Hydrological processes*, 13(14-15), 2149-2175.
- Bloschl, R. (1991). A spatially distributed snowmelt model for application in alpine terrain. *Snow, Hydrology and Forests in High Alpine Areas*.
- Boon, S. (2009). Snow ablation energy balance in a dead forest stand. *Hydrological Processes: An International Journal*, 23(18), 2600-2610.
- Bowling, L. C., Pomeroy, J. W., & Lettenmaier, D. P. (2004). Parameterization of blowing-snow sublimation in a macroscale hydrology model. *Journal of Hydrometeorology*, 5(5), 745-762.

- Bracht, J. (1949). Über die Wärmeleitfähigkeit des Erdbodens und des Schnees und den Wärmeumsatz im Erdboden.
- Braithwaite, R. J., Latenser, M., & Pfeffer, W. T. (1994). Variations of near-surface firn density in the lower accumulation area of the Greenland ice sheet, Pâkitsoq, West Greenland. *Journal of Glaciology*, 40(136), 477-485.
- Brauchli, T., Trujillo, E., Huwald, H., & Lehning, M. (2017). Influence of slope-scale snowmelt on catchment response simulated with the Alpine3D model. *Water Resources Research*, 53(12), 10723-10739.
- Brooks, R. H., & Corey, A. T. (1966). Properties of porous media affecting fluid flow. *Journal of the irrigation and drainage division*, 92(2), 61-90.
- Brown, R. D., & Mote, P. W. (2009). The response of Northern Hemisphere snow cover to a changing climate. *Journal of Climate*, 22(8), 2124-2145.
- Brubaker, K., Rango, A., & Kustas, W. (1996). Incorporating radiation inputs into the snowmelt runoff model. *Hydrological processes*, 10(10), 1329-1343.
- Brucker, L., Picard, G., Arnaud, L., Barnola, J. M., Schneebeli, M., Brunjail, H., ... & Fily, M. (2011). Modeling time series of microwave brightness temperature at Dome C, Antarctica, using vertically resolved snow temperature and microstructure measurements. *Journal of Glaciology*, 57(201), 171-182.
- Brun, E., & Touvier, F. (1987). Etude expérimentale de la convection thermique dans la neige. *Le journal de physique colloques*, 48(C1), C1-257.
- Buckingham, D., Skalka, C., & Bongard, J. (2015). Inductive machine learning for improved estimation of catchment-scale snow water equivalent. *Journal of Hydrology*, 524, 311-325.
- Bulovic, N., McIntyre, N., & Trancoso, R. (2024). Climate change risks to mine closure. *Journal of Cleaner Production*, 142697.
- Burns, S. P., Molotch, N. P., Williams, M. W., Knowles, J. F., Seok, B., Monson, R. K., ... & Blanken, P. D. (2014). Snow temperature changes within a seasonal snowpack

- and their relationship to turbulent fluxes of sensible and latent heat. *Journal of Hydrometeorology*, 15(1), 117-142.
- Bussière, B. & Guitonny, M. (2020). *Hard Rock Mine Reclamation: From Prediction to Management of Acid Mine Drainage*. CRC Press, Taylor and Francis Group.
- Cacciuttolo, C., & Marinovic Pulido, A. (2022). Sustainable management of thickened tailings in Chile and Peru: a review of practical experience and socio-environmental acceptance. *Sustainability*, 14(17), 10901.
- Cacciuttolo, C., & Tabra, K. (2015). *Water management in the closure of tailings storage facilities*. Santiago: 10a ICARD IMWA.
- Cacciuttolo, C., Pastor, A., Valderrama, P., & Atencio, E. (2023). Process water management and seepage control in tailings storage facilities: Engineered environmental solutions applied in Chile and Peru. *Water*, 15(1), 196.
- Caldwell, J. (2017). *Tailings History: 2006 and 2017*. Proceedings of the Tailings and Mine Wastes Conference, Banff, AB.
- Calonne, N., Geindreau, C., Flin, F., Morin, S., Lesaffre, B., Rolland du Roscoat, S., & Charrier, P. (2012). 3-D image-based numerical computations of snow permeability: links to specific surface area, density, and microstructural anisotropy. *The Cryosphere*, 6(5), 939-951.
- Campbell, G. S., & Norman, J. M. (2000). *An introduction to environmental biophysics*. Springer Science & Business Media.
- Carbonell, R. G., & Whitaker, S. (1984). Heat and mass transfer in porous media. In *Fundamentals of transport phenomena in porous media* (pp. 121-198). Dordrecht: Springer Netherlands.
- Carman, P. C. (1937). Fluid flow through granular beds. *Transactions-Institution of Chemical Engineers*, 15, 150-166
- Carman, P. C. (1956). *Flow of gases through porous media*: Academic press

- Carroll, T. (1977). A comparison of the CRREL 500 cm³ tube and the ILTS 200 and 100 cm³ box cutters used for determining snow densities. *Journal of Glaciology*, 18(79), 334-337.
- Carroll, T.: A comparison of the CRREL 500cm³ tube and the ILTS 200 and 100cm³ box cutters used for determining snow densities, *J. Glaciol.*, 18, 334–337, 1977.
- Cavcar, M. (2000). The international standard atmosphere (ISA). *Anadolu University, Turkey*, 30(9), 1-6.
- Cavcar, M. (2000). The international standard atmosphere (ISA). *Anadolu University, Turkey*, 30(9), 1-6.
- Cazorzi, F., & Dalla Fontana, G. (1996). Snowmelt modelling by combining air temperature and a distributed radiation index. *Journal of Hydrology*, 181(1-4), 169-187.
- Chakraborty, K., Mehrotra, K., Mohan, C. K., & Ranka, S. (1992). Forecasting the behavior of multivariate time series using neural networks. *Neural networks*, 5(6), 961-970.
- CHANGE, O. C. (2007). Intergovernmental panel on climate change. *World Meteorological Organization*, 52, 1-43.
- Che, T., Li, X., Jin, R., Armstrong, R., & Zhang, T. (2008). Snow depth derived from passive microwave remote-sensing data in China. *Annals of glaciology*, 49, 145-154.
- Chen, R., Lü, S., Kang, E., Ji, X., Yang, Y., & Zhang, J. (2006). A distributed water-heat coupled (DWHC) model for mountainous watershed of an inland river basin (I): model structure and equations. *Advances in Earth Science*, 21(8), 806.
- Chen, Y. N., Yang, Q., Luo, Y., Shen, Y., Pan, X. L., Li, L., & Li, Z. Q. (2012). Ponder on the issues of water resources in the arid region of northwest China. *Arid Land Geography*, 35(1), 1-9.
- Cheng, B., & Titterington, D. M. (1994). Neural networks: A review from a statistical perspective. *Statistical science*, 2-30.

- Cherkauer, K. A., & Lettenmaier, D. P. (1999). Hydrologic effects of frozen soils in the upper Mississippi River basin. *Journal of Geophysical Research: Atmospheres*, 104(D16), 19599-19610.
- Cherkauer, K. A., & Lettenmaier, D. P. (2003). Simulation of spatial variability in snow and frozen soil. *Journal of Geophysical Research: Atmospheres*, 108(D22).
- Chivers, B. D., Wallbank, J., Cole, S. J., Sebek, O., Stanley, S., Fry, M., & Leontidis, G. (2020). Imputation of missing sub-hourly precipitation data in a large sensor network: A machine learning approach. *Journal of Hydrology*, 588, 125126.
- Clemente, J. S., & Huntsman, P. (2019). Potential climate change effects on the geochemical stability of waste and mobility of elements in receiving environments for Canadian metal mines south of 60° N. *Environmental Reviews*, 27(4), 478-518.
- Clifton, A., Manes, C., Rüedi, J. D., Guala, M., & Lehning, M. (2008). On shear-driven ventilation of snow. *Boundary-layer meteorology*, 126, 249-261.
- Cline, D. W. (1997). Snow surface energy exchanges and snowmelt at a continental, midlatitude Alpine site. *Water Resources Research*, 33(4), 689-701.
- Clyde, G. (1931). Snow-melting characteristics. Tech. Bull. 231, Utah Agric. Exp. Sta., Logan, UT.
- Cohen, J., Ye, H., & Jones, J. (2015). Trends and variability in rain-on-snow events. *Geophysical Research Letters*, 42(17), 7115-7122.
- Colbeck, S. (1974). The capillary effects on water percolation in homogeneous snow. *Journal of Glaciology*, 13, 85-97
- Colbeck, S. (1978). The Difficulties of Measuring the Water Saturation and Porosity of Snow. *Journal of Glaciology*, 20(82), 189-201.
- Colbeck, S. C. (1975). A theory for water flow through a layered snowpack. *Water Resources Research*, 11(2), 261-266.
- Colbeck, S. C., Akitaya, E., Armstrong, R. L., Gubler, H., Lafeuille, J., Lied, K., Mcclung, D. M., Morris, E. M. (1990). The International Classification for Seasonal Snow on

- the Ground. International Commission on Snow and Ice (IAHS), World Data Center A for Glaciology, University of Colorado, Boulder, CO, USA
- Combarous, M. A., & Bories, S. A. (1975). Hydrothermal convection in saturated porous media. In *Advances in hydroscience* (Vol. 10, pp. 231-307). Elsevier.
- COMSOL, A. (2018). *Subsurface flow module user's guide*. COMSOL Multiphysics, 5.
- Conger, S. M., & McCLUNG, D. M. (2009). Comparison of density cutters for snow profile observations. *Journal of Glaciology*, 55(189), 163-169.
- Conway, H., & Benedict, R. (1994). Infiltration of water into snow. *Water Resources Research*, 30(3), 641-649.
- Côté, J., & Konrad, J. M. (2009). Assessment of structure effects on the thermal conductivity of two-phase porous geomaterials. *International Journal of Heat and Mass Transfer*, 52(3-4), 796-804.
- Côté, J., Rahimi, M., Konrad, J.M. (2012). Thermal conductivity of compacted snow. 15th International Conference on Cold Regions Engineering, ed. Brian Morse, ASCE, Québec, Canada.
- Daanen, R. P. (2004). *Modeling liquid water flow in snow*. University of Minnesota
- Daanen, R. P., & Nieber, J. L. (2009). Model for coupled liquid water flow and heat transport with phase change in a snowpack. *Journal of Cold Regions Engineering*, 23(2), 43-68
- Dadic, R., Mott, R., Lehning, M., & Burlando, P. (2010). Wind influence on snow depth distribution and accumulation over glaciers. *Journal of Geophysical Research: Earth Surface*, 115(F1).
- Davies, J. A., & Idso, S. B. (1979). Estimating the surface radiation balance and its components.
- De Oliveira, V. A., Rodrigues, A. F., Morais, M. A. V., Terra, M. D. C. N. S., Guo, L., & de Mello, C. R. (2021). Spatiotemporal modelling of soil moisture in an Atlantic forest through machine learning algorithms. *European Journal of Soil Science*, 72(5), 1969-1987.

- De Quervain, M. (1956). Zur Wärmeleitung von Schnee. Eidg. Institut für Schnee-und Lawinenforschung, Weissfluhjoch/Davos.
- De Quervain, M. R. (1973). Snow structure, heat, and mass flux through snow.
- De Vries, D. A. (1963). Thermal properties of soil. Chapter 7 In: WR Van Wijk. Physics of Plant Environment.
- Debye, P., Anderson Jr, H. R., & Brumberger, H. (1957). Scattering by an inhomogeneous solid. II. The correlation function and its application. *Journal of applied Physics*, 28(6), 679-683.
- Dedieu, J. P., Carlson, B. Z., Bigot, S., Sirguey, P., Vionnet, V., & Choler, P. (2016). On the importance of high-resolution time series of optical imagery for quantifying the effects of snow cover duration on alpine plant habitat. *Remote Sensing*, 8(6), 481.
- Denoth, A., Foglar, A., Weiland, P., Mätzler, C., Aebischer, H., Tiuri, M., & Sihvola, A. (1984). A comparative study of instruments for measuring the liquid water content of snow. *Journal of Applied Physics*, 56(7), 2154-2160.
- Denoth, A., Foglar, A., Weiland, P., Mätzler, C., Aebischer, H., Tiuri, M., & Sihvola, A. (1984). A comparative study of instruments for measuring the liquid water content of snow. *Journal of Applied Physics*, 56(7), 2154-2160.
- Derksen, C., & Brown, R. (2012). Spring snow cover extent reductions in the 2008–2012 period exceeding climate model projections. *Geophysical Research Letters*, 39(19).
- Desilets, D., Zreda, M., & Ferré, T. P. (2010). Nature's neutron probe: Land surface hydrology at an elusive scale with cosmic rays. *Water Resources Research*, 46(11).
- Devaux, J. (1933). L'économie radio-thermique des champs de neige et des glaciers. In *Annales de Physique* (Vol. 10, No. 20, pp. 5-67). EDP Sciences.
- DeWalle, D. R., & Rango, A. (2008). *Principles of snow hydrology*. Cambridge University Press.
- DeWalle, D. R., Henderson, Z., & Rango, A. (2002, May). Spatial and temporal variations in snowmelt degree-day factors computed from SNOTEL data in the Upper Rio

- Grande basin. In Proceedings of the Western Snow Conference (Vol. 70, p. 73). Colorado State University.
- Dibb, J. E., & Fahnestock, M. (2004). Snow accumulation, surface height change, and firn densification at Summit, Greenland: Insights from 2 years of in situ observation. *Journal of Geophysical Research: Atmospheres*, 109(D24)
- Dickinson, H. C., & Osborne, N. S. (1915). Specific heat and heat of fusion of ice (No. 248). US Government Printing Office.
- Ding, J., & Cui, C. (2017). Simulation and validation of enhanced snowmelt runoff model with topographic factor. *Transactions of the Chinese Society of Agricultural Engineering*, 33(19), 179-186.
- Ding, M., Zhang, T., Yang, D., Allison, I., Dou, T., & Xiao, C. (2021). Brief communication: Evaluation of multiple density-dependent empirical snow conductivity relationships in East Antarctica. *The Cryosphere*, 15(9), 4201-4206.
- Dingman SL (1994) Physical hydrology. MacMillan Publishing Company, New York
- Dominé, F., & Shepson, P. B. (2002). Air-snow interactions and atmospheric chemistry. *Science*, 297(5586), 1506-1510.
- Domine, F., Albert, M., Huthwelker, T., Jacobi, H. W., Kokhanovsky, A. A., Lehning, M., & Simpson, W. R. (2008). Snow physics as relevant to snow photochemistry. *Atmospheric chemistry and physics*, 8(2), 171-208.
- Domine, F., Lauzier, T., Cabanes, A., Legagneux, L., Kuhs, W. F., Techmer, K., & Heinrichs, T. (2003). Snow metamorphism as revealed by scanning electron microscopy. *Microscopy research and technique*, 62(1), 33-48
- Domine, F., Salvatori, R., Legagneux, L., Salzano, R., Fily, M., & Casacchia, R. (2006). Correlation between the specific surface area and the short wave infrared (SWIR) reflectance of snow. *Cold Regions Science and Technology*, 46(1), 60-68.
- Domine, F., Taillandier, A. S., & Simpson, W. R. (2007). A parameterization of the specific surface area of seasonal snow for field use and for models of snowpack evolution. *Journal of Geophysical Research: Earth Surface*, 112(F2).

- Dorsey, N. E. (1940). Properties of ordinary water-substance in all its phases: water-vapor, water, and all the ices.
- Dozier, J. (1980). A clear-sky spectral solar radiation model for snow-covered mountainous terrain. *Water Resources Research*, 16(4), 709-718.
- Dozier, J., & Warren, S. G. (1982). Effect of viewing angle on the infrared brightness temperature of snow. *Water resources research*, 18(5), 1424-1434.
- Dozier, J., Davis, R. E., & Perla, R. (1987). On the objective analysis of snow microstructure. *Avalanche Formation, Movement and Effects*, 162, 46-59.
- Dunkle, Robert V., and J. T. Bevans. "An approximate analysis of the solar reflectance and transmittance of a snow cover." *Journal of Atmospheric Sciences* 13.2 (1956): 212-216.
- East, D., & Fernandez, R. (2021). Managing water to minimize risk in tailings storage facility design, construction, and operation. *Mine Water and the Environment*, 40(1), 36-41.
- Edwards, A. C., Scalenghe, R., & Freppaz, M. (2007). Changes in the seasonal snow cover of alpine regions and its effect on soil processes: a review. *Quaternary international*, 162, 172-181.
- Eidsvik, K. J., Holstad, A., Lie, I., & Utne, T. (2004). A prediction system for local wind variations in mountainous terrain. *Boundary-Layer Meteorology*, 112, 557-586.
- Eiriksson, D., Whitson, M., Luce, C. H., Marshall, H. P., Bradford, J., Benner, S. G., ... & McNamara, J. P. (2013). An evaluation of the hydrologic relevance of lateral flow in snow at hillslope and catchment scales. *Hydrological Processes*, 27(5), 640-654.
- Environnement Canada. (2009). Code de Pratiques Écologiques pour les Mines de Métaux.
- ERMITE-Consortium, Younger, P. L., & Wolkersdorfer, C. (2004). Mining impacts on the freshwater environment: technical and managerial guidelines for catchment scale management. *Mine water and the environment*, 23(Suppl 1), s2-s80.
- Essery, R., Li, L., & Pomeroy, J. (1999). A distributed model of blowing snow over complex terrain. *Hydrological processes*, 13(14-15), 2423-2438.

- Fang, S. F., Pei, H., Liu, Z. H., Dai, W., & Zhao, Q. D. (2008). Study on the distributed snowmelt runoff process based on RS and GIS. *J. Remote Sens*, 12(4), 655-662.
- Fausto, R. S., Box, J. E., Vandecrux, B., Van As, D., Steffen, K., MacFerrin, M. J., ... & Braithwaite, R. J. (2018). A snow density dataset for improving surface boundary conditions in Greenland ice sheet firn modeling. *Frontiers in Earth Science*, 6, 51.
- Federer, C. A., & Lash, D. (1978). BROOK: A hydrologic simulation model for eastern forests.
- Federer, C. A., Pierce, R. S., & Hornbeck, J. W. (1972). Snow management seems unlikely in the Northeast. *Proceedings series*.
- Fedoseeva, V. I., & Fedoseev, N. F. (1988). Evaluation of the coefficient of diffusion of water vapour in snow cover. *Meteorologiya i Gidrologiya*, 2, 132-35.
- Fernandes, C. G., Lee, O., & Wakabayashi, Y. (2009). Minimum cycle cover and Chinese postman problems on mixed graphs with bounded tree-width. *Discrete Applied Mathematics*, 157(2), 272-279.
- Fierz, C. R. L. A., Armstrong, R. L., Durand, Y., Etchevers, P., Greene, E., McClung, D. M., ... & Sokratov, S. A. (2009). The international classification for seasonal snow on the ground. Fierz, C. & Baunach, T. (2000) Quantifying grain-shape changes in snow subjected to large temperature gradients. *Ann. Glaciol.* 31, 439–444.
- Finsterwalder, S. (1887). Der suldenferner. *Zeitschrift des Deutschen und Osterreichischen Alpenvereins*, 18, 72-89.
- Finnis, J. (2013). Projected impacts of climate change for the province of Newfoundland & Labrador.
- Fitzpatrick, N., Radić, V., & Menounos, B. (2017). Surface energy balance closure and turbulent flux parameterization on a mid-latitude mountain glacier, Purcell Mountains, Canada. *Frontiers in Earth Science*, 5, 67.
- Flanner, M. G., Shell, K. M., Barlage, M., Perovich, D. K., & Tschudi, M. A. (2011). Radiative forcing and albedo feedback from the Northern Hemisphere cryosphere between 1979 and 2008. *Nature Geoscience*, 4(3), 151-155.

- Flerchinger, G. N., & Hanson, C. L. (1989). Modeling soil freezing and thawing on a rangeland watershed. *Transactions of the ASAE*, 32(5), 1551-1554.
- Fletcher, C. G. (2005). Investigations into seasonal predictability of North Atlantic winter climate. University of London, University College London (United Kingdom).
- Fletcher, C. G., Zhao, H., Kushner, P. J., & Fernandes, R. (2012). Using models and satellite observations to evaluate the strength of snow albedo feedback. *Journal of Geophysical Research: Atmospheres*, 117(D11).
- Flin, F., Brzoska, J. B., Lesaffre, B., Coléou, C., & Pieritz, R. A. (2004). Three-dimensional geometric measurements of snow microstructural evolution under isothermal conditions. *Annals of glaciology*, 38, 39-44.
- Flood, I., & Kartam, N. (1994). Neural networks in civil engineering. I: Principles and understanding. *Journal of computing in civil engineering*, 8(2), 131-148.
- Freeze, R. A. (1971). Three-dimensional, transient, saturated-unsaturated flow in a groundwater basin. *Water Resources Research*, 7(2), 347-366.
- Freudiger, D., Kohn, I., Seibert, J., Stahl, K., & Weiler, M. (2017). Snow redistribution for the hydrological modeling of alpine catchments. *Wiley Interdisciplinary Reviews: Water*, 4(5), e1232.
- Freudiger, D., Kohn, I., Stahl, K., & Weiler, M. (2014). Large-scale analysis of changing frequencies of rain-on-snow events with flood-generation potential. *Hydrology and Earth System Sciences*, 18(7), 2695-2709.
- Galbraith, P. S., & Larouche, P. (2013). Trends and variability in air and sea surface temperatures in eastern Canada. *Aspects of Climate Change in the Northwest Atlantic off Canada*. Canadian Technical Report of Fisheries and Aquatic Science, 3045, 1-18.
- Gallet, J. C., Domine, F., Arnaud, L., Picard, G., & Savarino, J. (2010). Vertical profiles of the specific surface area of the snow at Dome C, Antarctica. *Cryos. Discuss*, 4(3), 1647-1708.

- Gallet, J. C., Domine, F., Zender, C. S., & Picard, G. (2009). Measurement of the specific surface area of snow using infrared reflectance in an integrating sphere at 1310 and 1550 nm. *The Cryosphere*, 3(2), 167-182.
- Geiger, R. (1966). *The climate near the ground* Harvard Univ. Press, Cambridge, Mass.
- Gelfan, A. L. E. X. A. N. D. E. R. (2006). Physically based model of heat and water transfer in frozen soil and its parameterization by basic soil data. IAHS publication, 303, 293.
- Gergely, M., Schneebeli, M., & Roth, K. (2010). First experiments to determine snow density from diffuse near-infrared transmittance. *Cold regions science and technology*, 64(2), 81-86.
- Geris, J., Comte, J. C., Franchi, F., Petros, A. K., Tirivarombo, S., Selepeng, A. T., & Villholth, K. G. (2022). Surface water-groundwater interactions and local land use control water quality impacts of extreme rainfall and flooding in a vulnerable semi-arid region of Sub-Saharan Africa. *Journal of Hydrology*, 609, 127834.
- Ghormley, J. A., & Hochanadel, C. J. (1971). Amorphous ice: Density and reflectivity. *Science*, 171(3966), 62-64.
- Giauque, W. F., & Stout, J. W. (1936). The Entropy of Water and the Third Law of Thermodynamics. The Heat Capacity of Ice from 15 to 273° K. *Journal of the American Chemical Society*, 58(7), 1144-1150.
- Giddings, J. C., & LaChapelle, E. (1962). The formation rate of depth hoar. *Journal of Geophysical Research*, 67(6), 2377-2383.
- Glen, J. W. (1997). Paterson, WSB 1994. *The physics of glaciers*. Oxford, New York, Tokyo, Pergamon, ix, 480 pp. ISBN 0-08037945 1, HB. ISBN 0-08037944 3, Flexicover. *Journal of Glaciology*, 43(145), 594-594.
- Goering, D. J. (2003). Passively cooled railway embankments for use in permafrost areas. *Journal of Cold Regions Engineering*, 17(3), 119-133
- Gogoi, M. M., & Babu, S. S. (2016, May). Aerosol optical properties over the Svalbard region of Arctic: ground-based measurements and satellite remote sensing. In

- Remote Sensing of the Atmosphere, Clouds, and Precipitation VI (Vol. 9876, pp. 194-200).
- Golubev, V. N., & Frolov, A. D. (2000). Model of structure and mechanical properties of dry granular snow. *Annals of Glaciology*, 31, 434-438.
- Gray DM, Male DH (1981) Handbook of snow, principles, processes, management, and use. Pergamon Press, New York
- Gray, D. M., & Landine, P. G. (1988). An energy-budget snowmelt model for the Canadian Prairies. *Canadian Journal of Earth Sciences*, 25(8), 1292-1303.
- Grell, G. A., Dudhia, J., & Stauffer, D. R. (1994). A description of the fifth-generation Penn State/NCAR Mesoscale Model (MM5).
- Grenfell, T. C. & Warren, S. G. (1999) Representation of a nonspherical ice particle by a collection of independent spheres for scattering and absorption of radiation. *J. Geophys. Res.* 104(D24), 31 697– 31 709.
- Grenier, C., Anbergen, H., Bense, V., Chanzy, Q., Coon, E., Collier, N., ... & Voss, C. (2018). Groundwater flow and heat transport for systems undergoing freeze-thaw: Intercomparison of numerical simulators for 2D test cases. *Advances in water resources*, 114, 196-218.
- Grundstein, A. J., and Leathers, D. J. (1999). A spatial analysis of snow-surface energy exchanges over the northern Great Plains of the United States in relation to synoptic scale forcing mechanisms. *Int. J. Climatol.* 19, 489–511.
- Grünewald, T., Wolfsperger, F., and Lehning, M. (2018). Snow farming: conserving snow over the summer season. *Cryosphere* 12, 385–400.
- Guide, E. U., & Multiphysics, C. O. M. S. O. L. (2006). V6. 0. Lowell, MA, USA: Diagnosys LLC.
- Guo, J., Li, Z., Li, F., & Zhang, S. (2021). Evaluation on snow coverage and snow depth simulated by VIC-CAS model based on multi-source remote sensing data in mountainous upper reach of the Shule River basin. *J. Glaciol. Geocryol*, 43, 650-661.

- Gururajan, M. P. (2015). Dry Snow Metamorphism.
- Gutmann, E. D., Larson, K. M., Williams, M. W., Nievinski, F. G., & Zavorotny, V. (2012). Snow measurement by GPS interferometric reflectometry: an evaluation at Niwot Ridge, Colorado. *Hydrological Processes*, 26(19), 2951-2961.
- Guyomarc'h, G., & Mérindol, L. (1998). Validation of an application for forecasting blowing snow. *Annals of Glaciology*, 26, 138-143.
- Hamlet, A. F., and Lettenmaier, D. P. (2007). Effects of 20th century warming and climate variability on flood risk in the western US. *Water Resour. Res.* 43: W06427.
- Hansen, A. C., & Foslien, W. E. (2015). A macroscale mixture theory analysis of deposition and sublimation rates during heat and mass transfer in dry snow. *The Cryosphere*, 9(5), 1857-1878.
- Harding, R. J., & Pomeroy, J. W. (1996). The energy balance of the winter boreal landscape. *Journal of Climate*, 9(11), 2778-2787.
- Hardy, J., & Albert, D. (1993). The Permeability of Temperate Snow. Paper presented at the Proceedings of the Annual Meeting-Eastern Snow Conference
- Harlan, R. L. (1973). Analysis of coupled heat-fluid transport in partially frozen soil. *Water Resources Research*, 9(5), 1314-1323.
- Hermassi, M., Valderrama, C., Gibert, O., Moreno, N., Font, O., Querol, X., ... & Cortina, J. L. (2016). Integration of powdered Ca-activated zeolites in a hybrid sorption-membrane ultrafiltration process for phosphate recovery. *Industrial & Engineering Chemistry Research*, 55(21), 6204-6212.
- Harr, R. D. (1981). Some characteristics and consequences of snowmelt during rainfall in western Oregon. *Journal of Hydrology*, 53(3-4), 277-304.
- Hartman, M. D., Baron, J. S., Lammers, R. B., Cline, D. W., Band, L. E., Liston, G. E., & Tague, C. (1999). Simulations of snow distribution and hydrology in a mountain basin. *Water Resources Research*, 35(5), 1587-1603.

- Hashin, Z., & Shtrikman, S. (1962). A variational approach to the theory of the effective magnetic permeability of multiphase materials. *Journal of applied Physics*, 33(10), 3125-3131.
- Hashin, Z., Shtrikman, S. (1962). A variational approach on the theory of the effective magnetic permeability of multiphase materials. *Journal of Applied Physics* 33, 3125-3131.
- He, S. W., Nan, Z. T., Zhang, L., & Yu, W. (2015). Spatial-temporal distribution of water and energy fluxes in the upper reaches of the Heihe River simulated with VIC model. *J. Glaciol. Geocryol*, 37, 211-225.
- Hedstrom, N. R., & Pomeroy, J. W. (1998). Accumulation of intercepted snow in the boreal forest: measurements and modelling. *Hydrological Processes*, 12(1), 611-1.
- Heusser, C. J. (1995). Late-Quaternary vegetation response to climatic-glacial forcing in North Pacific America. *Physical Geography*, 16(2), 118-149.
- Hirashima, H., Yamaguchi, S., Sato, A., & Lehning, M. (2010). Numerical modeling of liquid water movement through layered snow based on new measurements of the water retention curve. *Cold Regions Science and Technology*, 64(2), 94-103.
- Hock, R. (1999). A distributed temperature-index ice-and snowmelt model including potential direct solar radiation. *Journal of glaciology*, 45(149), 101-111.
- Hori, M., Aoki, T., Tanikawa, T., Motoyoshi, H., Hachikubo, A., Sugiura, K., ... & Takahashi, F. (2006). In-situ measured spectral directional emissivity of snow and ice in the 8–14 μm atmospheric window. *Remote Sensing of Environment*, 100(4), 486-502.
- Hu, X., Yang, J., Tu, Y., Su, Z., Guan, Q., & Ma, Z. (2024). Hydrogel-Based Interfacial Solar-Driven Evaporation: Essentials and Trails. *Gels*, 10(6), 371.
- Hyun, S. W., Kim, S., Jeong, H., Ko, H. S., & Shin, D. H. (2024). Development of snow removal system using embedded piped inside road with solar thermal energy collector and packed bed latent heat thermal energy storage. *Journal of Energy Storage*, 83, 110737.

- Il Jeong, D., & Sushama, L. (2018). Rain-on-snow events over North America based on two Canadian regional climate models. *Climate Dynamics*, 50, 303-316.
- Illangasekare, T. H., Walter Jr, R. J., Meier, M. F., & Pfeffer, W. T. (1990). Modeling of meltwater infiltration in subfreezing snow. *Water Resources Research*, 26(5), 1001-1012.
- Immerzeel, W. W., Van Beek, L. P., & Bierkens, M. F. (2010). Climate change will affect the Asian water towers. *science*, 328(5984), 1382-1385.
- Izumi, K., & Huzioka, T. (1975). Studies of metamorphism and thermal conductivity of snow. I.
- Jaafar, H., & Picot, J. J. C. (1970). Thermal conductivity of snow by a transient state probe method. *Water Resources Research*, 6(1), 333-335.
- Jafari, M., Sharma, V., & Lehning, M. (2022). Convection of water vapour in snowpacks. *Journal of Fluid Mechanics*, 934, A38.
- Jansson, M. (1901). Über die Wärmeleitungsfähigkeit des Schnees. *Ofversigt K. Vetenskapsakad. Forh.*, 58, 207-222.
- Jansson, P. E., & Halldin, S. (1979). Model for annual water and energy flow in a layered soil. In *Developments in Agricultural and Managed Forest Ecology* (Vol. 9, pp. 145-163). Elsevier.
- Jansson, P. E., & Moon, D. S. (2001). A coupled model of water, heat and mass transfer using object orientation to improve flexibility and functionality. *Environmental Modelling & Software*, 16(1), 37-46.
- Jin, Z., Charlock, T. P., Yang, P., Xie, Y., & Miller, W. (2008). Snow optical properties for different particle shapes with application to snow grain size retrieval and MODIS/CERES radiance comparison over Antarctica. *Remote Sensing of Environment*, 112(9), 3563-3581.
- Jóhannesson, T., Sigurdsson, O., Laumann, T., & Kennett, M. (1995). Degree-day glacier mass-balance modelling with applications to glaciers in Iceland, Norway, and Greenland. *Journal of Glaciology*, 41(138), 345-358.

- Johanson, R. C., Imhoff, J. C., Kittle, J. L., & Donigan, A. S. (1984). Hydrological Simulation Program--FORTRAN(HSPF): User's Manual for Release 8. 0. EPA-600/3-84-006 June 1984. Environmental Protection Agency, Athens, GA. 767 p, 138 p, 49 Ref, 5 Append. Contract/Grant, (68-01).
- Johnson, J. B., Sturm, M. A. T. T. H. E. W., Perovich, D. K., & Benson, C. S. (1987). Field observations of thermal convection in a subarctic snow cover. *Intl Assoc. Hydrol. Sci. Publ*, 162, 105-118.
- Jordan, D. R. (1991). A new reading of a phylactery from Beirut. *Zeitschrift für Papyrologie und Epigraphik*, 61-69.
- Jordan, R. E. (1991). A one-dimensional temperature model for a snow cover: Technical documentation for SNTHERM. 89.
- Jordan, R. E., Andreas, E. L., & Makshtas, A. P. (1999). Heat budget of snow-covered sea ice at North Pole 4. *Journal of Geophysical Research: Oceans*, 104(C4), 7785-7806
- Jost, G., Moore, R. D., Smith, R., & Gluns, D. R. (2012). Distributed temperature-index snowmelt modelling for forested catchments. *Journal of Hydrology*, 420, 87-101.
- Juras, R., Pavlásek, J., Vitvar, T., Šanda, M., Holub, J., Jankovec, J., & Linda, M. (2016). Isotopic tracing of the outflow during artificial rain-on-snow event. *Journal of Hydrology*, 541, 1145-1154.
- Kaimal, J. C., & Finnigan, J. J. (1994). *Atmospheric boundary layer flows: their structure and measurement*. Oxford university press.
- Kane, H. S. (1969). A neutron probe for the determination of snow density and its use in Antarctica. Research Foundation and the Institute of Polar Studies, The Ohio State University.
- Kargl, G., Zohrer, A., (2006). Reconstruction of grain size distributions in granular and regolith soil with ground penetrating instruments. *Geophysical Research Abstracts*, vol. 8, 04280.
- Kattelmann, R. (1985). Macropores in snowpacks of Sierra Nevada. *Annals of Glaciology*, 6, 272-273.

- Kattelman, R. (1997). Flooding from rain-on-snow events in the Sierra Nevada. IAHS Publications-Series of Proceedings and Reports-Intern Assoc Hydrological Sciences, 239, 59-66.
- Katto, Y., & Masuoka, T. (1967). Criterion for the onset of convective flow in a fluid in a porous medium. *International Journal of Heat and Mass Transfer*, 10(3), 297-309.
- Keeler, C. M. (1964). Relationship between Climate, Ablation, and Run-Off on an Arctic Glacier. McGill University (Canada).
- Kelly, R. E., & Pal, D. (1978). Thermal convection with spatially periodic boundary conditions: resonant wavelength excitation. *Journal of Fluid Mechanics*, 86(3), 433-456.
- Kendra, J. R., Ulaby, F. T., & Sarabandi, K. (1994). Snow probe for in situ determination of wetness and density. *IEEE Transactions on Geoscience and Remote Sensing*, 32(6), 1152-1159.
- Kerbrat, M., Pinzer, B., Huthwelker, T., Gäggeler, H. W., Ammann, M., & Schneebeli, M. (2008). Measuring the specific surface area of snow with X-ray tomography and gas adsorption: comparison and implications for surface smoothness. *Atmospheric Chemistry and Physics*, 8(5), 1261-1275.
- Kersten, M. S. (1949). Thermal properties of soils.
- Kiedrzyńska, E., Kiedrzyński, M., & Zalewski, M. (2015). Sustainable floodplain management for flood prevention and water quality improvement. *Natural Hazards*, 76, 955-977.
- Klever, N. (1985). Air and water-vapour convection in snow. *Annals of glaciology*, 6, 39-42.
- Klute, A. (1988). *Methods of soil analysis 2d ed., pt. 1; physical and mineralogical methods*. *Soil Science*, 146(2), 138.
- Knox, S. H., Carey, S. K., & Humphreys, E. R. (2012). Snow surface energy exchanges and snowmelt in a shrub-covered bog in eastern Ontario, Canada. *Hydrological Processes*, 26(12), 1876-1890.

- Kodaira, N., & Inada, M. (1955). Measurement of snowfall intensity by radar. *Papers in Meteorology and Geophysics*, 6(2), 126-129.
- Kojima, K. (1954) Visco-elastic property of snow. *Low Temp. Sci., Series A*, 12.
- Kojima, K. (1956). Viscous compression of natural snow-layer II. *Low Temperature Science*, 15, 117-135.
- Kojima, K. (1957). Viscous compression of natural snow-layers III. *Low Temperature Science*, 16, 167-196.
- Kojima, K. (1958). Sekisetsuso no nensei asshuku. IV [Viscous compression of natural snow layers. IV]. *Low Temp. Sci.*, 53-64.
- Kokhanovsky, A. A. and Zege, E., (2004): Scattering optics of snow, *Appl. Optics*, 43, 1589–1602.
- Kokhanovsky, A., & Schreier, M. (2009). The determination of snow specific surface area, albedo and effective grain size using AATSR space-borne measurements. *International Journal of Remote Sensing*, 30(4), 919-933.
- Kokhanovsky, A., Rozanov, V. V., Aoki, T., Odermatt, D., Brockmann, C., Krüger, O., ... & Hori, M. (2011). Sizing snow grains using backscattered solar light. *International Journal of Remote Sensing*, 32(22), 6975-7008.
- Kolomyts, E. G. (1984) *Kristallo-morfologicheskii atlas snega: posobie dlya snegolavinykh stantsii*. [Acrytallomorphological atlas of snow: a handbook for snow-avalanche stations]. Gidrometeoizdat, Leningrad, Russia (in Russian).
- Kondrat'eva, A. S. (1954). Thermal conductivity of the snow cover and physical processes caused by the temperature gradient (p. 0012). *Snow, Ice and Permafrost Research Establishment, Corps of Engineers, US Army*.
- Kozeny, J. (1927). *Über kapillare Leitung des Wassers im Boden:(Aufstieg, Versickerung und Anwendung auf die Bewässerung): Hölder-Pichler-Tempsky*.
- Kratzert, F., Klotz, D., Brenner, C., Schulz, K., & Herrnegger, M. (2018). Rainfall–runoff modelling using long short-term memory (LSTM) networks. *Hydrology and Earth System Sciences*, 22(11), 6005-6022.

- Kustas, W. P., Rango, A., & Uijlenhoet, R. (1994). A simple energy budget algorithm for the snowmelt runoff model. *Water resources research*, 30(5), 1515-1527.
- Kuusisto, E. (1980). On the values and variability of degree-day melting factor in Finland. *Hydrology Research*, 11(5), 235-242.
- Kuvaeva, G. M. (1975). Physical properties of snow cover of the Greater Caucasus.
- Kuvaeva, G. M., Sulakvelidze, G. K., Chitadze, V. S., Chotorlishvili, L. S., & El'Mesov, A. M. (1975). Physical properties of snow cover of the Greater Caucasus.
- Kuyucak, N. (2021). Water in Mining and Environment for Sustainability. *Mine Water and the Environment*, 40(4), 815-817.
- Lachance, O. (2014). Conductivité thermique et perméabilité intrinsèque de la neige compactée. Université Laval
- Lafleur PM, Hember RA, Admiral SW, Roulet NT. (2005). Annual and seasonal variability in evapotranspiration and water table at a shrub-covered bog in southern Ontario, Canada. *Hydrological Processes* 19(18): 3533– 3550.
- Laliberte, G. E., Corey, A. T., & Brooks, R. H. (1966). Properties of unsaturated porous media (Doctoral dissertation, Colorado State University. Libraries).
- Lange, M.A. (1985). Measurements of thermal parameters in Antarctic snow and firn. *Ann. Glaciol.*, 6, 100-104.
- Langlois, A., Kohn, J., Royer, A., Cliche, P., Brucker, L., Picard, G., ... & Willemet, J. M. (2009). Simulation of snow water equivalent (SWE) using thermodynamic snow models in Québec, Canada. *Journal of Hydrometeorology*, 10(6), 1447-1463.
- Lapwood, E. (1948, October). Convection of a fluid in a porous medium. In *Mathematical Proceedings of the Cambridge Philosophical Society* (Vol. 44, No. 4, pp. 508-521). Cambridge University Press.
- Latenser, M., & Schneebeli, M. (2003). Long-term snow climate trends of the Swiss Alps (1931–99). *International Journal of Climatology: A Journal of the Royal Meteorological Society*, 23(7), 733-750.

- Lazri, M., Labadi, K., Brucker, J. M., & Ameer, S. (2020). Improving satellite rainfall estimation from MSG data in Northern Algeria by using a multi-classifier model based on machine learning. *Journal of Hydrology*, 584, 124705.
- Leavesley, G. H. (1984). *Precipitation-runoff modeling system: User's manual* (Vol. 83, No. 4238). US Department of the Interior.
- Leavesley, G. H., & Stannard, L. G. (1995). The precipitation-runoff modeling system-PRMS. *Computer models of watershed hydrology.*, 281-310.
- Legagneux, L., Cabanes, A., & Dominé, F. (2002). Measurement of the specific surface area of 176 snow samples using methane adsorption at 77 K. *Journal of Geophysical Research: Atmospheres*, 107(D17), ACH-5.
- Legagneux, L., Lauzier, T., Domin, F., Kuhs, W. F., Heinrichs, T., & Techmer, K. (2003). Rate of decay of specific surface area of snow during isothermal experiments and morphological changes studied by scanning electron microscopy. *Canadian Journal of Physics*, 81(1-2), 459-468
- Lehning, M., Bartelt, P., Brown, B., Fierz, C., & Satyawali, P. (2002). A physical SNOWPACK model for the Swiss avalanche warning: Part II. Snow microstructure. *Cold regions science and technology*, 35(3), 147-167.
- Lehning, M., Doorschot, J., & Bartelt, P. (2000). A snowdrift index based on SNOWPACK model calculations. *Annals of Glaciology*, 31, 382-386.
- Lehning, M., Völksch, I., Gustafsson, D., Nguyen, T. A., Stähli, M., & Zappa, M. (2006). ALPINE3D: a detailed model of mountain surface processes and its application to snow hydrology. *Hydrological Processes: An International Journal*, 20(10), 2111-2128.
- Lesaffre, B., Pougatch, E. & Martin, E. (1998) Objective determination of snow-grain characteristics from images. *Ann. Glaciol.* 26, 112–118.
- Li, D., Lettenmaier, D. P., Margulis, S. A., & Andreadis, K. (2019). The role of rain-on-snow in flooding over the conterminous United States. *Water Resources Research*, 55(11), 8492-8513.

- Li, J., Guala, M., & Hong, J. (2022). Snow particle analyzer for simultaneous measurements of snow density and morphology. arXiv preprint arXiv:2209.11129.
- Li, P., Zha, Y., Shi, L., Tso, C. H. M., Zhang, Y., & Zeng, W. (2020). Comparison of the use of a physical-based model with data assimilation and machine learning methods for simulating soil water dynamics. *Journal of Hydrology*, 584, 124692.
- Li, X., & Koike, T. (2003). Frozen soil parameterization in SiB2 and its validation with GAME-Tibet observations. *Cold Regions Science and Technology*, 36(1-3), 165-182.
- Liang, X., Lettenmaier, D. P., Wood, E. F., & Burges, S. J. (1994). A simple hydrologically based model of land surface water and energy fluxes for general circulation models. *Journal of Geophysical Research: Atmospheres*, 99(D7), 14415-14428.
- Light, P. (1941). Analysis of high rates of snow melting. *Trans. AGU*, 195-205.
- Link, T., & Marks, D. (1999). Distributed simulation of snowcover mass-and energy-balance in the boreal forest. *Hydrological Processes*, 13(14-15), 2439-2452.
- Lipiec, J., & Hatano, R. (2003). Quantification of compaction effects on soil physical properties and crop growth. *Geoderma*, 116(1-2), 107-136.
- List, R. J. (1951). *Smithsonian meteorological tables*. Smithsonian miscellaneous collections.
- Lister, H., & Taylor, P. F. (1961). Heat balance and ablation on an Arctic glacier. *CA Reitzel*.
- Liston, G. E., & Sturm, M. (1998). A snow-transport model for complex terrain. *Journal of Glaciology*, 44(148), 498-516.
- Liu, Q., & Hu, R. (2017). Simulation of Heat and Mass Transfer during Artificial Ground Freezing in Saturated Saline Groundwater. In *Excerpt from the Proceedings of the 2017 COMSOL Conference in Rotterdam*.
- Liu, S., XIE, Z., Song, G., Ma, L., & Ageta, Y. (1996). Mass balance of Kangwure (flat-top) Glacier on the north side of Mt. Xixiabangma, China. *Bulletin of glacier research*, (14), 37-43.

- Loescher, H. W., Hanson, C. V., & Ocheltree, T. W. (2009). The psychrometric constant is not constant: A novel approach to enhance the accuracy and precision of latent energy fluxes through automated water vapor calibrations. *Journal of Hydrometeorology*, 10(5), 1271-1284.
- López-Moreno, J. I., Pomeroy, J., Revuelto, J., and Vicente-Serrano, S. M. (2013). Response of snow processes to climate change: spatial variability in a small basin in the Spanish Pyrenees. *Hydrol. Process.* 27, 2637–2650.
- Lougeay, R.L. (1969). Micro-climatological Studies Over the Seward Glacier Snowpack. *Climatological Investigations in the Icefield Ranges, Summer 1965*. Washington, D.C.: Research Paper No. 54, Arctic Institute of North America, pp. 51-102.
- Lu, H., Wei, W. S., Liu, M., Han, X., & Hong, W. (2015). Energy budget over seasonal snow surface at an open site and beneath forest canopy openness during the snowmelt period in western Tianshan Mountains, China. *Journal of Mountain Science*, 12, 298-312.
- Luce, C. H., Tarboton, D. G., & Cooley, K. R. (1998). The influence of the spatial distribution of snow on basin-averaged snowmelt. *Hydrological Processes*, 12(10-11), 1671-1683.
- Lundberg, A., Granlund, N., & Gustafsson, D. (2010). Towards automated ‘Ground truth’ snow measurements—A review of operational and new measurement methods for Sweden, Norway, and Finland. *Hydrological processes*, 24(14), 1955-1970.
- Lundy, C. C., Edens, M. Q., & Brown, R. L. (2002). Measurement of snow density and microstructure using computed tomography. *Journal of Glaciology*, 48(161), 312-316.
- Luo, L., Robock, A., Vinnikov, K. Y., Schlosser, C. A., Slater, A. G., Boone, A., ... & Yang, Z. L. (2003). Effects of frozen soil on soil temperature, spring infiltration, and runoff: Results from the PILPS 2 (d) experiment at Valdai, Russia. *Journal of Hydrometeorology*, 4(2), 334-351.

- Lyapustin, A., Tedesco, M., Wang, Y., Aoki, T., Hori, M., & Kokhanovsky, A. (2009). Retrieval of snow grain size over Greenland from MODIS. *Remote Sensing of Environment*, 113(9), 1976-1987.
- MacDonald, M. K., Pomeroy, J. W., & Pietroniro, A. (2010). On the importance of sublimation to an alpine snow mass balance in the Canadian Rocky Mountains. *Hydrology and Earth System Sciences*, 14(7), 1401-1415.
- Magnusson, J., Jonas, T., Lopez-Moreno, I., & Lehning, M. (2010). Snow cover response to climate change in a high alpine and half-glacierized basin in Switzerland. *Hydrology research*, 41(3-4), 230-240.
- Maier, H. R., & Dandy, G. C. (2000). Neural networks for the prediction and forecasting of water resources variables: a review of modelling issues and applications. *Environmental modelling & software*, 15(1), 101-124.
- Male, D. H., & Granger, R. J. (1979). Energy mass fluxes at the snow surface in a prairie environment.
- Male, D. H., & Granger, R. J. (1981). Snow surface energy exchange. *Water Resources Research*, 17(3), 609-627.
- Malnes, E., Buanes, A., Nagler, T., Bippus, G., Gustafsson, D., Schiller, C., & Wiesmann, A. (2015). User requirements for the snow and land ice services—CryoLand. *The Cryosphere*, 9(3), 1191-1202.
- Marchenko, S., Cheng, G., Lötstedt, P., Pohjola, V., Pettersson, R., Van Pelt, W., & Reijmer, C. (2019). Thermal conductivity of firn at Lomonosovfonna, Svalbard, derived from subsurface temperature measurements. *The Cryosphere*, 13(7), 1843-1859.
- Margulis, S. A., Cortés, G., Giroto, M., & Durand, M. (2016). A Landsat-era Sierra Nevada snow reanalysis (1985–2015). *Journal of Hydrometeorology*, 17(4), 1203-1221.

- Marks D, Domingo J, Susong D, Link T, Garen D (1999) A spatially distributed energy balance snowmelt model for application in mountain basins. *Hydrological Processes* 13:1935–1959
- Marks, D. G. (1988). *Climate, energy exchange, and snowmelt in Emerald Lake watershed, Sierra Nevada*. University of California, Santa Barbara.
- Marks, D., & Dozier, J. (1992). Climate and energy exchange at the snow surface in the alpine region of the Sierra Nevada: 2. Snow cover energy balance. *Water Resources Research*, 28(11), 3043-3054.
- Marks, D., & Winstral, A. (2001). Comparison of snow deposition, the snow cover energy balance, and snowmelt at two sites in a semiarid mountain basin. *Journal of Hydrometeorology*, 2(3), 213-227.
- Marks, D., Dozier, J. (1992). Climate and energy exchange at the snow surface in the alpine region of the Sierra Nevada: 2. Snow cover energy balance. *Water Resources Research*, 28(11), 3043-3054
- Marks, D., Kimball, J., Tingey, D., & Link, T. (1998). The sensitivity of snowmelt processes to climate conditions and forest cover during rain-on-snow: A case study of the 1996 Pacific Northwest flood. *Hydrological Processes*, 12(10-11), 1569-1587.
- Marks, D., Kimball, J., Tingey, D., & Link, T. (1998). The sensitivity of snowmelt processes to climate conditions and forest cover during rain-on-snow: A case study of the 1996 Pacific Northwest flood. *Hydrological Processes*, 12(10-11), 1569-1587.
- Marks, D., Winstral, A., Flerchinger, G., Reba, M., Pomeroy, J., Link, T., & Elder, K. (2008). Comparing simulated and measured sensible and latent heat fluxes over snow under a pine canopy to improve an energy balance snowmelt model. *Journal of Hydrometeorology*, 9(6), 1506-1522.
- Marsh, P. (1991). Water flux in melting snow covers. *Advances in porous media*, 1, 61-124

- Marsh, P., & Pomeroy, J. W. (1996). Meltwater fluxes at an arctic forest-tundra site. *Hydrological Processes*, 10(10), 1383-1400.
- Marshall, S. E. (1987). Parameterization of snow albedo for climate models. *IAHS Publ.*, 166, 43-50.
- Marshall, H. P., Conway, H., & Rasmussen, L. A. (1999). Snow densification during rain. *Cold Regions Science and Technology*, 30(1-3), 35-41.
- Martinec, J. (1975). Snowmelt-runoff model for stream flow forecasts. *Hydrology Research*, 6(3), 145-154.
- Martinec, J., & Rango, A. (1986). Parameter values for snowmelt runoff modelling. *Journal of hydrology*, 84(3-4), 197-219.
- Mary, A., Dumont, M., Dedieu, J. P., Durand, Y., Sirguey, P., Milhem, H., ... & Morin, S. (2013). Intercomparison of retrieval algorithms for the specific surface area of snow from near-infrared satellite data in mountainous terrain, and comparison with the output of a semi-distributed snowpack model. *The Cryosphere*, 7(2), 741-761.
- Matson, M., & Wiesnet, D. R. (1981). New data base for climate studies. *Nature*, 289 (5797), 451-456.
- Matzl, M., & Schneebeli, M. (2006). Measuring specific surface area of snow by near-infrared photography. *Journal of Glaciology*, 52(179), 558-564.
- Matzl, M., & Schneebeli, M. (2010). Stereological measurement of the specific surface area of seasonal snow types: Comparison to other methods, and implications for mm-scale vertical profiling. *Cold Regions Science and Technology*, 64(1), 1-8.
- Matzl, M., & Schneebeli, M. (2010). Stereological measurement of the specific surface area of seasonal snow types: Comparison to other methods, and implications for mm-scale vertical profiling. *Cold Regions Science and Technology*, 64(1), 1-8.
- Mätzler, C. (2002) Relation between grain-size and correlation length of snow. *J. Glaciol.* 48(162), 461-466.
- McCabe, G. J., Clark, M. P., & Hay, L. E. (2007). Rain-on-snow events in the western United States. *Bulletin of the American Meteorological Society*, 88(3), 319-328.

- McKay, G. A. (1970). Precipitation. Handbook on the principles of hydrology. Edited by DM Gray. Secretariat, Canadian National Committee for the International Hydrological Decade, Saskatoon, Sask. pp. II
- Meinicke, S., Dubil, K., Wetzel, T., & Dietrich, B. (2020). Characterization of heat transfer in consolidated, highly porous media using a hybrid-scale CFD approach. *International Journal of Heat and Mass Transfer*, 149, 119201.
- Melloh, R. A., Hardy, J. P., Bailey, R. N., & Hall, T. J. (2002). An efficient snow albedo model for the open and sub-canopy. *Hydrological Processes*, 16(18), 3571-3584.
- Mellor, M. (1964). Properties of snow: US Army Materiel Command, Cold Regions Research & Engineering Laboratory
- Mellor, M. (1974). A review of basic snow mechanics (pp. 251-291). Hanover, NH: US Army Cold Regions Research and Engineering Laboratory.
- Mendoza Zúñiga, P., Musselman, K. N., Revuelto, J., Deems, J. S., López Moreno, J. I., & McPhee, J. (2020). Interannual and seasonal variability of snow depth scaling behavior in a subalpine catchment.
- Merz, R., & Blöschl, G. (2003). A process typology of regional floods. *Water resources research*, 39(12).
- Minkowycz, W. J., Haji-Sheikh, A., & Vafai, K. F. (1999). On departure from local thermal equilibrium in porous media due to a rapidly changing heat source: the Sparrow number. *International journal of heat and mass transfer*, 42(18), 3373-3385.
- Monteith, J. L. (1973). *Principles of environmental physics*.
- Morid, S. (2000). Snowmelt-Runoff simulation for snowbound ungauged catchments (Doctoral dissertation, IIT Delhi).
- Morid, S., Gosain, A. K., & Keshari, A. K. (2000, December). An algorithm for monitoring snow water equivalent in ungauged catchments using GIS. In Submitted to International Conference of Integrated Water Resource Management.

- Morin, S., Domine, F., Arnaud, L., & Picard, G. (2010). In-situ monitoring of the time evolution of the effective thermal conductivity of snow. *Cold Regions Science and Technology*, 64(2), 73-80
- Morin, S., Domine, F., Dufour, A., Lejeune, Y., Lesaffre, B., Willemet, J. M., ... & Jacobi, H. W. (2013). Measurements and modeling of the vertical profile of specific surface area of an alpine snowpack. *Advances in water resources*, 55, 111-120.
- Morland, L., Kelly, R., & Morris, E. (1990). A mixture theory for a phase-changing snowpack. *Cold Regions Science and Technology*, 17(3), 271-285
- Morris, E. (1987). Modelling of water flow through snowpacks *Seasonal Snowcovers: Physics, Chemistry, Hydrology* (pp. 179-208): Springer.
- Morris, E. M., & Cooper, J. D. (2003). Density measurements in ice boreholes using neutron scattering. *Journal of Glaciology*, 49(167), 599-604.
- Mosley-Thompson, E., McConnell, J. R., Bales, R. C., Li, Z., Lin, P. N., Steffen, K., ... & Bathke, D. (2001). Local to regional-scale variability of annual net accumulation on the Greenland ice sheet from PARCA cores. *Journal of Geophysical Research: Atmospheres*, 106(D24), 33839-33851.
- Mote, P. W. (2006). Climate-driven variability and trends in mountain snowpack in Western North America. *J. Clim.* 19, 6209–6220.
- Mott, R., & Lehning, M. (2010). Meteorological modeling of very high-resolution wind fields and snow deposition for mountains. *Journal of Hydrometeorology*, 11(4), 934-949.
- Mott, R., Faure, F., Lehning, M., Henning, L. Ö. W. E., Hynek, B., Michlmayer, G., & Schöner, W. (2008). Simulation of seasonal snow-cover distribution for glacierized sites on Sonnblick, Austria, with the Alpine3D model. *Annals of Glaciology*, 49, 155-160.
- Mott, R., Vionnet, V., & Grünewald, T. (2018). The seasonal snow cover dynamics: review on wind-driven coupling processes. *Frontiers in Earth Science*, 6, 197.

- Mualem, Y. (1976). A new model for predicting the hydraulic conductivity of unsaturated porous media. *Water Resources Research*, 12(3), 513-522.
- Mueller, S. (2015). What is Goldsim? Boliden Mining, Sweden. WaterSmart-Seminar on Management of water balance in mining areas, 28th of August 2015. Finnish Environment Institute, Helsinki.
- Multiphysics, C. O. M. S. O. L. (2008). Variably Saturated Flow and Transport: Sorbing Solute. Earth Science Module Model Library.
- Multiphysics, C. O. M. S. O. L. (2019). Frozen Inclusion. COMSOL Multiphysics, 6.1.
- Munneke, P. K., Ligtenberg, S., Noel, B., Howat, I., Box, J. E., Mosley-Thompson, E., ... & van den Broeke, M. R. (2015, December). Taking the Firm into Account: Elevation Change of the Greenland Ice Sheet due to Surface Mass Balance and Firm Processes, 1960-2014. In 2015 AGU Fall Meeting. AGU.
- Munro, D. S., & Young, G. J. (1982). An operational net shortwave radiation model for glacier basins. *Water Resources Research*, 18(2), 220-230.
- Musselman, K. N., Clark, M. P., Liu, C., Ikeda, K., & Rasmussen, R. (2017). Slower snowmelt in a warmer world. *Nature Climate Change*, 7(3), 214-219.
- Musselman, K. N., Lehner, F., Ikeda, K., Clark, M. P., Prein, A. F., Liu, C., ... & Rasmussen, R. (2018). Projected increases and shifts in rain-on-snow flood risk over western North America. *Nature Climate Change*, 8(9), 808-812.
- Nakai, Y., Sakamoto, T., Terajima, T., Kitamura, K., & Shirai, T. (1999). Energy balance above a boreal coniferous forest: a difference in turbulent fluxes between snow-covered and snow-free canopies. *Hydrological Processes*, 13(4), 515-529.
- Nakano, Y., & Froula, N. H. (1973, July). Sound and shock transmission in frozen soils. In *Proceedings of the 2nd International Conference on Permafrost, North American Contribution, Yakutsk, USSR* (pp. 359-369).
- Nakaya, U., & Kuroiwa, D. (1970). Physical properties and internal structure of Greenland snow (Vol. 89). Corps of Engineers, US Army Cold Regions Research and Engineering Laboratory.

- Narita, H. (1971). Specific surface of deposited snow II, Low Temp.
- Negi, H. S., & Kokhanovsky, A. (2011). Retrieval of snow grain size and albedo of western Himalayan snow cover using satellite data. *The Cryosphere*, 5(4), 831-847.
- Nelson, J. (1998). Sublimation of ice crystals. *Journal of the atmospheric sciences*, 55(5), 910-919.
- Nield, D. A. (1968). Onset of thermohaline convection in a porous medium. *Water Resources Research*, 4(3), 553-560.
- Nield, D. A. (1998). Effects of local thermal nonequilibrium in steady convective processes in a saturated porous medium: forced convection in a channel. *Journal of porous media*, 1(2), 181-186.
- Niittynen, P., & Luoto, M. (2018). The importance of snow in species distribution models of arctic vegetation. *Ecography*, 41(6), 1024-1037.
- Niu, G. Y., & Yang, Z. L. (2006). Effects of frozen soil on snowmelt runoff and soil water storage at a continental scale. *Journal of Hydrometeorology*, 7(5), 937-952.
- Obled, C., & Harder, H. (1978). A review of snow melt in the mountain environment. *Proceedings, Modeling of Snow Cover Runoff*, 179-204.
- Ocampo Melgar, D., & Meza, F. J. (2020). Exploring the fingerprints of past rain-on-snow events in a central Andean Mountain range basin using satellite imagery. *Remote Sensing*, 12(24), 4173.
- Ochsner, T. E., Horton, R., & Ren, T. (2001). A new perspective on soil thermal properties. *Soil science society of America Journal*, 65(6), 1641-1647.
- Oerlemans, J., Anderson, B., Hubbard, A., Huybrechts, P., Johannesson, T., Knap, W. H., ... & Zuo, Z. (1998). Modelling the response of glaciers to climate warming. *Climate dynamics*, 14, 267-274.
- Olyphant, G. A. (1984). Insolation topoclimates and potential ablation in alpine snow accumulation basins: Front Range, Colorado. *Water Resources Research*, 20(4), 491-498.

- Osborn, G. (1982). Handbook of snow: Principles, processes, management & use, edited by DM Gray and DH Male. *Arctic*, 35(2), 346-346.
- Östin, R., & Andersson, S. (1991). Frost growth parameters in a forced air stream. *International Journal of Heat and Mass Transfer*, 34(4-5), 1009-1017.
- Painter, T. H., Molotch, N. P., Cassidy, M., Flanner, M., & Steffen, K. (2007). Contact spectroscopy for determination of stratigraphy of snow optical grain size. *Journal of Glaciology*, 53(180), 121-127.
- Pall, P., Tallaksen, L. M., & Stordal, F. (2019). A climatology of rain-on-snow events for Norway. *Journal of Climate*, 32(20), 6995-7016.
- Palm, E., & Tveitereid, M. (1979). On heat and mass flux through dry snow. *Journal of Geophysical Research: Oceans*, 84(C2), 745-749.
- Paltridge, G. W., & CMR, P. (1976). *Radiative Processes in Meteorology and Climatology*.
- Pawłowski, M., Lipiec, J., & Debicki, R. (1996). Computer-aided penetrometer system for measuring soil strength. *Polish Journal of Soil Science*, 29(1), 1-7.
- Pedersen, A., Speed, J. D. M., and Tombre, I. M. (2013). Prevalence of grubbing in the arctic tundra increases with the pink-footed goose population expansion. *Polar Biol.* 36, 1569–1575.
- Pellicciotti, F., Brock, B., Strasser, U., Corripio, J., Burlando, P., & Funk, M. (2003, December). The Distributed Application of an Enhanced Temperature-Index Melt Model Including Albedo and Global Radiation. In *AGU Fall Meeting Abstracts* (Vol. 2003, pp. C22B-02).
- Picard, G., Arnaud, L., Domine, F., & Fily, M. (2009). Determining snow specific surface area from near-infrared reflectance measurements: Numerical study of the influence of grain shape. *Cold Regions Science and Technology*, 56(1), 10-17.
- PIEVC [Public Infrastructure Engineering Vulnerability Committee] (2008): Water resources public infrastructure vulnerability assessment for Placentia, Newfoundland; Appendix B-2 in *Adapting to Climate Change: Canada's First*

- National Engineering Vulnerability Assessment of Public Infrastructure; Engineers Canada, 76 p.
- Picard, G., Brucker, L., Fily, M., Gallée, H., & Krinner, G. (2009). Modeling time series of microwave brightness temperature in Antarctica. *Journal of Glaciology*, 55(191), 537-551.
- Pitman, D., & Zuckerman, B. (1968). Effective Thermal Conductivity of Snow at -88 C, -27 C and -5 C. SAO Special Report, 267.
- Pitman, D., & Zuckerman, B. (1968). Effective Thermal Conductivity of Snow at -88 C, -27 C and -5 C. SAO Special Report, 267
- Pohl, S., Davison, B., Marsh, P., & Pietroniro, A. (2005). Modelling spatially distributed snowmelt and meltwater runoff in a small Arctic catchment with a hydrology land-surface scheme (WATCLASS). *Atmosphere-Ocean*, 43(3), 193-211.
- Pollock, E. (2009). Glaciers of the Canadian Rockies and their response to global climate change.
- Pomeroy, J. W., & Brun, E. (2001). Physical properties of snow. *Snow ecology: An interdisciplinary examination of snow-covered ecosystems*, 45, 118.
- Pomeroy, J. W., & Essery, R. L. H. (1999). Turbulent fluxes during blowing snow: field tests of model sublimation predictions. *Hydrological Processes*, 13(18), 2963-2975.
- Pomeroy, J. W., & Goodison, B. E. (1997). Winter and snow. *The surface climates of Canada*, 68-100.
- Pomeroy, J. W., & Gray, D. M. (1995). Snowcover accumulation, relocation, and management. (No Title).
- Pomeroy, J. W., Gray, D. M., & Landine, P. G. (1993). The prairie blowing snow model: characteristics, validation, operation. *Journal of Hydrology*, 144(1-4), 165-192.
- Pool, S., Molnar, P., Hunkeler, D., Lienert, C., Peleg, N., Sinreich, M., ... & Hosi, S. 13 *Hydrology and Hydrogeology*.

- Powers, D. J., Colbeck, S. C., & O'Neill, K. (1985). Thermal convection in snow. COLD REGIONS RESEARCH AND ENGINEERING LAB HANOVER NH.
- Powers, D., O'Neill, K., & Colbeck, S. C. (1985). Theory of natural convection in snow. *Journal of Geophysical Research: Atmospheres*, 90(D6), 10641-10649.
- Proksch, M., Löwe, H., & Schneebeli, M. (2015). Density, specific surface area, and correlation length of snow measured by high-resolution penetrometry. *Journal of Geophysical Research: Earth Surface*, 120(2), 346-362.
- Proksch, M., Rutter, N., Fierz, C., & Schneebeli, M. (2016). Intercomparison of snow density measurements: bias, precision, and vertical resolution. *The Cryosphere*, 10(1), 371-384.
- PSC, (2014). The Canadian disaster database, Public Safety Canada, Ottawa, Canada.
- Pulliainen, J., & Hallikainen, M. (2001). Retrieval of regional snow water equivalent from space-borne passive microwave observations. *Remote sensing of environment*, 75(1), 76-85.
- Punkkinen, H., Räsänen, L., Mroueh, U. M., Korkealaakso, J., Luoma, S., Kaipainen, T., ... & Krogerus, K. (2016). Guidelines for mine water management. *VTT Technology*, 266, 1-157.
- Purves, R. S., Barton, J. S., Mackaness, W. A., & Sugden, D. E. (1998). The development of a rule-based spatial model of wind transport and deposition of snow. *Annals of Glaciology*, 26, 197-202.
- Qu, S. M., Liu, H., Cui, Y. P., Shi, P., Bao, W. M., & Yu, Z. B. (2013). Test of newly developed conceptual hydrological model for simulation of rain-on-snow events in forested watershed. *Water Science and Engineering*, 6(1), 31-43.
- Rahimi, M., & Côté, J. (2016). Modélisation de l'effet du couvert de neige sur les transferts thermiques sol-atmosphère, Ph.D. dissertation, Laval University, Canada
- Rango, A. (1995). The Snowmelt Runoff Model (SRM). *Computer models of watershed hydrology.*, 477-520.

- Reeh, N., Fisher, D. A., Koerner, R. M., & Clausen, H. B. (2005). An empirical firn-densification model comprising ice lenses. *Annals of Glaciology*, 42, 101-106.
- Rees, D. A. S., & Riley, D. S. (1986). Free convection in an undulating saturated porous layer: resonant wavelength excitation. *Journal of Fluid Mechanics*, 166, 503-530.
- Rees, D. A. S., & Riley, D. S. (1989). The effects of boundary imperfections on convection in a saturated porous layer: near-resonant wavelength excitation. *Journal of Fluid Mechanics*, 199, 133-154.
- Reimer, A. (1980). The effect of wind on heat transfer in snow. *Cold Regions Science and Technology*, 3(2), 129-137.
- Ryberg, K. R. (2024). Why snow is crucial for water supply—and what will happen when it becomes scarce.
- Riche, F., Schneebeli, M., & Tschanz, S. A. (2012). Design-based stereology to quantify structural properties of artificial and natural snow using thin sections. *Cold regions science and technology*, 79, 67-74.
- Robinson, D. A., & Frei, A. (2000). Seasonal variability of Northern Hemisphere snow extent using visible satellite data. *The Professional Geographer*, 52(2), 307-315.
- Saadat, S., Pandey, G., & Tharmavaram, M. (2020). Microscopy for forensic investigations. *Technology in Forensic Science: Sampling, Analysis, Data and Regulations*, 101-127.
- Savard, J. P., Van Proosdij, D., & O'Carroll, S. (2016). Chapter 4: Perspectives on Canada's East Coast region; in *Canada's Marine Coasts in a Changing Climate*, (ed.) D.S. Lemmen, F.J. Warren, T.S. James and C.S.L Mercer Clarke; Government of Canada, Ottawa, ON, p. 99-152.
- Sawatsky, L. F., Beckstead, G., & Long, D. (1998). Integrated mine water management planning for environmental protection and mine profitability. *International Journal of Surface Mining, Reclamation and Environment*, 12(1), 37-39.
- Schmidt, R. A., & Gluns, D. R. (1991). Snowfall interception on branches of three conifer species. *Canadian Journal of Forest Research*, 21(8), 1262-1269.

- Schneebeli, M., & Johnson, J. B. (1998). A constant-speed penetrometer for high-resolution snow stratigraphy. *Annals of Glaciology*, 26, 107-111.
- Schneebeli, M., & Sokratov, S. A. (2004). Tomography of temperature gradient metamorphism of snow and associated changes in heat conductivity. *Hydrological Processes*, 18(18), 3655-3665.
- Schneiderbauer, S., & Prokop, A. (2011). The atmospheric snow-transport model: SnowDrift3D. *Journal of Glaciology*, 57(203), 526-542.
- Schuh, W., & Cline, R. (1990). Effect of soil properties on unsaturated hydraulic conductivity pore-interaction factors. *Soil science society of America journal*, 54(6), 1509- 1519
- Schweizer, J., van Herwijnen, A., & Reuter, B. (2011). Measurements of weak layer fracture energy. *Cold Regions Science and Technology*, 69(2-3), 139-144.
- Seiferlin, K., Kargl, G., & Kömle, N. (2003). The effect of cementation on the thermal conductivity of porous media. In *EGS-AGU-EUG Joint Assembly* (p. 10748).
- Seiferlin, K., Kömle, N. I., Kargl, G., & Spohn, T. (1996). Line heat-source measurements of the thermal conductivity of porous H₂O ice, CO₂ ice and mineral powders under space conditions. *Planetary and Space Science*, 44(7), 691-704.
- SHAL, L. S. Atmospheric Environment Service Nownsvew, Orntario.
- Sharma, V., & Yuden, K. (2021). Imputing missing data in hydrology using machine learning models. *Int. J. Eng. Res. Technol*, 10(2021), 78-82.
- Shen, C., Laloy, E., Elshorbagy, A., Albert, A., Bales, J., Chang, F. J., ... & Tsai, W. P. (2018). HESS Opinions: Incubating deep-learning-powered hydrologic science advances as a community. *Hydrology and Earth System Sciences*, 22(11), 5639-5656.
- Shertzer, R. H., & Adams, E. E. (2011). Anisotropic thermal conductivity model for dry snow. *Cold Regions Science and Technology*, 69(2-3), 122-128.
- Shimizu, H. (1970). Air permeability of deposited snow. *Contributions from the Institute of Low Temperature Science*, 22, 1-32

- Shockley, J. C. (2021). Modeling watershed sensitivity to climate change in systems affected by discharge of mine tailings (Doctoral dissertation, The University of Nebraska-Lincoln).
- Sihvola, A., & Tiuri, M. (1986). Snow fork for field determination of the density and wetness profiles of a snowpack. *IEEE Transactions on Geoscience and Remote Sensing*, (5), 717-721.
- Singh, P., & Kumar, N. (1996). Determination of snowmelt factor in the Himalayan region. *Hydrological sciences journal*, 41(3), 301-310.
- Singh, P., Spitzbart, G., Hübl, H., & Weinmeister, H. W. (1997). Hydrological response of snowpack under rain-on-snow events: a field study. *Journal of Hydrology*, 202(1-4), 1-20.
- Sommerfeld, R. A., & Rocchio, J. E. (1993). Permeability measurements on new and equiseperated snow. *Water resources research*, 29(8), 2485-2490.
- Sommerfeld, R., Rocchio, J. (1989). The Darcy permeability of finegrained compact snow. Paper presented at the Proceedings of the 46th Annual Eastern Snow Conference
- Sommerfeld, R., Rocchio, J. (1993). Permeability measurements on new and equitemperature snow. *Water Resources Research*, 29(8), 2485-2490.
- Spitz, K., & Trudinger, J. (2019). Tailings disposal: Concepts and practices. In *Mining and the Environment* (pp. 649-704). CRC Press.
- Stadler, D., Flühler, H., & Jansson, P. E. (1997). Modelling vertical and lateral water flow in frozen and sloped forest soil plots. *Cold Regions Science and Technology*, 26(3), 181-194.
- Steinacker, H. H. R. Hydrometeorological implications of the mass balance of Hintereisferner, 1952-53 to 1968-69.
- Stoy, P. C., Peitzsch, E., Wood, D., Rottinghaus, D., Wohlfahrt, G., Goulden, M., & Ward, H. (2018). On the exchange of sensible and latent heat between the atmosphere and melting snow. *Agricultural and Forest Meteorology*, 252, 167-174.

- Strachan, C. & Goodwin, S. (2015). The role of water management in tailings dam incidents. Proceedings of the Tailings and Mine Wastes Conference, Vancouver, BC, 26-28 October 2015.
- Sturm, M., & Johnson, J. B. (1991). Natural convection in the subarctic snow cover. *Journal of Geophysical Research: Solid Earth*, 96(B7), 11657-11671.
- Sturm, M., Benson, C. S. (1997). Vapor transport, grain growth and depth-hoar development in the subarctic snow. *Journal of Glaciology*, 43(143), 42-59.
- Sturm, M., Goldstein, M. A., and Parr, C. (2017). Water and life from snow: a trillion-dollar science question. *Water Resour. Res.* 53, 3534–3544.
- Sturm, M., Holmgren, J., König, M., & Morris, K. (1997). The thermal conductivity of seasonal snow. *Journal of Glaciology*, 43(143), 26-41.
- Sturm, M., Perovich, D. K., & Holmgren, J. (2002). Thermal conductivity and heat transfer through the snow on the ice of the Beaufort Sea. *Journal of Geophysical Research: Oceans*, 107(C10).
- Sugisaki, M., Suga, H., & Seki, S. (1968). Calorimetric study of the glassy state. IV. Heat capacities of glassy water and cubic ice. *Bulletin of the Chemical Society of Japan*, 41(11), 2591-2599.
- Surdyk, S. (2002). Using microwave brightness temperature to detect short-term surface air temperature changes in Antarctica: An analytical approach. *Remote Sensing of Environment*, 80(2), 256-271.
- Surfleet, C. G., & Tullos, D. (2013). Variability in effect of climate change on rain-on-snow peak flow events in a temperate climate. *Journal of Hydrology*, 479, 24-34.
- Takala, M., Luojus, K., Pulliainen, J., Derksen, C., Lemmetyinen, J., Kärnä, J. P., ... & Bojkov, B. (2011). Estimating northern hemisphere snow water equivalent for climate research through assimilation of space-borne radiometer data and ground-based measurements. *Remote Sensing of Environment*, 115(12), 3517-3529.

- Tang, M., Yu, S., You, S., & Jiang, P. (2024). The Characteristics and Application of Deuterium and Oxygen Isotopes to Karst Groundwater, Southwest China. *Water*, 16(13), 1812.
- Tarboton D. G, Chowdhury T. G, Jackson T. H (1995) A spatially distributed energy balance snowmelt model. Proceedings of symposium on biogeochemistry of seasonally snow-covered catchments, Boulder, Colorado
- Tarboton, D. G., & Luce, C. (1996). Utah Energy Balance Snow Accumulation and Melt Model (UEB)–Computer model technical description and user guide USDA Forest Service Research Technical Report.
- Tarboton, D. G., Chowdhury, T. G., Jackson, T. H. (1994). A spatially distributed energy balance snowmelt model.
- Taylor, B., & Taylor, E. M. (Eds.). (1997). Responding to global climate change in British Columbia and Yukon (Vol. 1). Environment Canada, Pacific and Yukon Region, Aquatic and Atmospheric Sciences Division.
- Tedesco, M., & Kokhanovsky, A. A. (2007). The semi-analytical snow retrieval algorithm and its application to MODIS data. *Remote Sensing of Environment*, 111(2-3), 228-241.
- Tedesco, M., Derksen, C., Deems, J. S., & Foster, J. L. (2015). Remote sensing of snow depth and snow water equivalent. *Remote Sensing of the Cryosphere*, 73-98.
- Thapa, S., Zhao, Z., Li, B., Lu, L., Fu, D., Shi, X., ... & Qi, H. (2020). Snowmelt-driven streamflow prediction using machine learning techniques (LSTM, NARX, GPR, and SVR). *Water*, 12(6), 1734.
- Tiuri, M. A. R. T. T. I., & Sihvola, A. (1985, August). Snow fork for field determination of the density and wetness profiles of a snowpack. In *Hydrologic Applications of Space Technology, Proceedings of the Cocoa Beach Workshop, Florida* (pp. 225-230).

- Tiuri, M., Sihvola, A., Nyfors, E. G., & Hallikaiken, M. (1984). The complex dielectric constant of snow at microwave frequencies. *IEEE Journal of oceanic Engineering*, 9(5), 377-382.
- Trabant, D., & Benson, C. (1972). Field experiments on the development of depth hoar. *Geological Society of America Memoir*, 135, 309-322.
- Trevelyan, J. (2021). *Learning engineering practice*. CRC Press.
- Trottier, M. O., Franklin, K., Portocarrero, J., Dufault, D., & Millar, R. (2023). The Impact of Climate Change on Extreme Events for Operation and Closure of Tailings Facilities.
- Trujillo, E., Ramírez, J. A., & Elder, K. J. (2007). Topographic, meteorologic, and canopy controls on the scaling characteristics of the spatial distribution of snow depth fields. *Water Resources Research*, 43(7).
- Turcotte, D. L. (1982). and G. Schubert, *Geodynamics*, 450 pp.
- United States Army, Corps of Engineers. (1956). *Snow hydrology*. Portland, OR.
- United States Army, Corps of Engineers. (1991). *Streamflow synthesis and reservoir regulation (SSARR) model user manual*. N. Pacific Div., Portland, OR.
- US Army Corps of Engineers (1998) *Runoff from snowmelt*. (EM 1110-2-1406), Washington, DC, USA
- Usowicz, B., Lipiec, J., & Usowicz, J. B. (2008). Thermal conductivity in relation to porosity and hardness of terrestrial porous media. *Planetary and Space Science*, 56(3-4), 438-447.
- Usul N, Turan B (2006) Flood forecasting and analysis within the Ulus Basin, Turkey, using geographic information systems. *Nat Hazards* 39:213–229.
- United Nations Economic Commission for Europe. *Safety Guidelines and Good Practices for Tailings Management Facilities*; United Nations Economic Commission for Europe: New York, NY, USA; Geneva, Switzerland, 2014.

- Vafakhah, M., Sedighi, F., & Javadi, M. R. (2014). Modeling the rainfall-runoff data in snow-affected watershed. *International Journal of Computer and Electrical Engineering*, 6(1), 40.
- Van Genuchten, M. T. (1980). A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. *Soil science society of America journal*, 44(5), 892-898
- Van Genuchten, M. T., & Nielsen, D. (1985). On describing and predicting the hydraulic properties of unsaturated soils. *Ann. Geophys*, 3(5), 615-628
- Van Mullem, J. A., Garen, D., Woodward, D., & Mockus, V. (2004). Chapter 11: Snowmelt, part 630 hydrology national engineering handbook. Washington, DC: US Dept. of Agriculture Natural Resources Conservation Service.
- Vanani, H. R., & Ostad-Ali-Askari, K. (2022). Correct path to use flumes in water resources management. *Applied Water Science*, 12(8), 187.
- Vick, B., Özişik, M. N., & Bayazitoğlu, Y. (1980). A method of analysis of low Peclet number thermal entry region problems with axial conduction. *Letters in Heat and Mass Transfer*, 7(4), 235-248.
- Vionnet, V., Brun, E., Morin, S., Boone, A., Martin, E., Faroux, S., Moigne, P.L., Willemet, J.M., (2012). The detailed snowpack scheme Crocus and its implementation in SURFEX v7.2. *Geosci. Model. Dev.* 5, 773–791. doi :10.5194/gmd-5-773-2012.
- Vionnet, V., Martin, E., Masson, V., Guyomarc'h, G., Naaim-Bouvet, F., Prokop, A., ... & Lac, C. (2014). Simulation of wind-induced snow transport and sublimation in alpine terrain using a fully coupled snowpack/atmosphere model. *The Cryosphere*, 8(2), 395-415.
- Wagner, T., Sivapalan, M., Troch, P. A., McGlynn, B. L., Harman, C. J., Gupta, H. V., ... & Wilson, J. S. (2010). The future of hydrology: An evolving science for a changing world. *Water Resources Research*, 46(5).

- Wakao, N., Kaguei, S., & Funazkri, T. (1979). Effect of fluid dispersion coefficients on particle-to-fluid heat transfer coefficients in packed beds: correlation of Nusselt numbers. *Chemical engineering science*, 34(3), 325-336.
- Walmsley, J. L., Salmon, J. R., & Taylor, P. A. (1982). On the application of a model of boundary-layer flow over low hills to real terrain. *Boundary-Layer Meteorology*, 23(1), 17-46.
- Walter MT, Brooks ES, McCool DK, King LG, Molnau M, Boll J (2005) Process-based snowmelt modeling: does it require more input data than temperature-index modeling.
- Wang, L., Koike, T., Yang, K., Jackson, T. J., Bindlish, R., & Yang, D. (2009). Development of a distributed biosphere hydrological model and its evaluation with the Southern Great Plains Experiments (SGP97 and SGP99). *Journal of Geophysical Research: Atmospheres*, 114(D8).
- Wang, L., Koike, T., Yang, K., Jin, R., & Li, H. (2010). Frozen soil parameterization in a distributed biosphere hydrological model. *Hydrology and Earth System Sciences*, 14(3), 557-571.
- Wang, X., & Baker, I. (2013). Observation of the microstructural evolution of snow under uniaxial compression using X-ray computed microtomography. *Journal of Geophysical Research: Atmospheres*, 118(22), 12-371.
- Wang, Z.L.; Liu, C.X.; Jiang, Q.X.; Fu, Q.; Chen, W.J.; Ying, Y.M. (2019). Simulation of soil water-heat process in black soil region of Songnen Plain based on COUPMODEL. *J. Northeast Agric. Univ.* 50, 50–58.
- Wankiewicz, A. (1978). A review of water movement in snow. *Modeling of Snow Cover Runoff*, 26-28
- Warren, S. G. (1982). Optical properties of snow. *Reviews of Geophysics*, 20(1), 67-89.
- Warscher, M., Strasser, U., Kraller, G., Marke, T., Franz, H., & Kunstmann, H. (2013). Performance of complex snow cover descriptions in a distributed hydrological

- model system: A case study for the high Alpine terrain of the Berchtesgaden Alps. *Water resources research*, 49(5), 2619-2637.
- Washburn, E. W. (1928). *International critical tables of numerical data, physics, chemistry, and technology*, vol III (p. 272). New York: McGraw-Hill.
- Wei, C. A. O., Yu, S. H. E. N. G., Jichun, W. U., Shengting, W. A. N. G., & Shuai, M. A. (2018). Seasonal variation of soil hydrological processes of active layer in source region of the Yellow River. *水科学进展*, 29(1), 1-10.
- Weltzin, J. F., Betancourt, J. L., Cook, B. I., Crimmins, T. M., Enquist, C. A., Gerst, M. D., ... & Running, S. W. (2020). Seasonality of biological and physical systems as indicators of climatic variation and change. *Climatic change*, 163(4), 1755-1771.
- Welch, C. M., Stoy, P. C., Rains, F. A., Johnson, A. V., & McGlynn, B. L. (2016). The impacts of mountain pine beetle disturbance on the energy balance of snow during the melt period. *Hydrological Processes*, 30(4), 588-602.
- Whalley, W. R., Lipiec, J., Stępniewski, W., & Tardieu, F. (2000). Control and measurement of the physical environment in root growth experiments.
- Wheeler, J. A., Cortés, A. J., Sedlacek, J.; Karrenberg, S., Van Kleunen, M., Wipf, S., et al. (2016). The snow and the willows: earlier spring snowmelt reduces performance in the low-lying alpine shrub *Salix herbacea*. *J. Ecol.* 104, 1041–1050.
- Wiebe, H., Heygster, G., Zege, E., Aoki, T., & Hori, M. (2013). Snow grain size retrieval SGSP from optical satellite data: Validation with ground measurements and detection of snow fall events. *Remote sensing of environment*, 128, 11-20.
- Wiesmann, A., Mätzler, C., & Weise, T. (1998). Radiometric and structural measurements of snow samples. *Radio Science*, 33(2), 273-289.
- Wigmosta, M. S., Vail, L. W., & Lettenmaier, D. P. (1994). A distributed hydrology-vegetation model for complex terrain. *Water resources research*, 30(6), 1665-1679.
- Wilson, W. T. (1941). An outline of the thermodynamics of snowmelt. *Eos, Transactions American Geophysical Union*, 22(1), 182-195.

- Winstral, A., & Marks, D. (2002). Simulating wind fields and snow redistribution using terrain-based parameters to model snow accumulation and melt over a semi-arid mountain catchment. *Hydrological Processes*, 16(18), 3585-3603.
- Winstral, A., Elder, K., & Davis, R. E. (2002). Spatial snow modeling of wind-redistributed snow using terrain-based parameters. *Journal of hydrometeorology*, 3(5), 524-538.
- Winstral, A., Marks, D., & Gurney, R. (2013). Simulating wind-affected snow accumulations at catchment to basin scales. *Advances in Water Resources*, 55, 64-79.
- Woodside, W. (1958). Calculation of the thermal conductivity of porous media. *Canadian Journal of Physics*, 36(7), 815-823
- Wosten, J., & Van Genuchten, M. T. (1988). Using texture and other soil properties to predict the unsaturated soil hydraulic functions. *Soil science society of America journal*, 52(6), 1762-1770
- WSB, Paterson. *The physics of glaciers*. Oxford: Pergamon, 1994
- Xie, Z., Hu, Z., Ma, Y., Sun, G., Gu, L., Liu, S., ... & Ma, W. (2019). Modeling blowing snow over the Tibetan Plateau with the Community Land Model: Method and preliminary evaluation. *Journal of Geophysical Research: Atmospheres*, 124(16), 9332-9355.
- Yamaguchi, S., Katsushima, T., Sato, A., & Kumakura, T. (2010). Water retention curve of snow with different grain sizes. *Cold Regions Science and Technology*, 64(2), 87-93
- Yamazaki, Y., Kubota, J., Ohata, T., Vuglinsky, V., & Mizuyama, T. (2006). Seasonal changes in runoff characteristics on a permafrost watershed in the southern mountainous region of eastern Siberia. *Hydrological Processes: An International Journal*, 20(3), 453-467.
- Yang, S., Yang, D., Chen, J., Santisirisomboon, J., Lu, W., & Zhao, B. (2020). A physical process and machine learning combined hydrological model for daily streamflow

- simulations of large watersheds with limited observation data. *Journal of Hydrology*, 590, 125206.
- Yang, Y., & Chen, R. (2011). Research Review on Hydrology in the Permafrost and Seasonal Frozen Regions. *Advances in earth science*, 26(7), 711.
- Ye, H., Yang, D., & Robinson, D. (2008). Winter rain on snow and its association with air temperature in northern Eurasia. *Hydrological Processes: An International Journal*, 22(15), 2728-2736.
- Yen, Y. C. (1963). Heat transfer by vapor transfer in ventilated snow. *Journal of Geophysical Research*, 68(4), 1093-1101.
- Yen, Y. C. (1969). Recent studies on snow properties. *Advances in Hydrosience*, 5, 173-214.
- Yen, Y. C. (1981). Review of thermal properties of snow, ice, and sea ice (Vol. 81, No. 10). US Army, Corps of Engineers, Cold Regions Research and Engineering Laboratory.
- Yong, Y., Ren-sheng, C. H. E. N., Xi-bin, J. I., Wen-wu, Q. I. N. G., Jun-feng, L. I. U., & Chun-tan, H. A. N. (2010). Heat and water transfer processes on alpine meadow frozen grounds of Heihe mountainous in Northwest China, 21(1), 30-35.
- Yosida, Z. (1955). Physical Studies on Deposited Snow. I.; Thermal Properties. *Contributions from the Institute of Low Temperature Science*, 7, 19-74.
- Yosida, Z., Oura, H., Kuroiwa, D., Huzioka, T., Kojima, K., & Kinoshita, S. (1958). Physical Studies on Deposited Snow. IV.; Mechanical Properties. (3). *Contributions from the Institute of Low Temperature Science*, 13, 55-100.
- You J (2004) Snow hydrology: the parameterization of subgrid processes within a physically based snow energy and mass balance model. Ph.D. dissertation, Utah State University, USA.
- Zahmatkesh, Z., Kumar Jha, S., Coulibaly, P., & Stadnyk, T. (2019). An overview of river flood forecasting procedures in Canadian watersheds. *Canadian Water Resources Journal/Revue canadienne des ressources hydriques*, 44(3), 213-229.

- Zanotti F, Endorzzi S, Bertoldi G, Rigon R (2004) The GEOTOP snow model. 61st Eastern Snow Conference Portland, Maine, USA.
- Zeiringer, B., Seliger, C., Greimel, F., & Schmutz, S. (2018). River hydrology, flow alteration, and environmental flow. *Riverine ecosystem management: Science for governing towards a sustainable future*, 67-89.
- Zege, E. P., Katsev, I. L., Malinka, A. V., Prikhach, A. S., Heygster, G., & Wiebe, H. (2011). Algorithm for retrieval of the effective snow grain size and pollution amount from satellite measurements. *Remote Sensing of Environment*, 115(10), 2674-2685.
- Zhang, L., Li, X., Zheng, D., Zhang, K., Ma, Q., Zhao, Y., & Ge, Y. (2021). Merging multiple satellite-based precipitation products and gauge observations using a novel double machine learning approach. *Journal of Hydrology*, 594, 125969.
- Zhang, T. (2005). Influence of the seasonal snow cover on the ground thermal regime: An overview. *Reviews of Geophysics*, 43(4).
- Zhang, Y., Chang, X., Liang, J., & He, R. X. (2016). Influence of frozen ground on hydrological processes in alpine regions: A case study in an upper reach of the Heihe River. *J. Glaciol. Geocryol*, 38, 1362-1372.
- Zhang, Y., Liu, S., & Wang, X. (2019). A dataset of spatial distribution of degree-day factors for glaciers in High Mountain Asia. *China Sci. Data*, 4(3), 141-151.
- Zhao, M., Srebric, J., Berghage, R. D., & Dressler, K. A. (2015). Accumulated snow layer influence on the heat transfer process through green roof assemblies. *Building and Environment*, 87, 82-91.
- Zhou, G., Cui, M., Wan, J., & Zhang, S. (2021). A review on snowmelt models: progress and prospect. *Sustainability*, 13(20), 11485.
- Zhou, J., Pomeroy, J. W., Zhang, W., Cheng, G., Wang, G., & Chen, C. (2014). Simulating cold regions hydrological processes using a modular model in the west of China. *Journal of Hydrology*, 509, 13-24.

- Zhou, Y.L.; Mu, Z.X.; Peng, L.; Yin, Z.Y.; Tang, R. (2018). Change of snowmelt runoff in western Tianshan Mountains under future climate scenarios. *J. China Hydrol.* 38, 12–17.
- Zohdi, T. I. (2015). *A finite element primer for beginners: the basics*. Springer International Publishing.
- Zuzel, J. F., & Cox, L. M. (1975). Relative importance of meteorological variables in snowmelt. *Water Resources Research*, 11(1), 174-176.
- Zuzel, J. F., Pikul Jr, J. L., & Rasmussen, P. E. (1990). Tillage and fertilizer effects on water infiltration. *Soil Science Society of America Journal*, 54(1), 205-208.

APPENDIX A Computing the thermal conductivity of snow

A.1 Computing the thermal conductivity of snow

By using equation (2.10), the thermal conductivity of snow can be predicted using regression equation and based on index of hardness and porosity index (Usovicz et al, 2008):

$$\lambda = a. \exp Hc + b. \phi + c \quad (\text{A.1})$$

Where λ ($\text{W m}^{-1} \text{K}^{-1}$) is the thermal conductivity; a, b, c are the parameters indicated by B coefficients; ϕ ($\text{m}^3 \text{m}^{-3}$) is the volumetric snow water content; H_c is the index of hardness (Sturmet al., 2002).

After examining the influencing factors on the thermal conductivity of snow, the models presented by researchers in recent years are shown to estimate it.

In the literature, there are several thermal conductivity models for snow (Sturm et al., 1997; Ostin and Andersson, 1991; Lange, 1985; Reimer, 1980; Côté and al., 2012). Generally, they are obtained by logarithmic, exponential, or power regressions between the effective thermal conductivity (λ_{eff}) and the density, presented in Table 2.7. These models do not consider the effects of temperature and grain size, but they are easy to use. Figure A.1 shows the regression equations (thermal conductivity vs. density) by 15 different authors for the time 1892 to 2012. Abel's regression equation, 1892 is an equation that is used as a reference to predict thermal conductivity. There are large (and mostly undocumented) differences in accuracy, temperature, and snow type in these datasets between 1892 and 1997. By dividing the steady-state heat flow by the steady-state temperature gradient, the thermal conductivity is determined. This method has been employed in three investigations (Jansson, 1901; De Quervain, 1956; Pitman and Zuckerman, 1967), but only the most recent study used a guarded form of heated plate, a method that is now acknowledged as crucial if correct results are to be obtained (Sturm et al., 1997).

Table A.1 Equations obtained by different types of regression (Sturm et al.1997)

Reference	Temperature [°c]	Regression equation
Adel's, 1892	-10 to -30	$\lambda = 10^{2.846 \rho^2}$
Jansson, 1901	-2 to -13	$\lambda = 0.02093 + 0.7953 \rho + 2.512 \rho^4$
VanDusen, 1929	-	$\lambda = 0.021 + 0.42 \rho + 2.16 \rho^3$
Devaux, 1933	-5 to -20	$\lambda = 0.0293 + 2.93 \rho^2$
Bracht, 1949	-3 to -13.5	$\lambda = 2.051 \rho^2$
Kondrat'eva, 1954	-2 to 13.5	$\lambda = 3.558 \rho^2$
Sulakvelidze, 1955	-2 to -13	$\lambda = 0.5107 \rho$
Yosida et al. 1955	-1 to -6	$\lambda = 10^{-1.378+2\rho}$
Lange, 1985	-4 to -20	$\lambda = 10^{-3+6.9\rho}$
Ostin and Andresson, 1991	-6.5 to -19.9	$\lambda = -0.0871 + 0.439 \rho + 1.05 \rho^2$
Sturm et al. 1997	-1 to -77	$\lambda = 0.138 - 1.01 \rho + 3.233 \rho^2, 0.156 \leq \rho \leq 0.6$ $\lambda = 0.023 + 0.234 \rho, \rho \leq 0.156$ $\lambda = 10^{-1.652+2.650 \rho}$
Côté et al. 2012	-12	$\lambda = \frac{(\lambda_{glace} k_{2p} - \lambda_{air})(1 - n) + \lambda_{air}}{1 + (k_{2p} - 1)(1 - n)}$

Transient approaches involve heating a source that is initially isothermal and in steady state within a block of snow using a point, line, or plate (Sturm et al., 1997). The temperature of the snow at or close to the source is used to calculate the thermal conductivity. There have been utilised numerous heat source and temperature probe configurations. Cylindrical and spherical heat sources were used by Devaux (1933). Two parallel needles, one holding a heater and the other a temperature-measuring device, were utilised by Bracht (1949). Jaafar and Picot (1970) employed a single needle that had both a heater and a thermometer. A heated plate was put into a block of snow that had previously included thermocouples by Kuvaeva and colleagues (1975). A heated strip that was inserted in frost samples was utilised by Stin and Andersson in 1991.

As shown in Table 2.8, In 1997, Sturm et al. Presented an updated set of 488 measurements with known temperature, type, and measurement accuracy. In quadratic form:

$$\lambda = \begin{cases} 0.138 - 1.01\rho + 3.233 \rho^2 & 0.156 \leq \rho \leq 0.6 \\ 0.023 + 0.234 \rho & \rho \leq 0.156 \end{cases} \quad (\text{A.2})$$

A logarithmic expression can also be used.:

$$\lambda = 10^{-1.652+2.650 \rho} \quad \rho \leq 0.6 \quad (\text{A.3})$$

When estimating values that are outside the range of the data, the first regression performs better than the second when estimating values for low-density snow. Snow types produced by kinetic growth exhibit behavior irrespective of density within the data set. Strong density dependence can be seen in wind-blown snow and rounded grain. The mean density of the new data set is higher than that of the previous data set, although the mean thermal conductivity is lower. This shift is explained by variations in the types of snow and sample temperatures between the sets. We demonstrate that there are well-defined limits to the geometric forms that naturally occurring seasonal snow can adopt using both data sets (Sturm et al., 1997).

These equations, along with the rest of the equations in Table A.1, provide a satisfactory correlation for typical porosities but do not adhere to the theoretical bounds anticipated at low and high porosities.

By utilizing a relative thermal conductivity model for porous 2-phase materials created by Côté and Konrad (2009), Côté and al. (2012) aimed to solve this issue. The latter limits the solid's and fluid's respective solid and fluid thermal conductivity values:

$$\lambda_{rel} = \frac{\lambda_{eff} - \lambda_f}{\lambda_{solid} - \lambda_f} \quad 0 \leq k_r \leq 1 \quad (A.4)$$

Where λ_{rel} is the relative thermal conductivity, λ_{eff} ($\text{W m}^{-1} \text{ }^\circ\text{C}^{-1}$) is the effective thermal conductivity of the snow sample, λ_f ($\text{W m}^{-1} \text{ }^\circ\text{C}^{-1}$) and λ_{solid} ($\text{W m}^{-1} \text{ }^\circ\text{C}^{-1}$) are the thermal conductivities respectively fluid and solid.

Effectively, Equation A.4 produces a value of λ_{rel} of 0 for air and 1 for ice. By using an empirical parameter, Côté and Konrad (2009) were able to establish a connection between the relative thermal conductivity and the porosity of the porous material:

$$\lambda_{rel} = \frac{\kappa_{2p}(1-n)}{1+(\kappa_{2p}-1)(1-n)} \quad (A.5)$$

Where κ_{2p} is the empirical parameter that considers the structure of materials, namely the size, shape, and organization of the grains in a granular material.

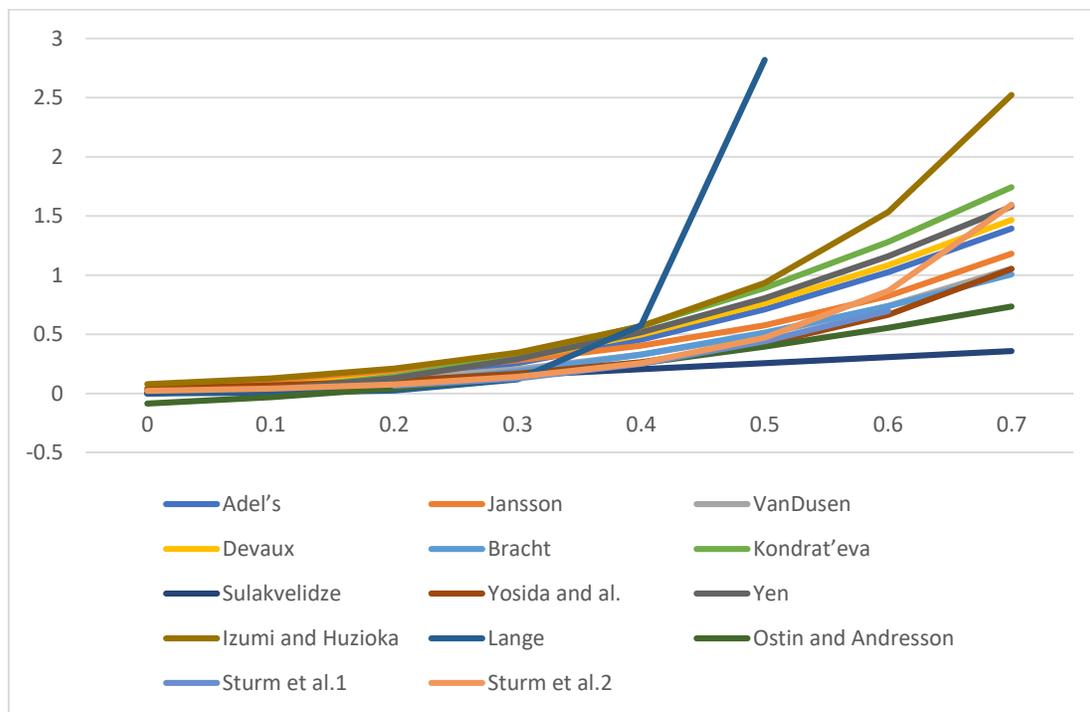


Figure A.1 Regressions developed are shown for comparison.

A.2 The range of potential values for κ_{2p}

The range of potential values for κ_{2p} as a function of the ratio λ_f/λ_s is depicted in Figure A.2, which is taken from Côté and al. (2012) and is based on the restrictions of Hashin and Shtrikman (1962) that fall within the restrictions of Weiner (parallel and series thermal circuit). The higher and lower Hashin and Shtrikman limitations are represented by the HSH and HSB limits, whereas the upper and lower Weiner limits are represented by the WH and WB limits. The following equations are used to derive these limitations (Côté and Konrad, 2009):

$$\kappa_{2p,HSH} = \frac{\lambda_f}{3\lambda_s} + \frac{2}{3} \quad (\text{A.6})$$

$$\kappa_{2p,HSB} = \frac{3(\lambda_f/\lambda_s)}{1+2(\lambda_f/\lambda_s)} \quad (\text{A.7})$$

$$\kappa_{2p,WH} = 1 \quad (\text{A.8})$$

$$\kappa_{2p,WB} = \frac{\lambda_f}{\lambda_s} \quad (\text{A.9})$$

Pitman and Zuckerman (1968) data were used to determine the λ_f/λ_s ratio's variation range, which is 0.0054 to 0.019. This variation is mostly caused by how f and s change as a function of temperature (-5 to -88°C), as determined by Côté et al (2012). Therefore, for the lowest $\lambda_f - \lambda_s$ and for the larger ratios, the value of κ_{2p} can change between 0.016 and 0.668 and between 0.055 and 0.673. The potential values of κ_{2p} are displayed in the shaded area of Figure A-2.

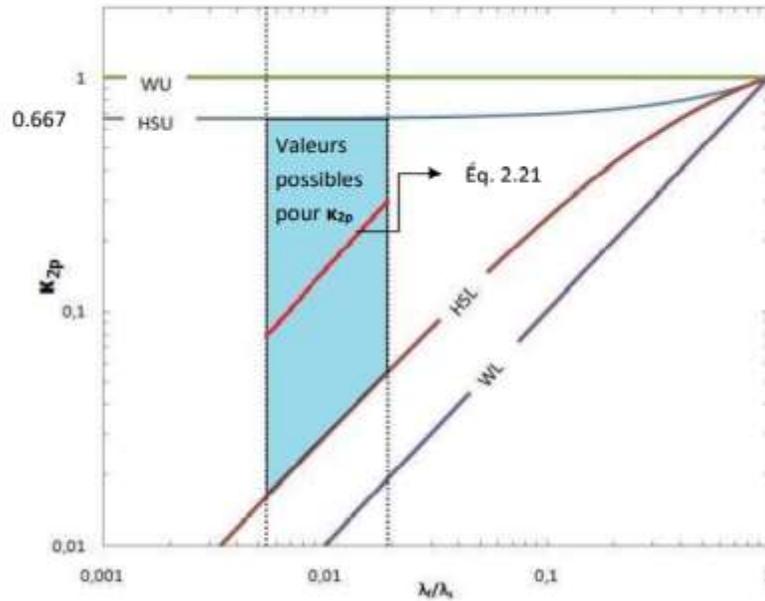


Figure A.2 Possible values and illustration of limits for κ_{2p} (redrawn from Côté and al., (2012)).

The developed thermal conductivity model of Côté et al. (2009 and 2012)

By substituting the expression from equation 2.14 for the term in equation 2.13's λ_{rel} , one can derive a direct relationship for the conductivity of snow as a function of the parameter κ_{2p} and the conductivity values of ice and air. The equation that results is:

$$\lambda = \frac{(\lambda_{glace}\kappa_{2p} - \lambda_{air})(1-n) + \lambda_{air}}{1 + (\kappa_{2p} - 1)(1-n)} \quad (\text{A.10})$$

Where λ_{ice} ($\text{W m}^{-1} \text{ } ^\circ\text{C}^{-1}$) is the conductivity value of ice and λ_{air} ($\text{W m}^{-1} \text{ } ^\circ\text{C}^{-1}$) is the thermal conductivity of air.

Regardless of the value of κ_{2p} falling within the acceptable ranges, this equation respects the theoretical bounds for the projected theoretical conductivity. As determined by Côté and al. based on the findings of Pitman and Zuckerman (1967), the value of ice can be estimated as a function of the temperature T ($^\circ\text{C}$) as follows:

$$\lambda_{glace} = 2.22 - 0.011 T \quad (\text{A.11})$$

Côté et al. (2012) claim that the equation developed from the data put forth by Pitman and Zuckerman (1967) is how the thermal conductivity of the air in the sample is determined:

$$\lambda_{air} = 0.072(-T)^{-0.32} \quad (\text{A.12})$$

Pitman and Zuckerman (1967) measured the thermal conductivity of snow samples at temperatures ranging from -5 to -88°C, and Côté and al. (2012) developed a helpful relation to determine κ_{2p} as a function of the ratio λ_f/λ_s :

$$\kappa_{2p} = 18.7 \left(\frac{\lambda_{air}}{\lambda_{glace}} \right)^{1.05} \quad (\text{A.13})$$

Figure A.3 is drawn from Equation A.13. The models from Sturm et al. (1992) and Côté et al. (2012) were utilized in comparison to this study. The first was a compilation of prior findings, while the second provided theoretical foundations and relied on the boundaries of the physical properties of air and ice.

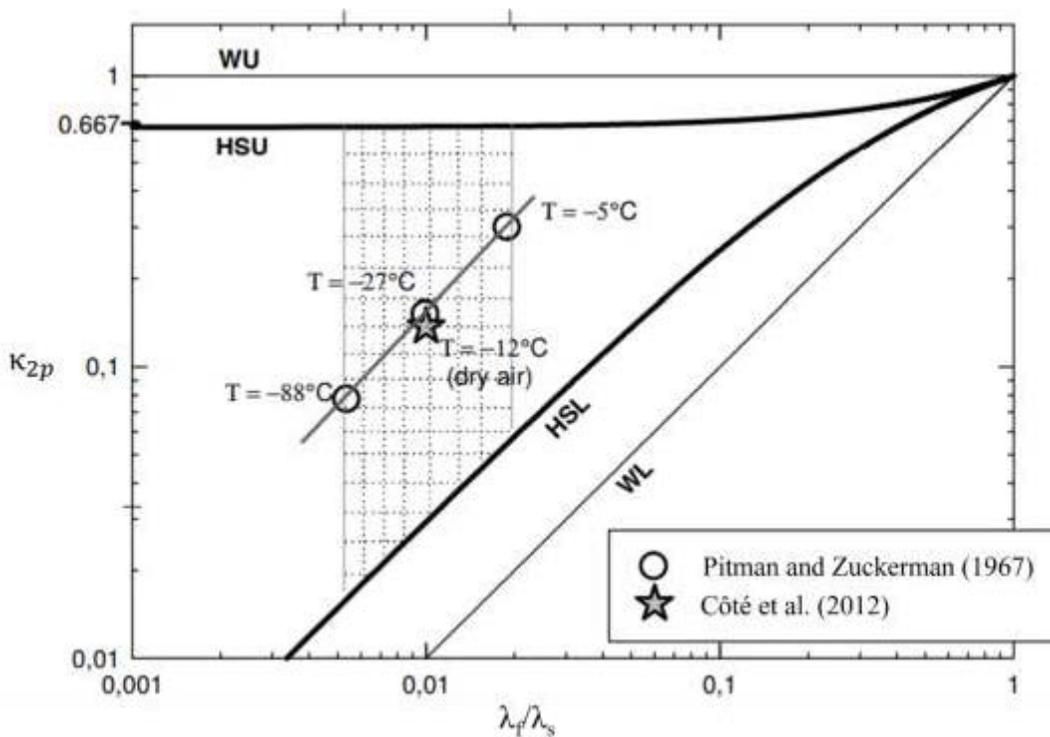


Figure A.3 κ_{2p} values for compacted snow at various temperatures (Côté et al., 2012).

APPENDIX B Effective thermal conductivity type in COMSOL Multiphysics

There are eight different types for effective thermal conductivity in COMSOL Multiphysics:

B.1 Plane layers parallel to heat flow

The default option of "Plane layers parallel to heat flow" computes the effective conductivity of the solid-fluid system by taking the weighted arithmetic mean, or volume average, of the conductivities of both the fluid and the porous matrix.

$$\lambda_{eff} = \theta_{solid}\lambda_{solid} + \varepsilon_p\lambda_f \quad (\text{B.1})$$

B.2 Plane layers perpendicular to heat flow

The "Plane layers perpendicular to heat flow" option computes the effective conductivity of the solid-fluid system by taking the weighted harmonic mean, or reciprocal average, of the conductivities of both the fluid and the porous matrix.

$$\frac{1}{\lambda_{eff}} = \frac{\theta_{solid}}{\lambda_{solid}} + \frac{\varepsilon_p}{\lambda_f} \quad (\text{B.2})$$

B.3 Power law

The "Power law" option computes the effective conductivity of the solid-fluid system by taking the weighted geometric mean of the conductivities of both the fluid and the porous matrix.

$$\lambda_{eff} = \lambda_{solid}^{\theta_{solid}} \cdot \lambda_f^{\varepsilon_p} \quad (\text{B.3})$$

B.4 Solid spherical inclusions

The "Solid spherical inclusions" option calculates the effective conductivity of the solid-fluid system using a specific method or formula.

$$\lambda_{eff} = \lambda_f \frac{2\lambda_f + \lambda_{solid} - 2(\lambda_f - \lambda_{solid})\theta_{solid}}{2\lambda_f + \lambda_{solid} + (\lambda_f - \lambda_{solid})\theta_{solid}} \quad (\text{B.4})$$

B.5 Fluid spherical inclusions

The "Fluid spherical inclusions" option calculates the effective conductivity of the solid-fluid system using a specific method or formula.

$$\lambda_{eff} = \lambda_{solid} \frac{2\lambda_{solid} + \lambda_f - 2(\lambda_{solid} - \lambda_f)\varepsilon_p}{2\lambda_{solid} + \lambda_f + (\lambda_{solid} - \lambda_f)\varepsilon_p} \quad (B.5)$$

B.6 Wrapped screen

The "Wrapped screen" option computes the effective conductivity of the solid-fluid system using a specific method or formula.

$$\lambda_{eff} = \lambda_f \frac{\lambda_f + \lambda_{solid} - (\lambda_f - \lambda_{solid})\theta_{solid}}{\lambda_f + \lambda_{solid} + (\lambda_f - \lambda_{solid})\theta_{solid}} \quad (B.6)$$

B.7 Sintered metal fibers

The "Sintered metal fibers" option computes the effective conductivity of the solid-fluid system using a specific method or formula.

$$\lambda_{eff} = \varepsilon_p^2 \lambda_f + \theta_{solid}^2 \lambda_{solid} + \frac{4\varepsilon_p \theta_{solid} \lambda_f \lambda_{solid}}{\lambda_f + \lambda_{solid}} \quad (B.7)$$

B.8 Equivalent thermal conductivity

It is also feasible to directly define λ_{eff} . When choosing "Equivalent thermal conductivity" from the Effective thermal conductivity options, a specific value for λ_{eff} must be provided. The default λ_{eff} value is derived from the material properties. If a Porous Material node is activated, the property from the Homogenized Properties section is used.

APPENDIX C Heat Transfer Equations in Porous Media in COMSOL Multiphysic

Applying the mixture rule to the energies in the heat transfer equations of solid and fluid allows derivation of the equation for heat transfer in porous media, assuming no deformation or movement of solids (Bejan, 2013):

$$\rho_{solid} C_{p,solid} \frac{\partial T_{solid}}{\partial t} + \nabla \cdot q_{solid} = Q_{solid} \quad (C.1)$$

Where ρ_{solid} is the density of solid (Kg m^{-3}), $C_{p,solid}$ is the solid heat capacity at constant pressure, T_{solid} is the temperature of solid phase, and q_{solid} is the conductive heat flux in solid phase (J m^{-2}). For the fluid domain, the equation simplifies by neglecting pressure work and viscous dissipation (COMSOL, 2008):

$$\rho_f C_{p,f} \frac{\partial T_f}{\partial t} + p_f C_{p,f} u_f \cdot \nabla \cdot q_f = Q_f \quad (C.2)$$

Multiplying equation C.1 by the solid volume fraction, and equation C.2 by the porosity, and then summing the results allows for the application of the mixture rule (COMSOL, 2008).

The hypothesis of local thermal equilibrium states that the temperature of both fluid and solid phases is the same (COMSOL, 2008):

$$T_f = T_{solid} = T \quad (C.3)$$

The section Local Thermal Equilibrium below explains the theory behind this hypothesis. The section Local Thermal Non-Equilibrium shows the theory for using two temperatures to model heat transfer in porous media (COMSOL, 2008).

As stated in Equation C.3, the classical local equilibrium hypothesis for heat transfer in porous media assumes that the solid and fluid temperatures are equal at each point (COMSOL, 2008). The derivation of the energy equation using this assumption, which is valid for many applications, is explained in the Local Thermal Equilibrium section below. Nield in 1998 demonstrates that the temperatures of solid and fluid are the same in steady conduction problems where only fixed temperature conditions are applied. Many problems

with slow motion can also assume that the phase temperatures are equal if there is no difference in volumetric internal heating between the two materials.

For conduction in porous plates, Minkowycz et al., 1998 gives criteria based on the dimensionless Sparrow number, S_p , to determine if temperature equilibrium is still valid or if a non-equilibrium point of view is better. Amiri and Vafai in 1998 studied how the Darcy number, Da , and the ratio of phase conductivities affect transient heat transfer in packed beds. The Sparrow and Darcy numbers are given by:

$$S_p = \frac{h_{sf} H_t^2}{\lambda_{p_{eff}} r_h}, Da = \frac{K}{d^2} \quad (C.4)$$

Where h_{sf} the interstitial heat transfer coefficient between solid and fluid phases ($W m^{-2} K^{-1}$), H_t is the plate layer thickness (m), $\lambda_{p_{eff}}$ is the equivalent thermal conductivity of the porous medium ($W m^{-1} K^{-1}$), r_h is the hydraulic radius (m), K is the permeability (m^2), and d is the average particle diameter (m).

Amiri and Vafai, 1998, and Minkowycz et al., 1999, indicate discrepancies in temperature between phases with low values of S_p (less than 100 or 500) and high values of Da (10^{-7}). However, assessing the validity of local thermal equilibrium is generally not straightforward (COMSOL, 2008). Instead of assuming that the two phases of the porous medium have the same temperature, the Local Thermal Non-Equilibrium approach, explained below, uses two separate energy equations to calculate two different temperature fields for each phase (COMSOL, 2008). This method increases the number of variables to solve, but it also offers a more general framework for heat transfer in porous media without having to check the validity of the equilibrium assumption (COMSOL, 2008).

C.1 Local Thermal Equilibrium

According to Equation C.5, the solid and fluid phases of the porous medium share the same temperature, T , under the local thermal equilibrium hypothesis. The Heat Transfer in Porous Media Interface uses a different form of the heat equation (Bear et al., 1990), which is based on T , to solve for heat transfer in porous media:

$$(\rho_f C_{pf})_{eff} \frac{\partial T}{\partial t} + \rho C_p u \cdot \nabla T + \nabla \cdot q = \varphi \quad (C.5)$$

$$q = -\lambda_{eff} \nabla T \quad (C.6)$$

Where ρ_f is the fluid density, C_{pf} is the fluid heat capacity at constant pressure, $(\rho_f C_{pf})_{eff}$ ($J m^{-3} K^{-1}$) is the effective volumetric heat capacity at constant pressure, defined by (Bear et al., 1990):

$$(\rho C_p)_{eff} = \theta_p \rho_p C_{\rho,p} + (1 - \theta_p) \rho C_\rho \quad (C.7)$$

λ_{eff} is the effective thermal conductivity (either a scalar or a tensor, based on the anisotropy of the thermal conductivity), q is the conductive heat flux, u ($m s^{-1}$) is the velocity field, which can be either an analytic expression or computed from a Fluid Flow interface. It represents the Darcy velocity, meaning the volume flow rate per unit cross sectional area. The average linear velocity (the velocity inside the pores) can be obtained as $u_f = u/(1-\theta_p)$, where $(1-\theta_p)$ is the fluid's volume fraction, or the same as the porosity, θ_p is volume fraction of solid material in porous media, ϕ is the heat source (or sink). Make one or more heat sources separate physics features.

The temperature is constant and does not vary with time for a steady-state problem, and the terms with time derivatives of Equation C.8 are eliminated (COMSOL, 2008). Solid-fluid thermal conductivity, $\lambda_{s,f,eff}$, depends on the solid-fluid conductivity, $\lambda_{s,f}$, and the fluid conductivity, λ_f , and is complicated by the medium geometry. Three isotropic medium models are proposed by Bejan (2013):

- Heat conduction in solids and fluids occurs in parallel, so the effective thermal conductivity is the weighted arithmetic mean of λ_f and $\lambda_{s,f}$: (COMSOL, 2008):

$$\lambda_{s,f,eff} = \theta_{s,f} \lambda_{s,f} + (1 - \theta_p) \lambda_f \quad (C.8)$$

$\lambda_{s,f,eff}$, cannot be higher than the volume average model, which is based on the average of the heat transfer rates of the solid and the fluid (COMSOL, 2008).

- When the heat moves in a straight line through both fluid and solid, the heat flow rate depends on the combined effect of the conductivities λ_f and $\lambda_{s,f}$, which is calculated by the weighted harmonic mean (COMSOL, 2008).

$$\frac{1}{\lambda_{s,f,eff}} = \frac{\theta_{s,f}}{\lambda_{s,f}} + \frac{(1-\theta_p)}{\lambda_f} \quad (C.9)$$

The effective thermal conductivity cannot be lower than the value given by this model that uses the inverse average of the conductivities (COMSOL, 2008).

- The final approximation is obtained by the weighted geometric average of λ_f and $\lambda_{s,f}$ (COMSOL, 2008).

$$\lambda_{s,f\,eff} = \lambda_{s,f}^{\theta_{s,f}} \cdot \lambda_f^{1-\theta_p} \quad (C.10)$$

If the conductivities λ_f and $\lambda_{s,f}$ are similar, this model gives a reasonable approximation (COMSOL, 2008).

C.2 Local Thermal Non-Equilibrium

In porous media with a temperature difference between the fluid and the porous matrix, the Local Thermal Non-Equilibrium Interface facilitates heat transfer (COMSOL, 2008).

C.3 Equation for Local Non-Equilibrium Heat Transfer

The heat transfer in porous media for binary systems of fluid phase and rigid porous matrix that are not in thermal equilibrium is controlled by two equations. They are the standard heat equations for fluids and solids, with a factor of θ_p and $(1 - \theta_p)$ for each, and an extra term that measures the heat transfer between the two phases (Bejan, 2013)

$$\left\{ \begin{array}{l} \theta_p \rho_{solid} C_{p,solid} \frac{\partial T_{solid}}{\partial t} + \nabla \cdot q_{solid} = q_{sf}(T_f - T_{solid}) + \theta_p Q_{solid} \\ q_{solid} = -\theta_p \lambda_{solid} \nabla T_{solid} \\ (1 - \theta_p) \rho_f C_{p,f} \frac{\partial T_f}{\partial t} + (1 - \theta_p) \rho_f C_{p,f} u_f \cdot \nabla T_f + \nabla \cdot q_f = q_{sf}(T_{solid} - T_f) + \\ (1 - \theta_p) Q_f \\ q_f = -(1 - \theta_p) \lambda_f \nabla T_f \end{array} \right. \quad (C.11)$$

Where θ_p is the solid volume fraction, ρ_{solid} and ρ_f are the solid and fluid densities (Kg m^{-3}), $C_{p,s}$ and $C_{p,f}$ are the solid and fluid heat capacities at constant pressure ($\text{J Kg}^{-1} \text{K}^{-1}$), q_{solid} and q_f are the solid and fluid conductive heat fluxes (J m^{-2}), λ_{solid} and λ_f are the solid and fluid thermal conductivities ($\text{J m}^{-1} \text{K}^{-1}$), q_{sf} is the interstitial convective

heat transfer coefficient ($\text{J m}^{-3} \text{K}^{-1}$), Q_{solid} and Q_f are the solid and fluid heat sources (J m^{-3}), and u_f is the fluid velocity vector (m s^{-1}).

The porous velocity u_p (m s^{-1}), which can be obtained from Darcy's law or Brinkman equations, is frequently used to calculate the fluid velocity. The formula is (COMSOL, 2008):

$$u_f = \frac{u_p}{1 - \theta_p} \quad (\text{C.12})$$

These are the simplified forms of the heat equations in the fluid domain (COMSOL, 2008):

$$\begin{cases} (1 - \theta_p)\rho_f C_{p,f} \frac{\partial T_f}{\partial t} + \rho_f C_{p,f} u_p \cdot \nabla T_f + \nabla \cdot q_f = q_{sf}(T_{\text{solid}} - T_f) + (1 - \theta_p)Q_f \\ q_f = -(1 - \theta_p)\lambda_f \nabla T_f \end{cases} \quad (\text{C.13})$$

When the temperatures of the two phases are not the same, the Local Thermal Non-Equilibrium multiphysics coupling introduces the opposite heat sources $q_{sf}(T_f - T_s)$ and $q_{sf}(T_s - T_f)$ that each phase gets from or gives to the other. The temperature of the porous medium, T_p , is defined as follows (Carbonell and Whitaker, 1984):

$$T_p = \frac{\theta_p \rho_{\text{solid}} C_{p,s} T_{\text{solid}} + (1 - \theta_p) \rho_f C_{p,f} T_f}{\theta_p \rho_s C_{p,s} + (1 - \theta_p) \rho_f C_{p,f}} \quad (\text{C.14})$$

C.4 Correlation for the interstitial convective heat transfer coefficient

The spherical pellet bed configuration has a built-in correlation for q_{sf} that can be used with the Local Thermal Non-Equilibrium Multiphysics feature (Bejan, 2013):

$$q_{sf} = \text{SSA } h_{sf} \quad (\text{C.15})$$

For a bed of spherical particles with radius r_p , the specific surface area, a_{sf} (m^{-1}), is (Bejan, 2013):

$$a_{sf} = \frac{6\theta_p}{2r_p} \quad (\text{C.16})$$

The relation for the interstitial heat transfer coefficient, h_{sf} ($\text{W m}^{-2} \text{K}^{-1}$), is (COMSOL, 2008):

$$\frac{1}{h_{sf}} = \frac{2r_p}{\lambda_f Nu} + \frac{2r_p}{\beta \lambda_{solid}} \quad (C.17)$$

The fluid-to-solid Nusselt number, Nu , is obtained from the following correlation, and β is equal to 10 for spherical particles (Wakao et al., 1979):

$$Nu = 2 + 1.1 p_r^{1/3} Re_p^{0.6} \quad (C.18)$$

The definitions of the Prandtl number, P_r , and the particle Reynolds number, Re_p , are (Wakao et al., 1979):

$$P_r = \frac{\mu C_{p,f}}{\lambda_f} \quad \text{and} \quad Re_p = \frac{2r_p \rho_f \|u_f\|}{\mu} \quad (C.19)$$

C.5 Effective thermal conductivity type

In this project among the eight different types for effective thermal conductivity in the COMSOL Multiphysics (Appendix B), the “Plane layers parallel to heat flow” model was chosen. This model simplifies the mathematical formulation, allowing for easier and faster calculations. This is crucial when managing large snow piles where quick decision-making is essential. By using this model, computational resource requirements are reduced, which is beneficial when dealing with extensive simulations needed for predicting the melting behavior of large snow piles. Faster simulation times mean more timely and efficient snow management operations. The default option of “Plane layers parallel to heat flow” computes the effective conductivity of the solid-fluid system by taking the weighted arithmetic mean, or volume average, of the conductivities of both the fluid and the porous matrix. This approach ensures that the model remains computationally efficient while providing accurate predictions of thermal behavior in the system. The choice of the “Plane layers parallel to heat flow” model assumed that the porous media is considered uniform. This uniformity implies that there is no significant difference between using a perpendicular or parallel model for the heat flow. The parallel model was selected because it simplifies the calculations and reduces computational time, which is advantageous for large-scale simulations.

By choosing this model, the research benefits from a balance between computational efficiency and the accuracy of the thermal predictions, making it a suitable choice for the study of snowmelt in large piles.

C.6 Plane layers parallel to heat flow

The default option of "Plane layers parallel to heat flow" computes the effective conductivity of the solid-fluid system by taking the weighted arithmetic mean, or volume average, of the conductivities of both the fluid and the porous matrix.

$$\lambda_{eff} = \theta_{solid}\lambda_{solid} + \varepsilon_p\lambda_f \quad (\text{C.20})$$

APPENDIX D Geometric Properties of the 70 Modeled SMPs

Table D.1 Geometric Properties of the 70 Modeled SMPs

Number of Pile	Type of Pile	Weather Function (Holt or Goldex)	Height (m)	Width (m)	Radius (m)	Length (m)	Area (m²)	Volume (m³)	Melt Duration (D)
1	Cone	2023	3	-	12.5	-	490.87	509.3	32
2	Cone	2023	4	-	15.5	-	754.76	1036.4	50
3	Cone	2023	5.6	-	20	-	1256.63	2400.3	53
4	Cone	2023	6	-	21.5	-	1451.46	2966.7	64
5	Cone	2023	7.33	-	23	-	1661.06	4142.7	68
6	Cone	2023	8	-	26	-	2123.71	5747	74
7	Cone	2023	9	-	29	-	2640.74	8028.6	81
8	Cone	2023	10	-	32	-	3216	10856	92
9	Cone	2022	6	-	11	-	380.13	792.19	67
10	Cone	2022	7.3	-	14	-	615.75	1547.4	75
11	Cone	2022	8	-	17	-	907.92	2474.1	78
12	Cone	2022	9	-	20	-	1256.63	3847	81
13	Cone	2022	10	-	23	-	1661.9	5618.2	91
14	Ramp	2023	3	9	-	21	189	330.75	35
15	Ramp	2023	4	12	-	24	288	672	45

16	Ramp	2023	5	15	-	27	405	1181.3	54
17	Ramp	2023	5.8	18	-	30	540	1827	58
18	Ramp	2023	7	21	-	33	693	2829.8	76
19	Ramp	2023	8	24	-	36	864	4032	87
20	Ramp	2023	9	27	-	39	1053	5528.2	91
21	Ramp	2023	10	30	-	42	1260	7350	110
22	Ridge	2022	3.5	25	-	50	1250	2552.1	66
23	Ridge	2022	4.5	28	-	53	1484	3895.5	69
24	Ridge	2022	5.5	31	-	56	1736	5569.7	79
25	Ridge	2022	6.5	34	-	59	2006	7606.1	93
26	Ridge	2022	7.5	37	-	62	2294	10036	97
27	Ridge	2022	8.5	40	-	65	2600	12892	104
28	Ridge	2022	9.5	43	-	68	2924	16204	113
29	Cubic	2022	3.5	33	-	33	1089	2223.4	65
30	Cubic	2022	4.5	37	-	37	1369	3593.6	73
31	Cubic	2022	5.5	40	-	40	1600	5133.3	77
32	Cubic	2022	6.5	43	-	43	1849	7010.8	82
33	Cubic	2022	7.5	46	-	46	2116	9257.5	90
34	Cubic	2022	8.5	49	-	49	2401	11905	97
35	Cubic	2022	9.5	52	-	52	2704	14985	120

36	Cone	2022	3	-	12.5	-	490.87	509.3	32
37	Cone	2022	4	-	15.5	-	754.76	1036.4	50
38	Cone	2022	5.6	-	20	-	1256.63	2400.3	53
39	Cone	2022	6	-	21.5	-	1451.46	2966.7	64
40	Cone	2022	7.33	-	23	-	1661.06	4142.7	68
41	Cone	2022	8	-	26	-	2123.71	5747	74
42	Cone	2022	9	-	29	-	2640.74	8028.6	81
43	Cone	2022	10	-	32	-	3216	10856	92
44	Ramp	2022	3	9	-	21	189	330.75	59
45	Ramp	2022	4	12	-	24	288	672	66
46	Ramp	2022	5	15	-	27	405	1181.3	70
47	Ramp	2022	5.8	18	-	30	540	1827	74
48	Ramp	2022	7	21	-	33	693	2829.8	85
49	Ramp	2022	8	24	-	36	864	4032	93
50	Ramp	2022	9	27	-	39	1053	5528.2	97
51	Ramp	2022	10	30	-	42	1260	7350	112
52	Cone	2023	6	-	11	-	380.13	792.19	48
53	Cone	2023	7.3	-	14	-	615.75	1547.4	55
54	Cone	2023	8	-	17	-	907.92	2474.1	69
55	Cone	2023	9	-	20	-	1256.63	3847	72

56	Cone	2023	10	-	23	-	1661.9	5618.2	78
57	Ridge	2023	3.5	25	-	50	1250	2552.1	41
58	Ridge	2023	4.5	28	-	53	1484	3895.5	51
59	Ridge	2023	5.5	31	-	56	1736	5569.7	57
60	Ridge	2023	6.5	34	-	59	2006	7606.1	65
61	Ridge	2023	7.5	37	-	62	2294	10036	81
62	Ridge	2023	8.5	40	-	65	2600	12892	85
63	Ridge	2023	9.5	43	-	68	2924	16204	91
64	Cubic	2023	3.5	33	-	33	1089	2223.4	42
65	Cubic	2023	4.5	37	-	37	1369	3593.6	57
66	Cubic	2023	5.5	40	-	40	1600	5133.3	60
67	Cubic	2023	6.5	43	-	43	1849	7010.8	73
68	Cubic	2023	7.5	46	-	46	2116	9257.5	78
69	Cubic	2023	8.5	49	-	49	2401	11905	87
70	Cubic	2023	9.5	52	-	52	2704	14985	92

APPENDIX E Detailed Results for Each SMP

Pile Number 1

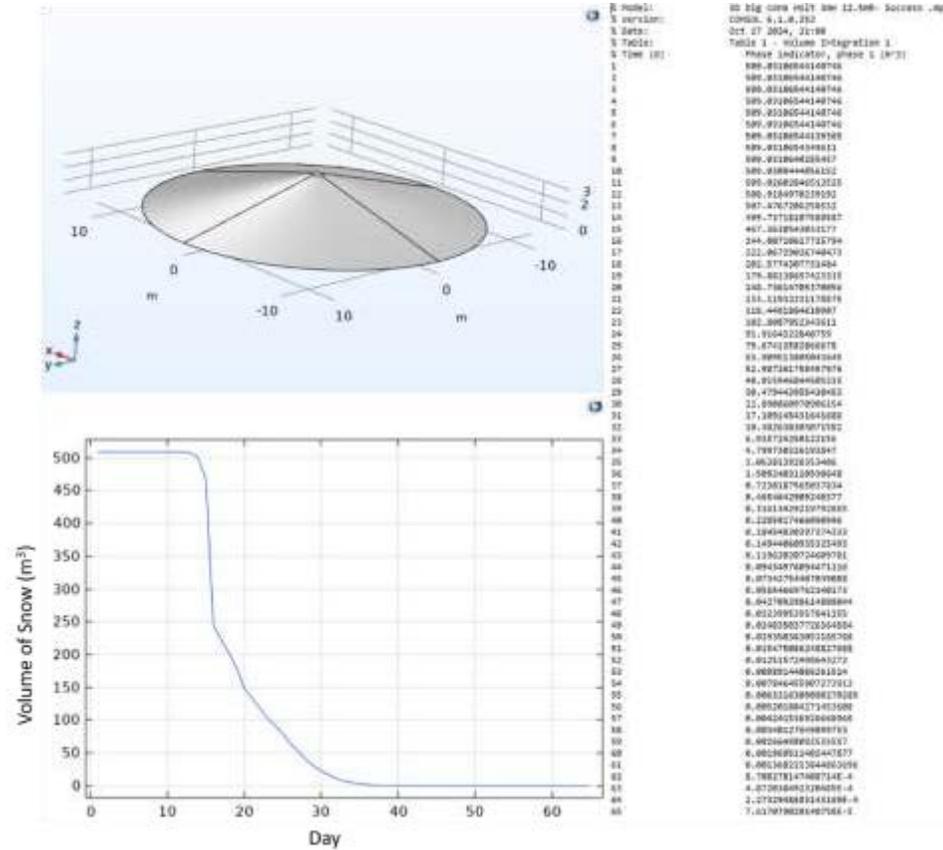


Figure E.1 Numerical modeling results for the cone (3 m height, and 12.5 m radius) SMP with 2023 weather function

Pile Number 2

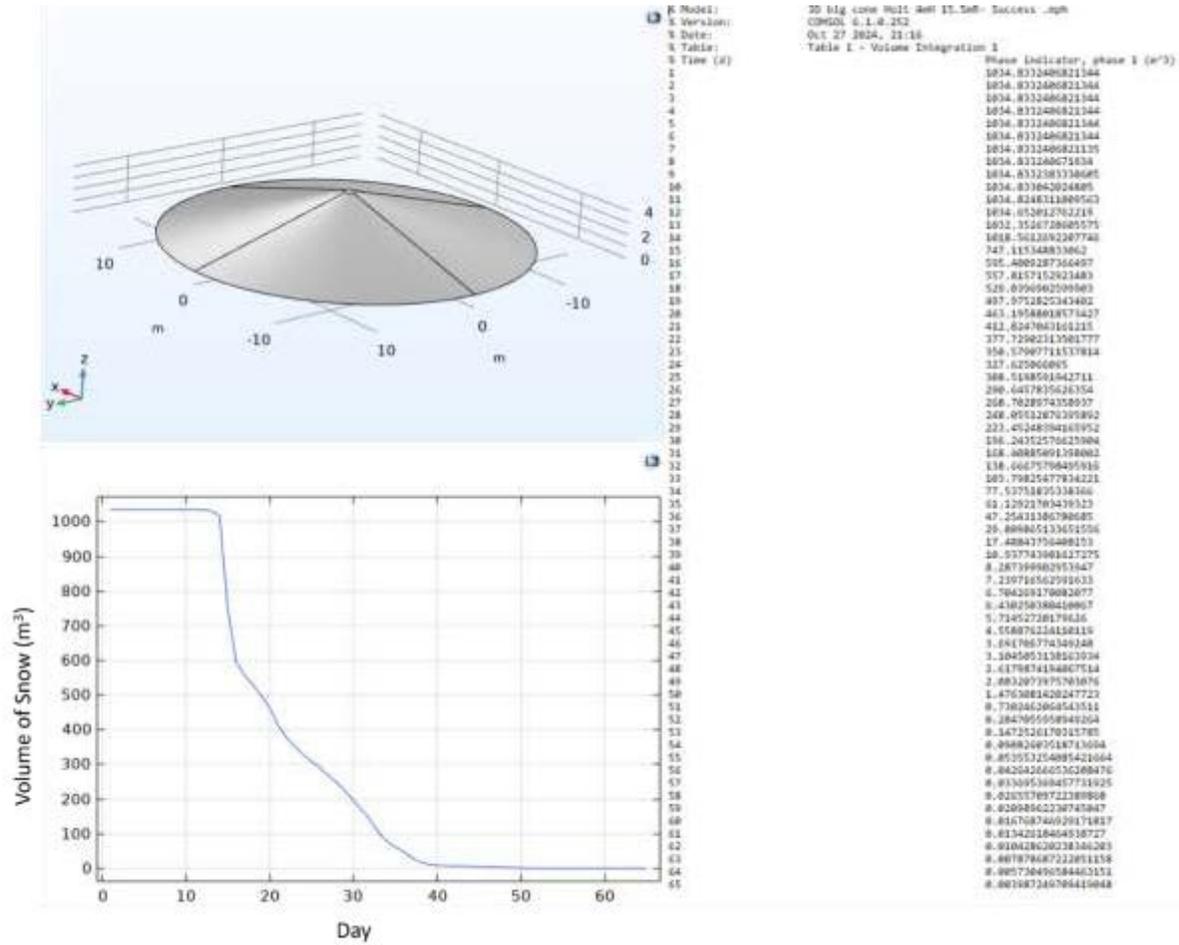


Figure E.2 Numerical modeling results for the cone (4 m height, and 15.5 m radius) SMP with 2023 weather function

Pile Number 3

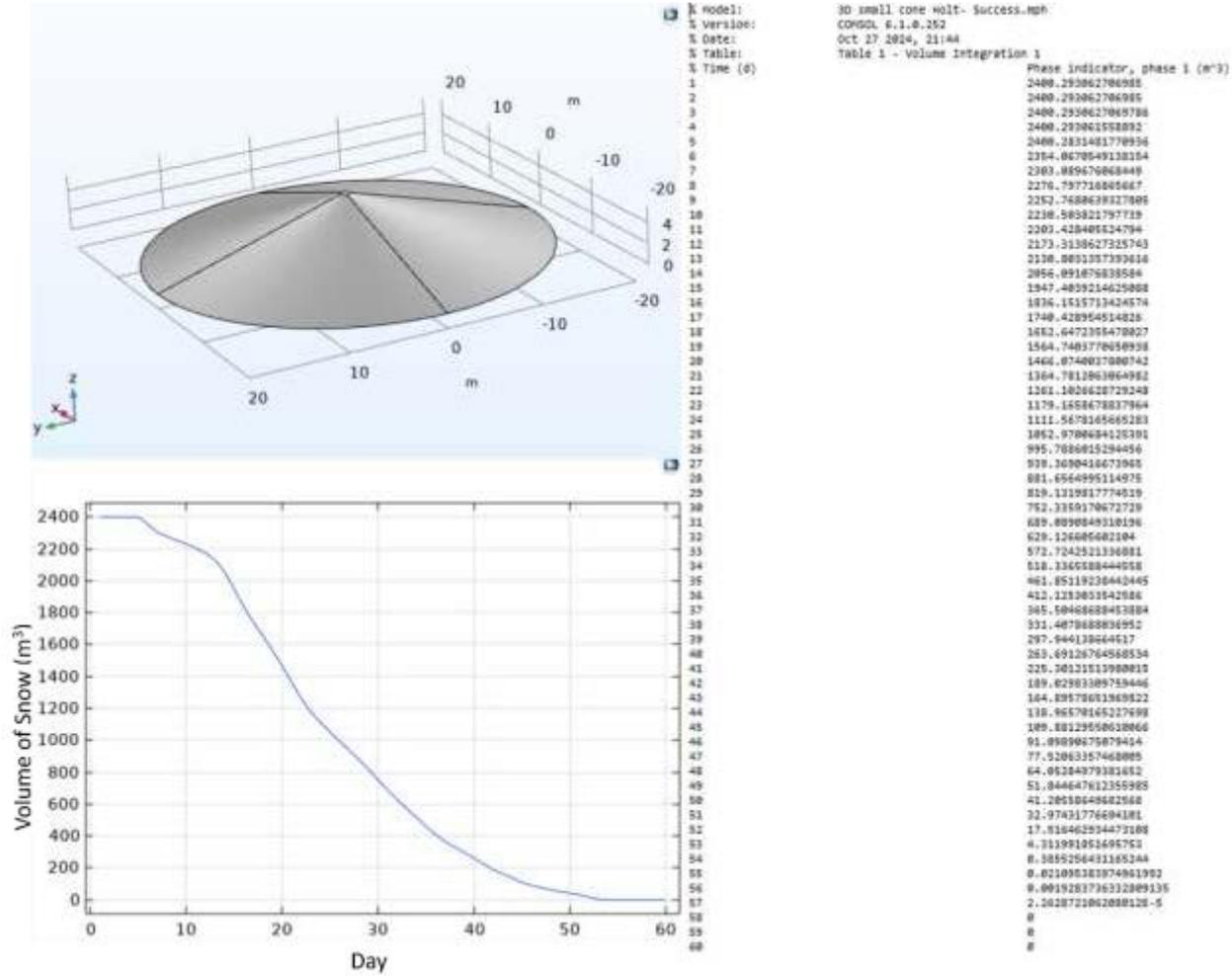


Figure E.3 Numerical modeling results for the cone (5.6 m height, and 20 m radius) SMP with 2023 weather function

Pile Number 4

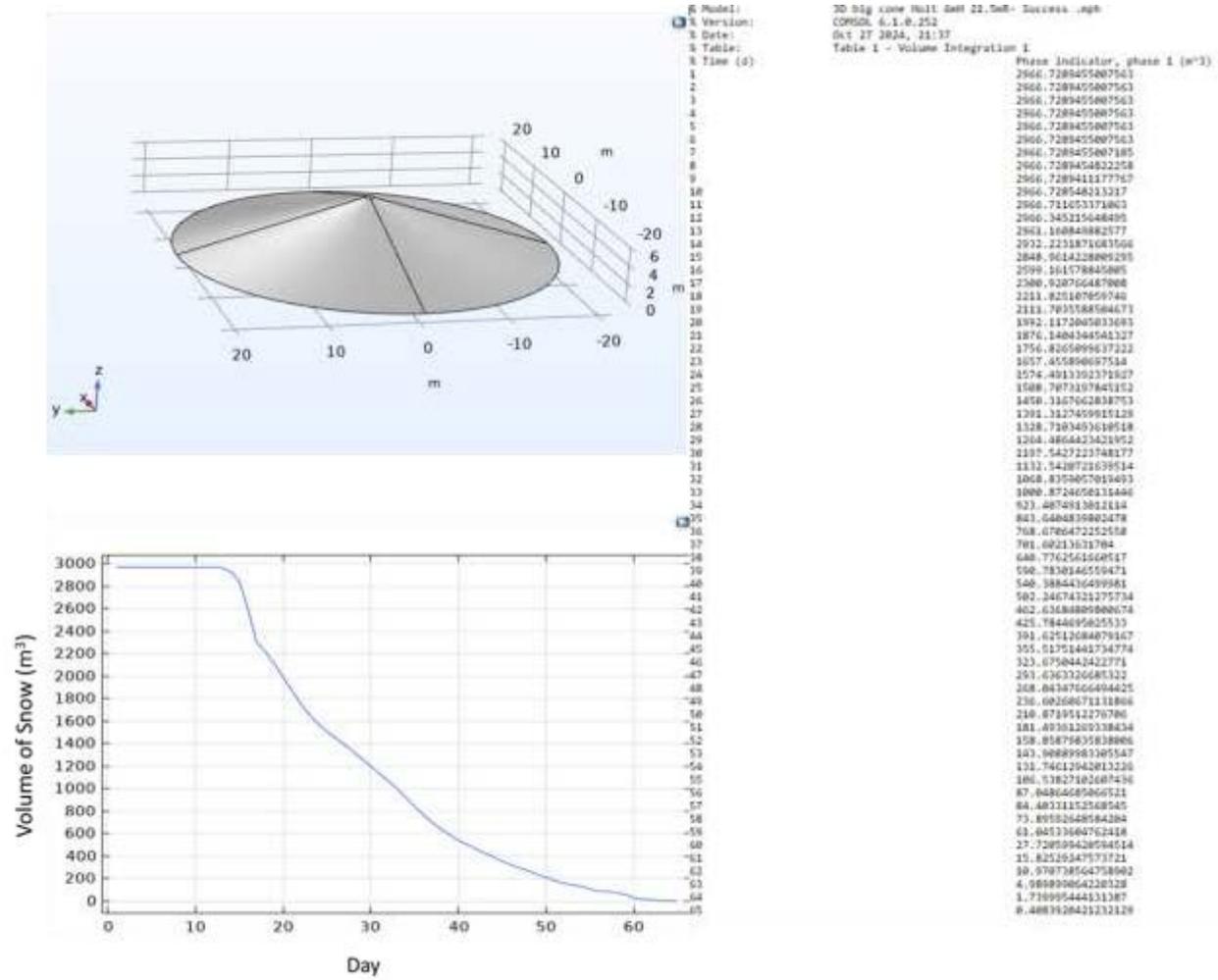


Figure E.4 Numerical modeling results for the cone (6 m height, and 21.5 m radius) SMP with 2023 weather function

Pile Number 5

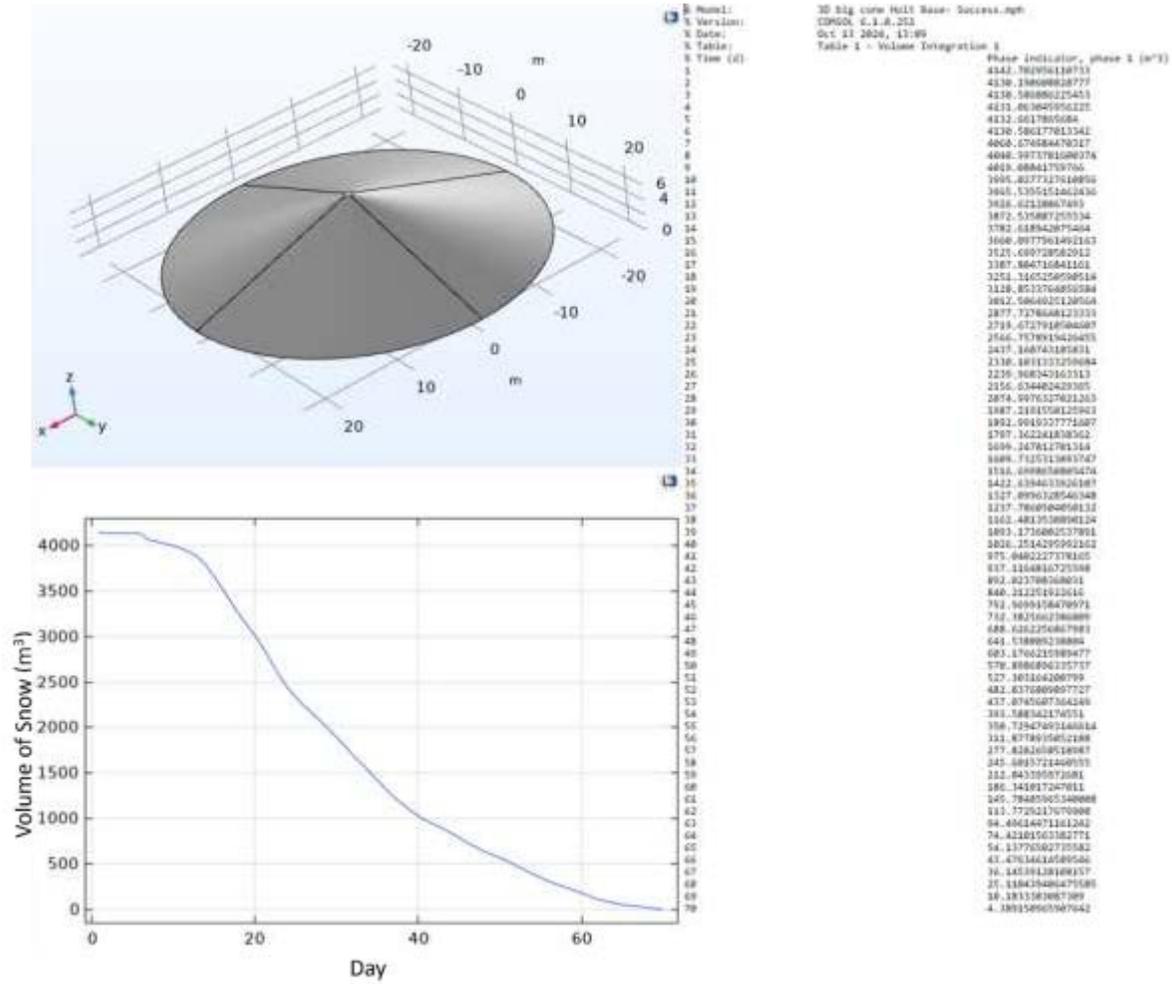


Figure E.5 Numerical modeling results for the cone (7.33 m height, and 23 m radius) SMP with 2023 weather function

Pile Number 6

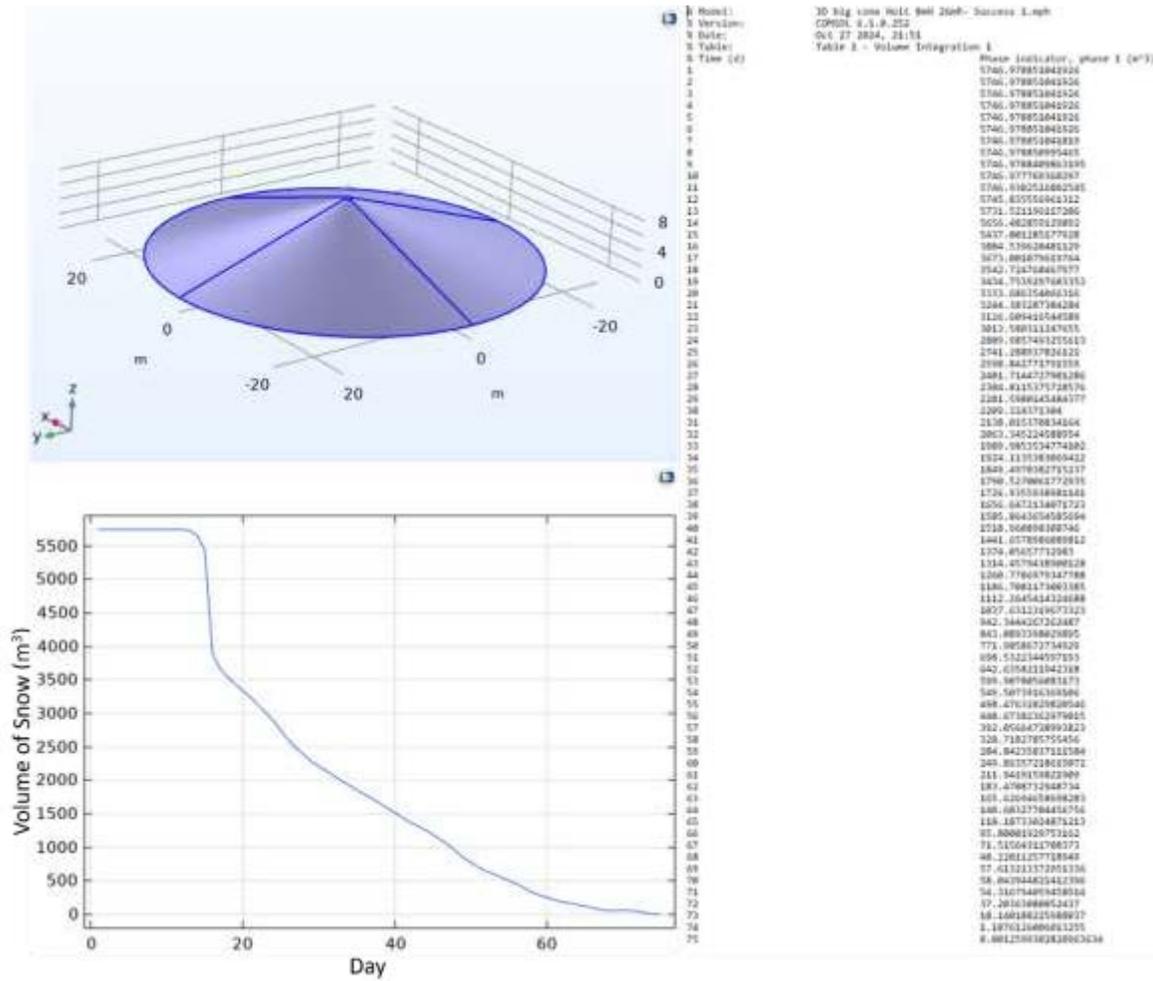


Figure E.6 Numerical modeling results for the cone (8 m height, and 26 m radius) SMP with 2023 weather function

Pile Number 7

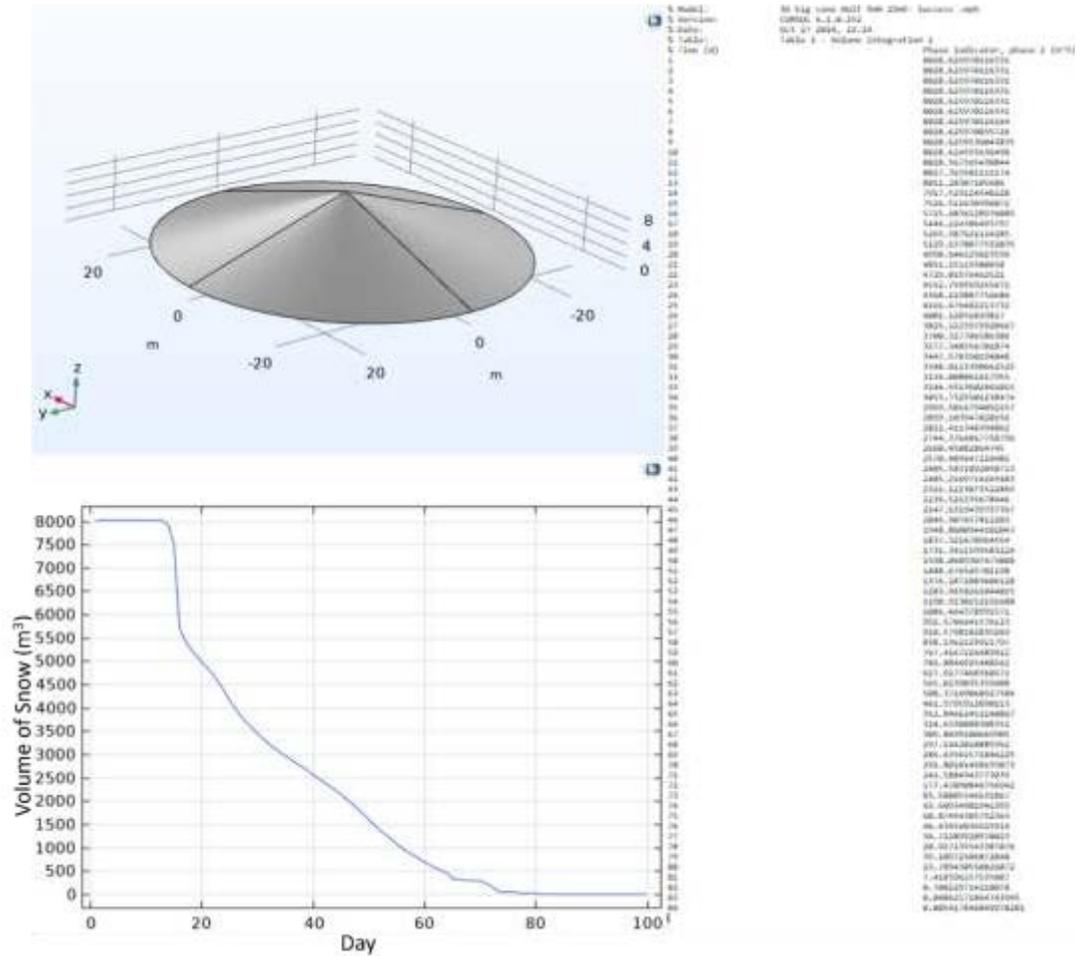


Figure E.7 Numerical modeling results for the cone (9 m height, and 29 m radius) SMP with 2023 weather function

Pile Number 8

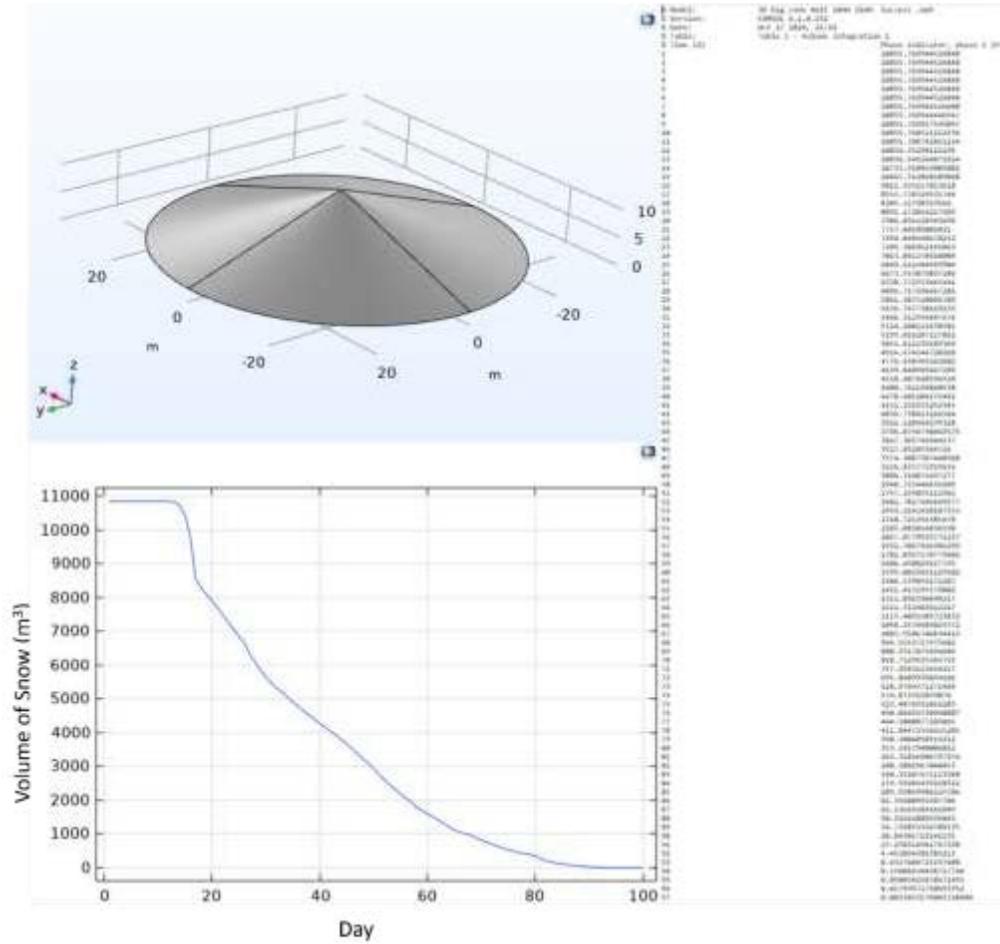


Figure E.8 Numerical modeling results for the cone (10 m height, and 32 m radius) SMP with 2023 weather function

Pile Number 9

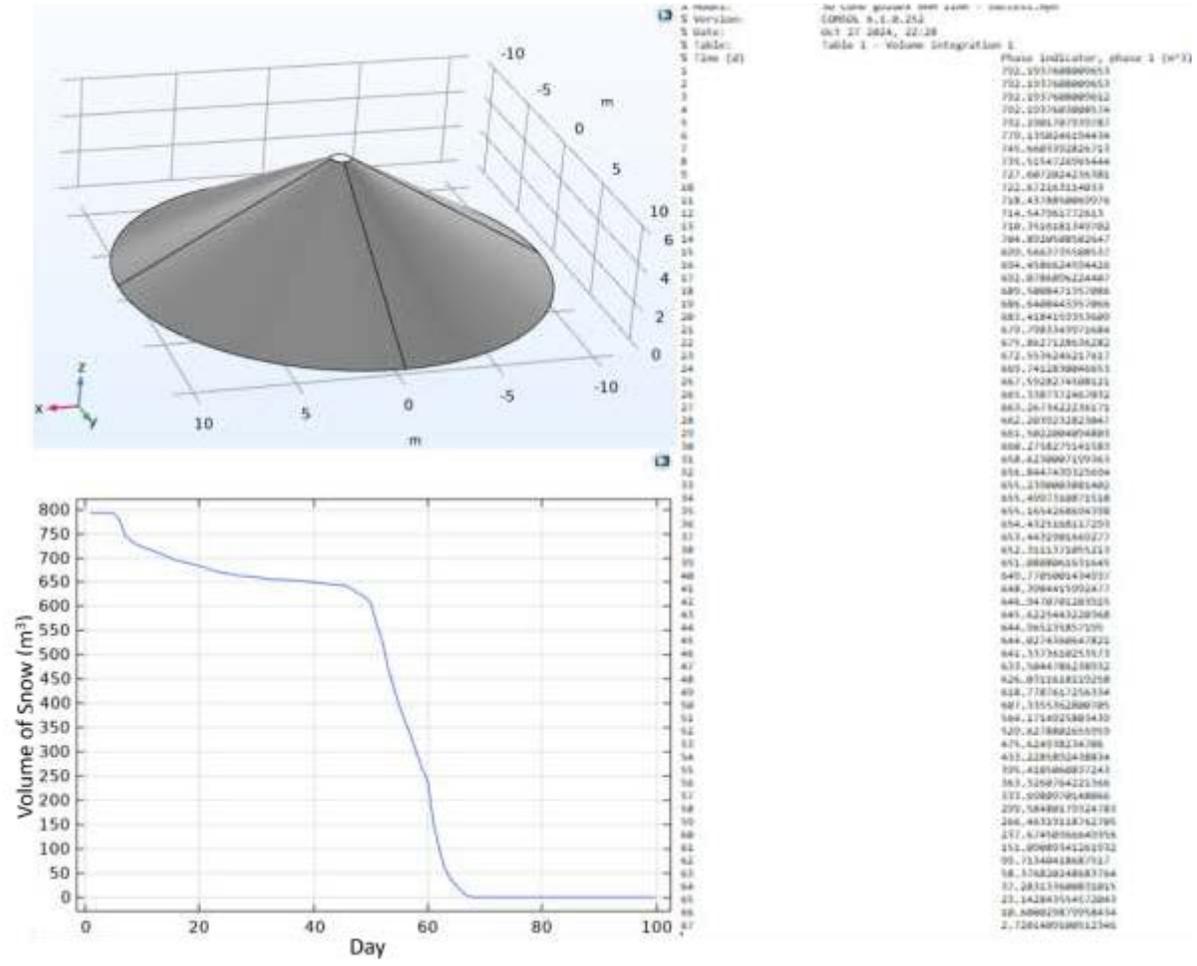


Figure E.9 Numerical modeling results for the cone (6 m height, and 11 m radius) SMP with 2022 weather function

Pile Number 10

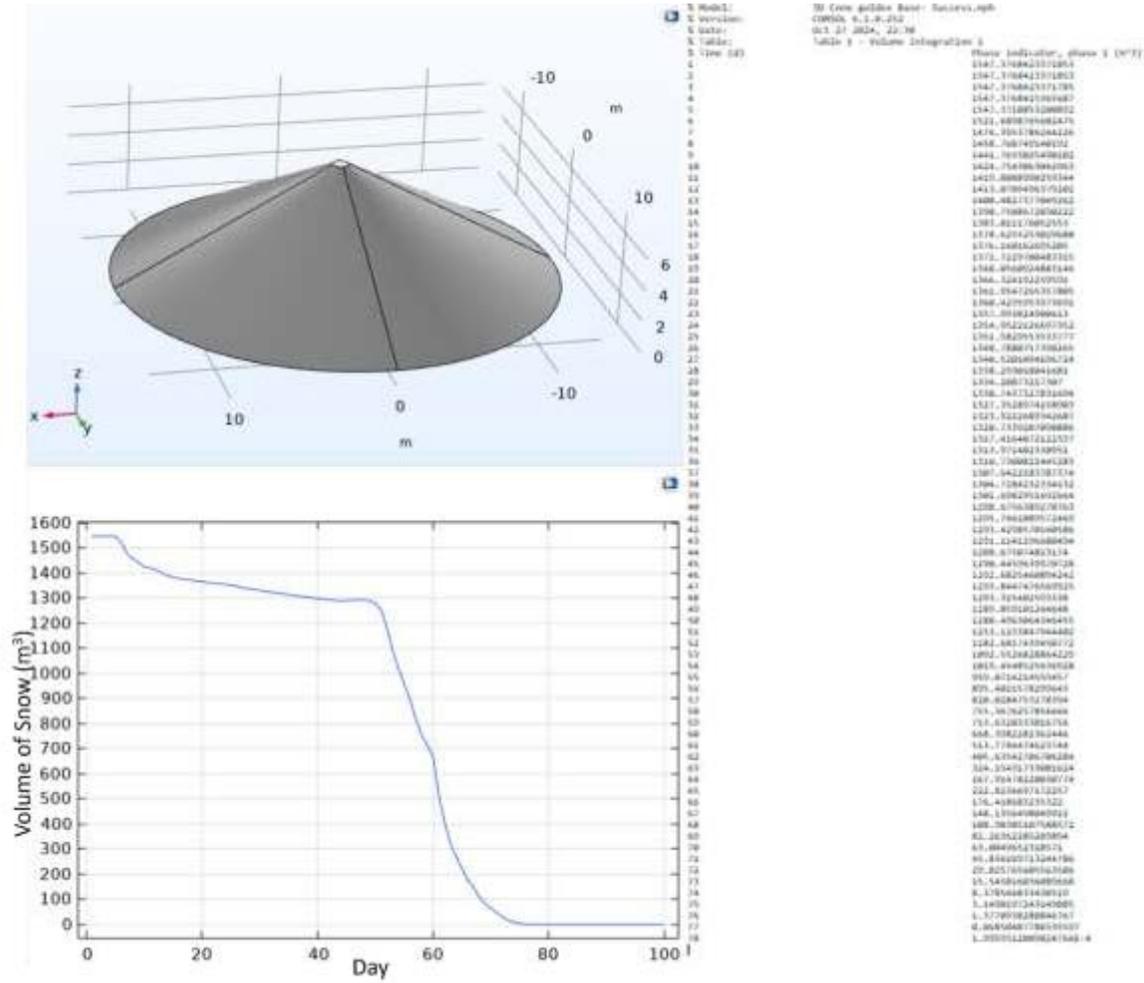


Figure E.10 Numerical modeling results for the cone (7.3 m height, and 14 m radius) SMP with 2022 weather function

Pile Number 11

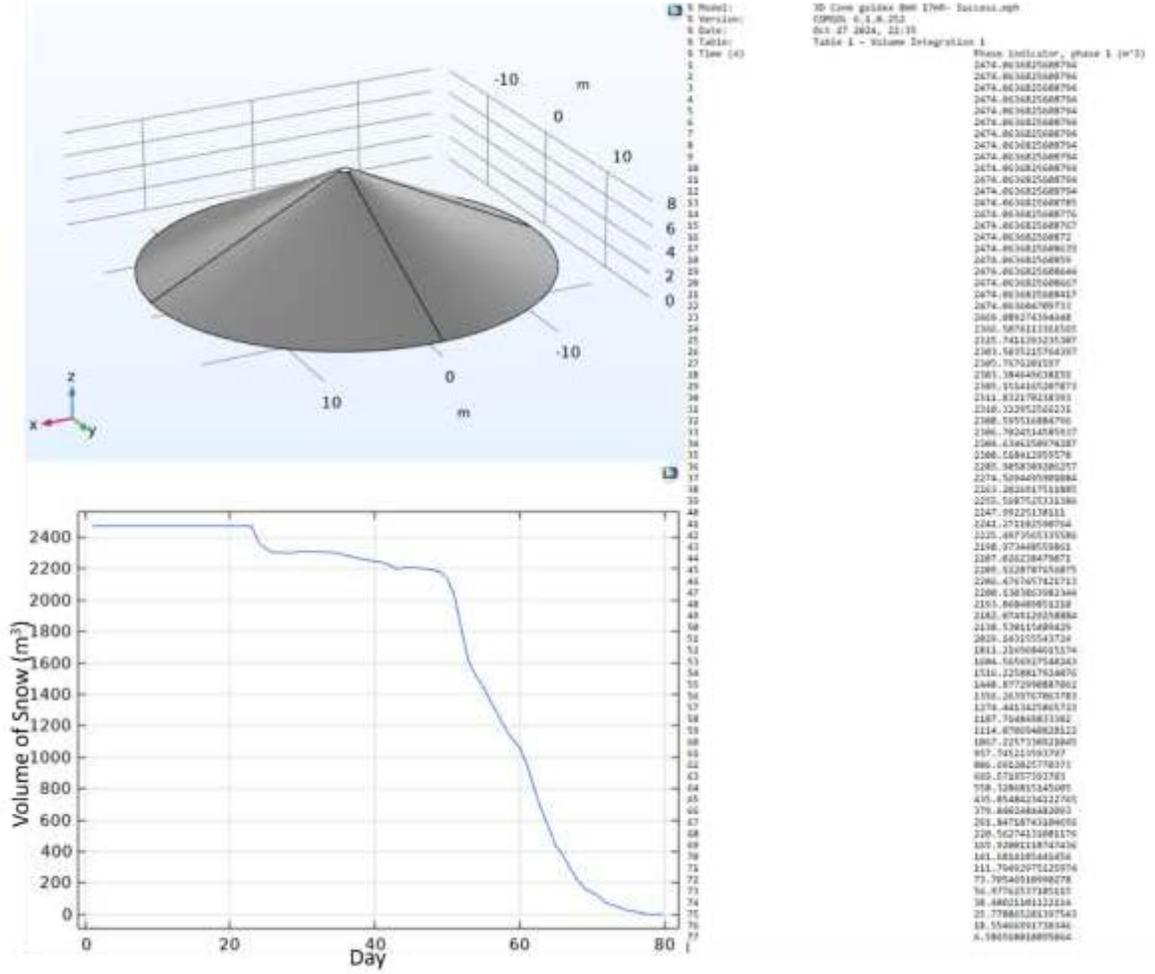


Figure E.11 Numerical modeling results for the cone (8 m height, and 17 m radius) SMP with 2022 weather function

Pile Number 12

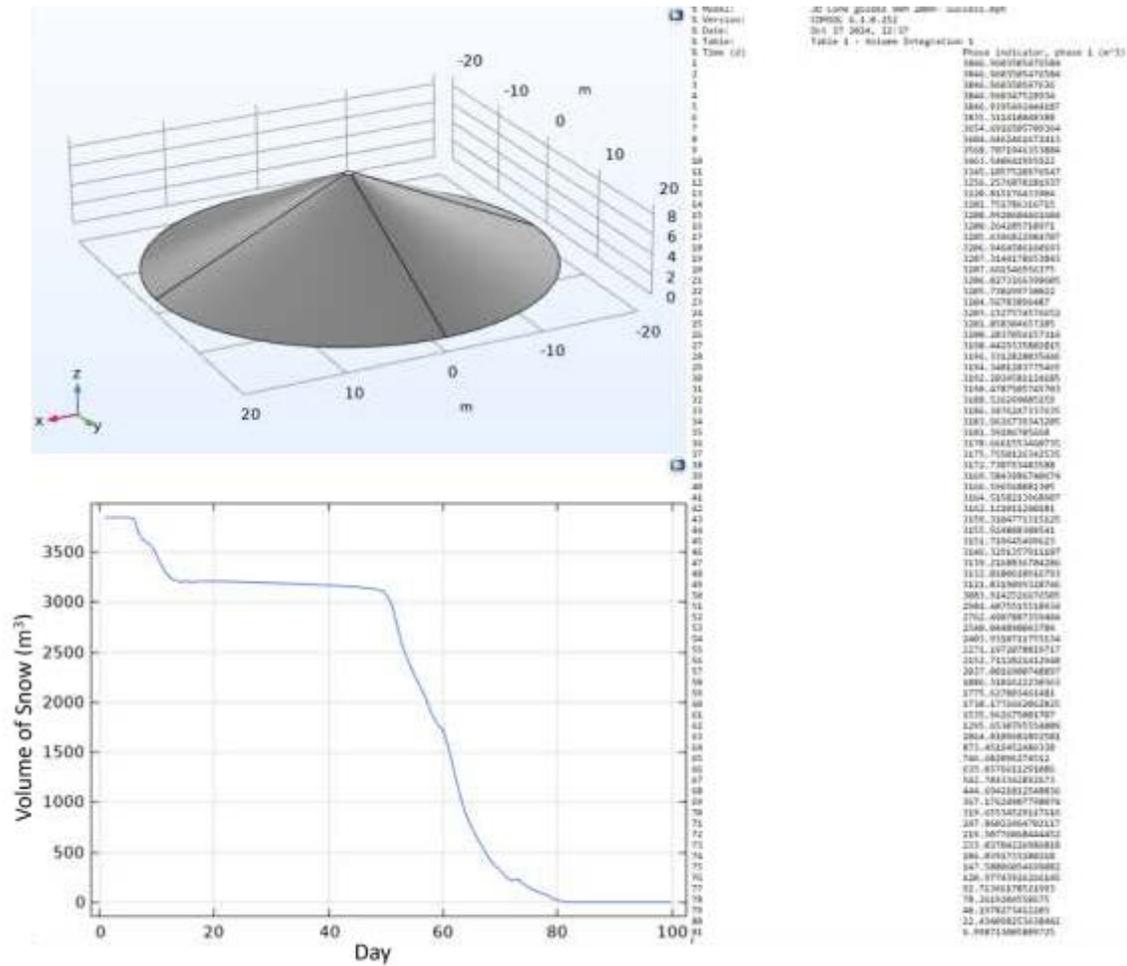


Figure E.12 Numerical modeling results for the cone (9 m height, and 20 m radius) SMP with 2022 weather function

Pile Number 13

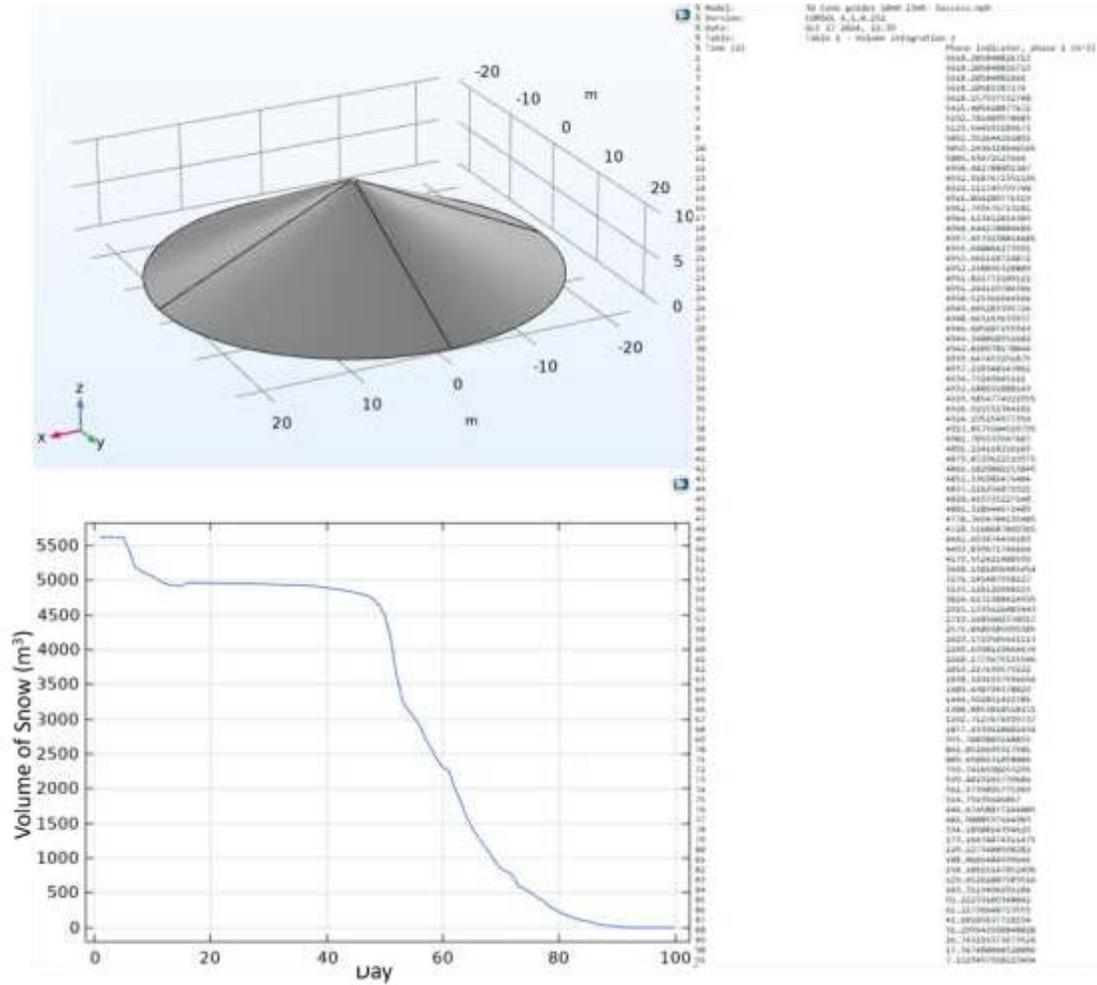


Figure E.13 Numerical modeling results for the cone (10 m height, and 23 m radius) SMP with 2022 weather function

Pile Number 14

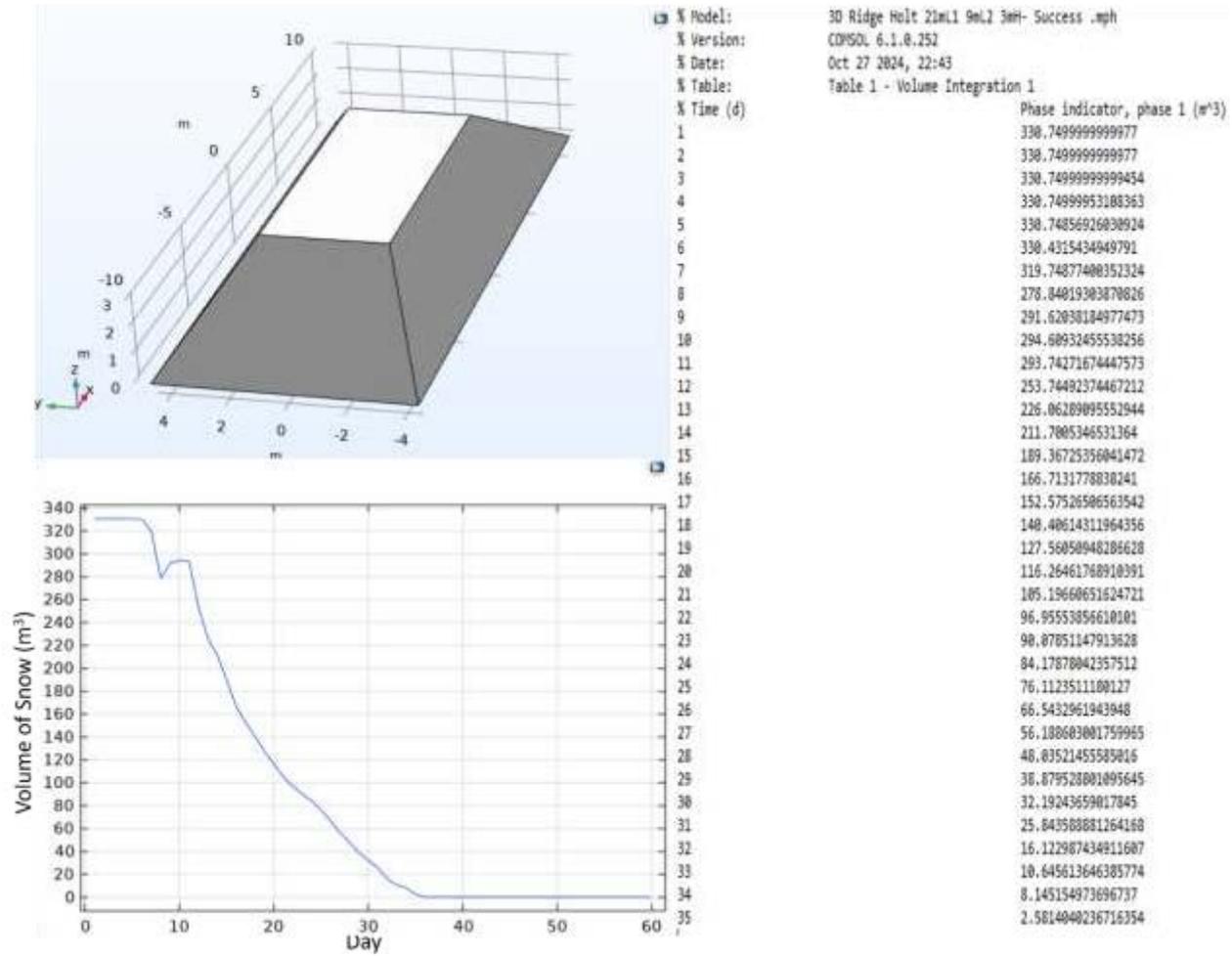


Figure E.14 Numerical modeling results for the ramp (3m height, 9 m width, and 21 length) SMP with 2023 weather function

Pile Number 15

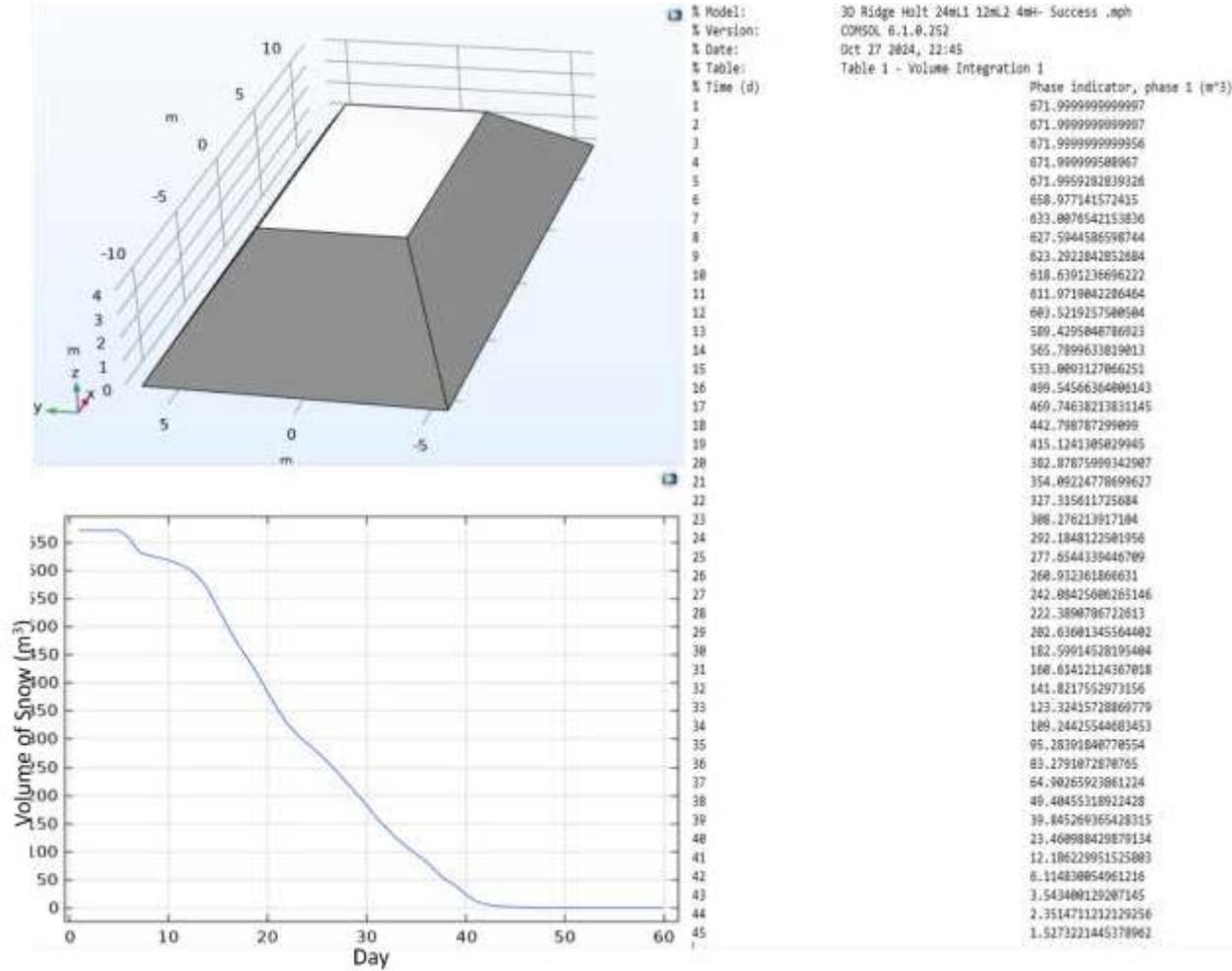


Figure E.15 Numerical modeling results for the ramp (4 m height, 12 m width, and 24 length) SMP with 2023 weather function

Pile Number 16

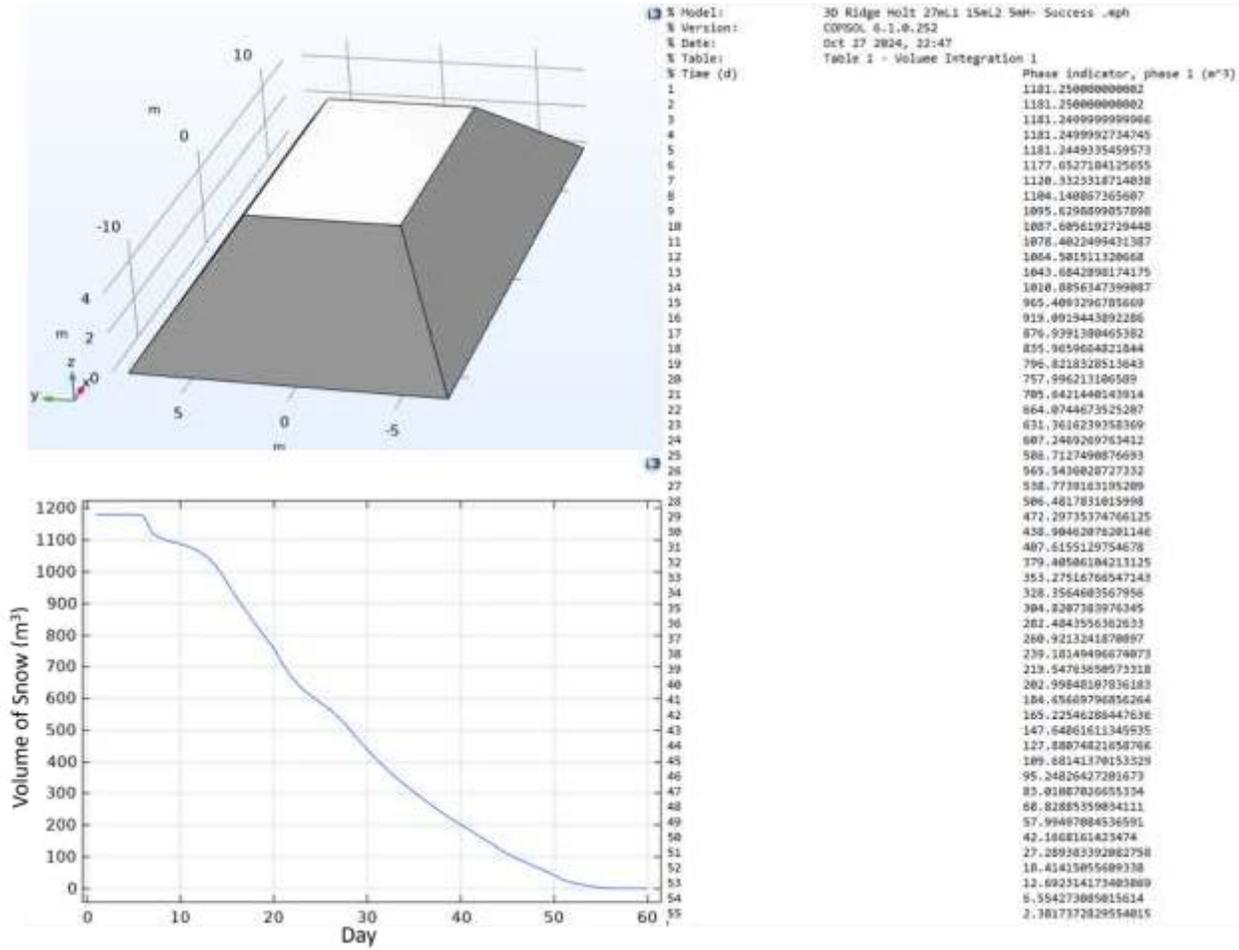


Figure E.16 Numerical modeling results for the ramp (5 m height, 15 m width, and 27 length) SMP with 2023 weather function

Pile Number 18

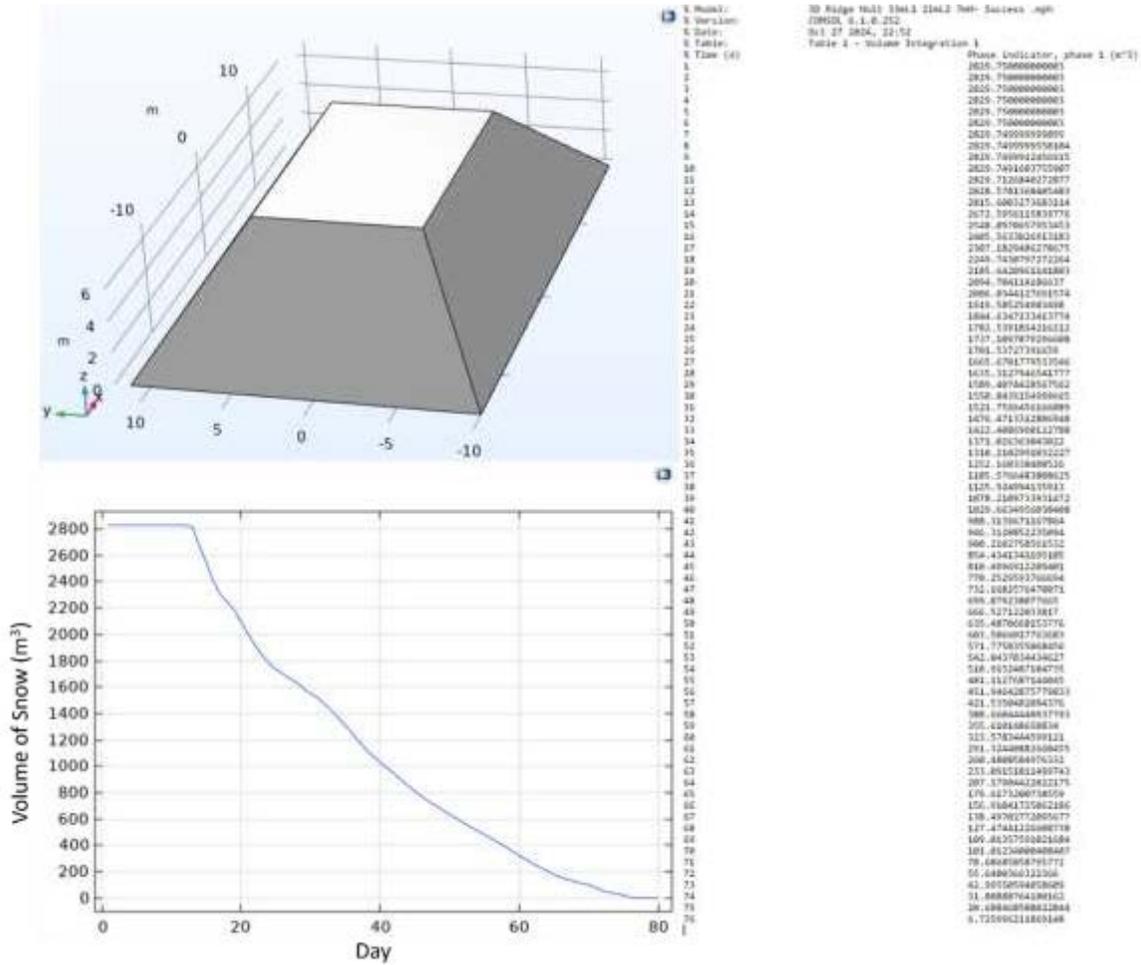


Figure E.18 Numerical modeling results for the ramp (7 m height, 21 m width, and 33 length) SMP with 2023 weather function

Pile Number 19

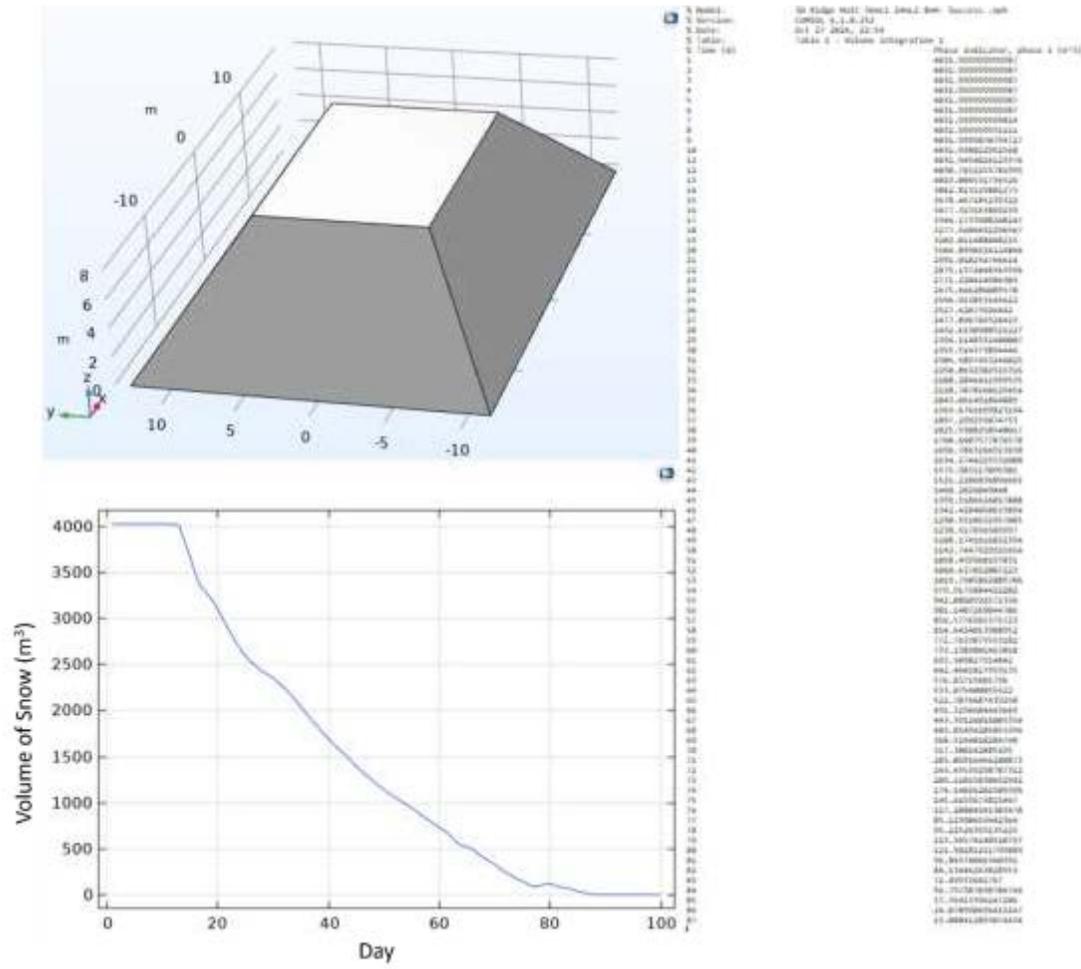


Figure E.19 Numerical modeling results for the ramp (8 m height, 24 m width, and 36 length) SMP with 2023 weather function

Pile Number 20

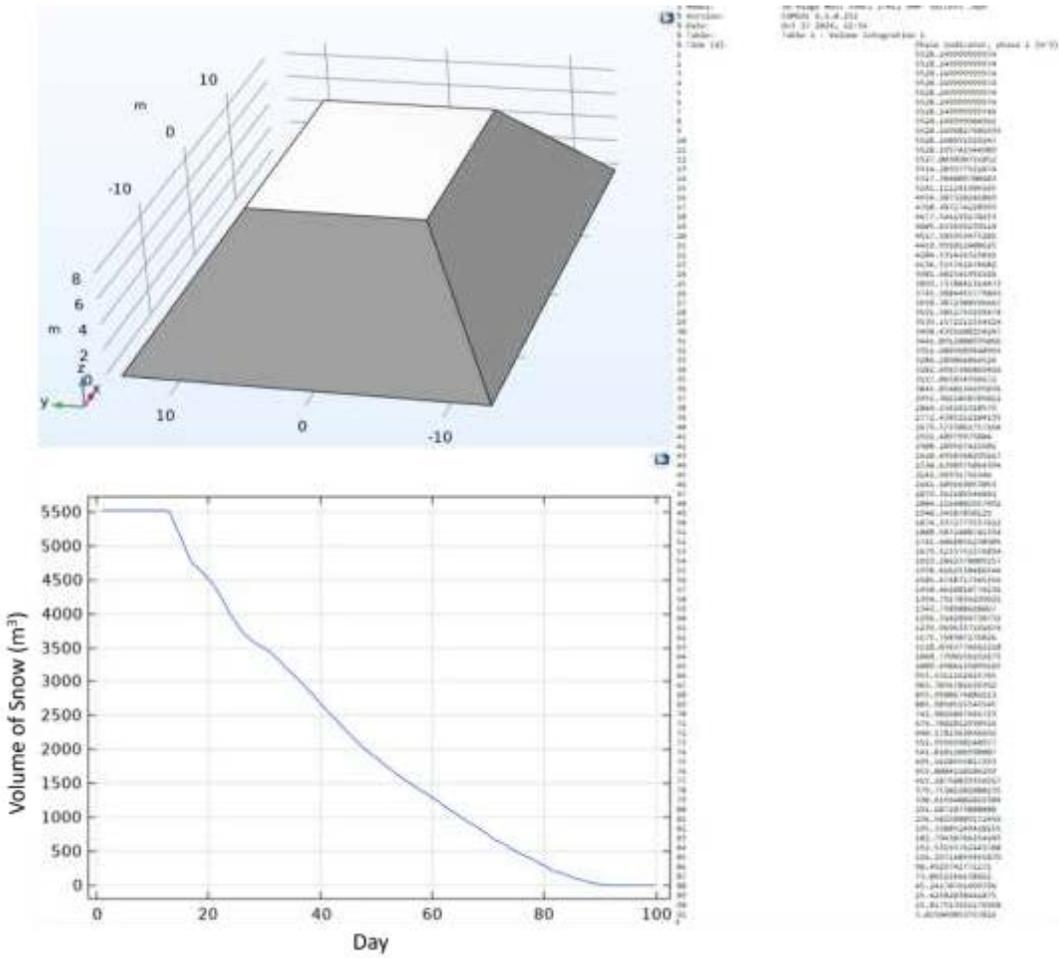


Figure E.20 Numerical modeling results for the ramp (9 m height, 27 m width, and 39 length) SMP with 2023 weather function

Pile Number 21

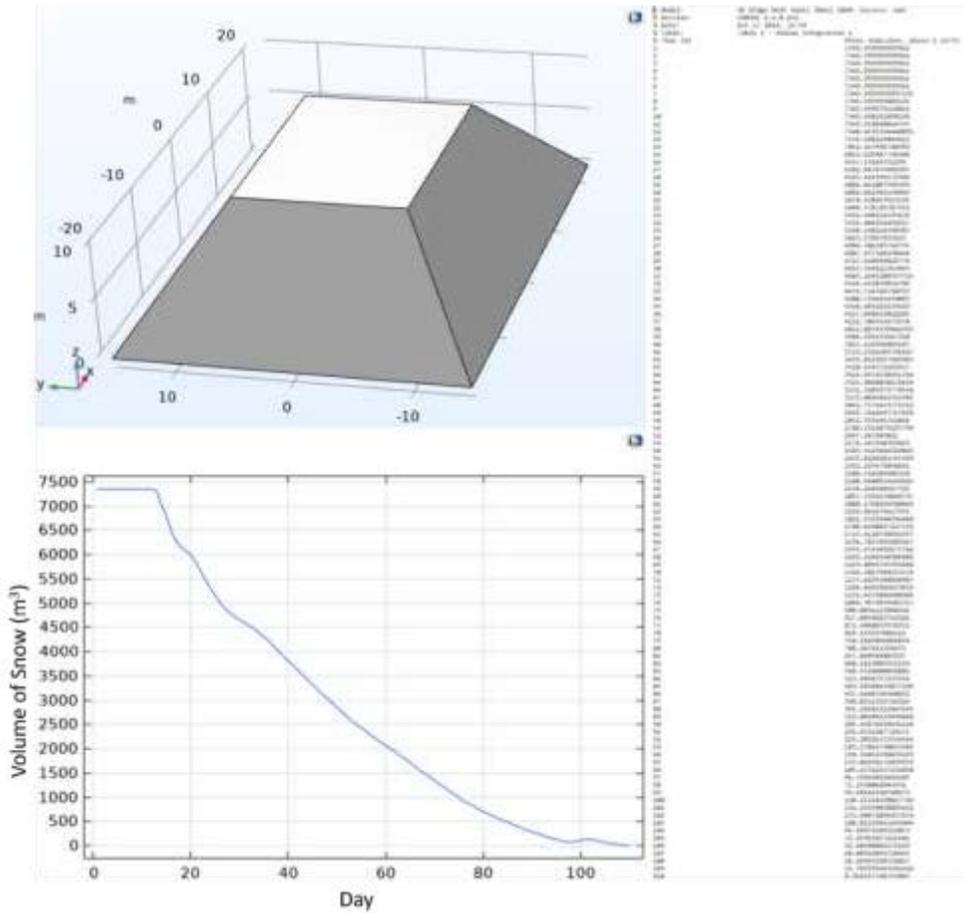


Figure E.21 Numerical modeling results for the ramp (10 m height, 30 m width, and 42 length) SMP with 2023 weather function

Pile Number 22

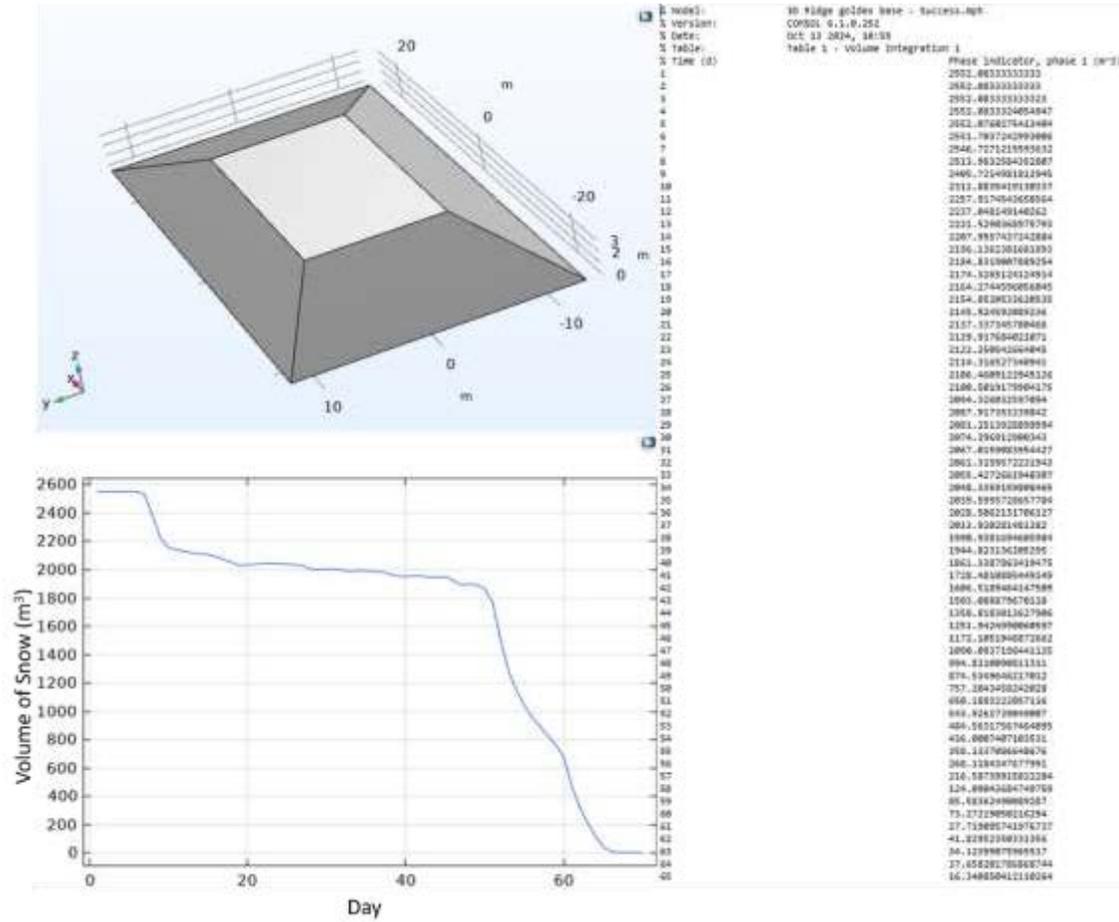


Figure E.22 Numerical modeling results for the ridge (3.5 m height, 25 m width, and 50 m length) SMP with 2022 weather function

Pile Number 23

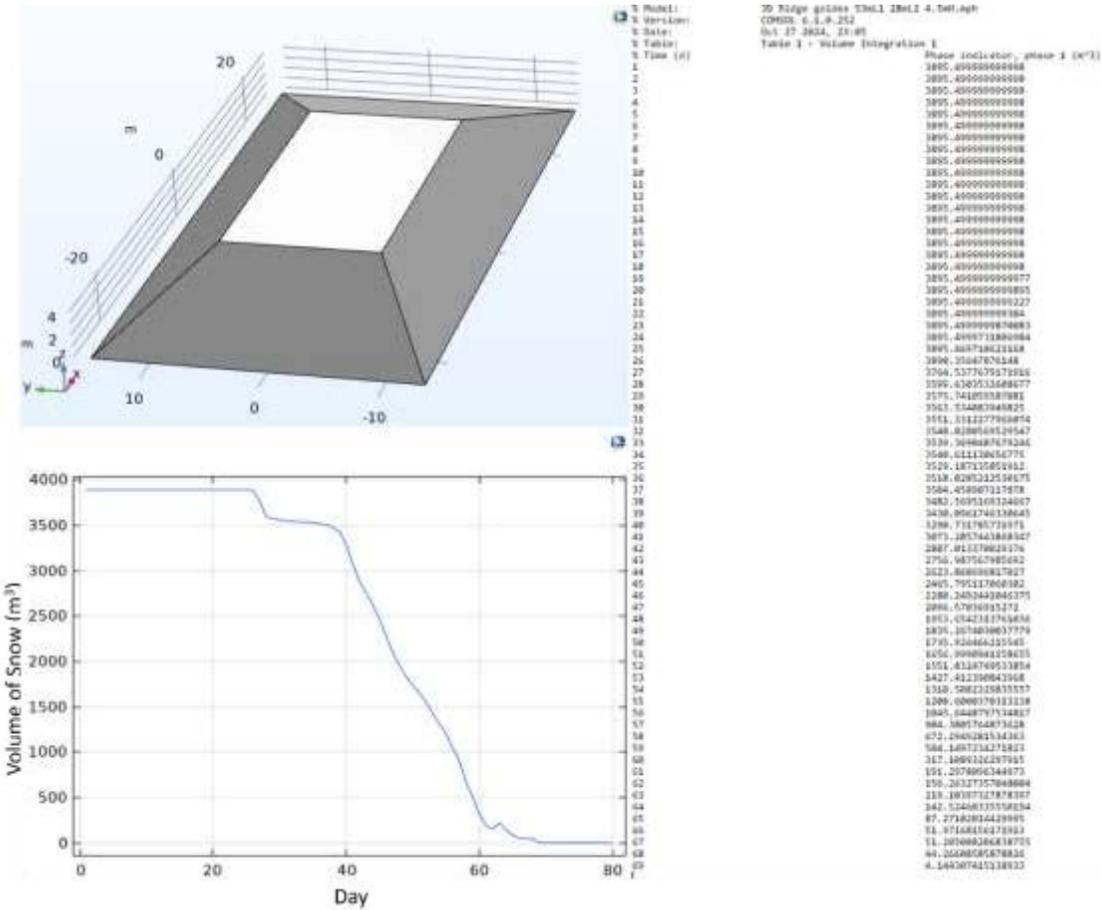


Figure E.23 Numerical modeling results for the ridge (4.5 m height, 28 m width, and 53 m length) SMP with 2022 weather function

Pile Number 24

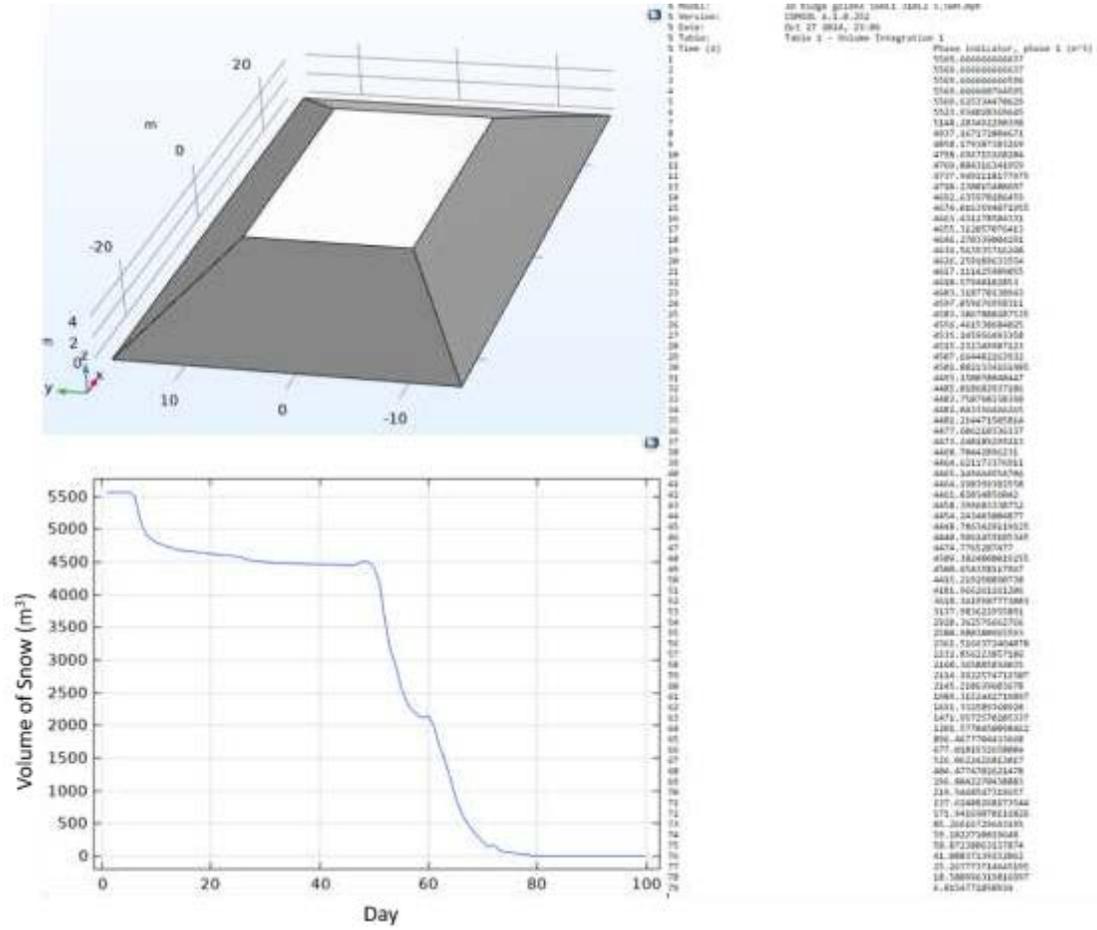


Figure E.24 Numerical modeling results for the ridge (5.5 m height, 31 m width, and 56 m length) SMP with 2022 weather function

Pile Number 25

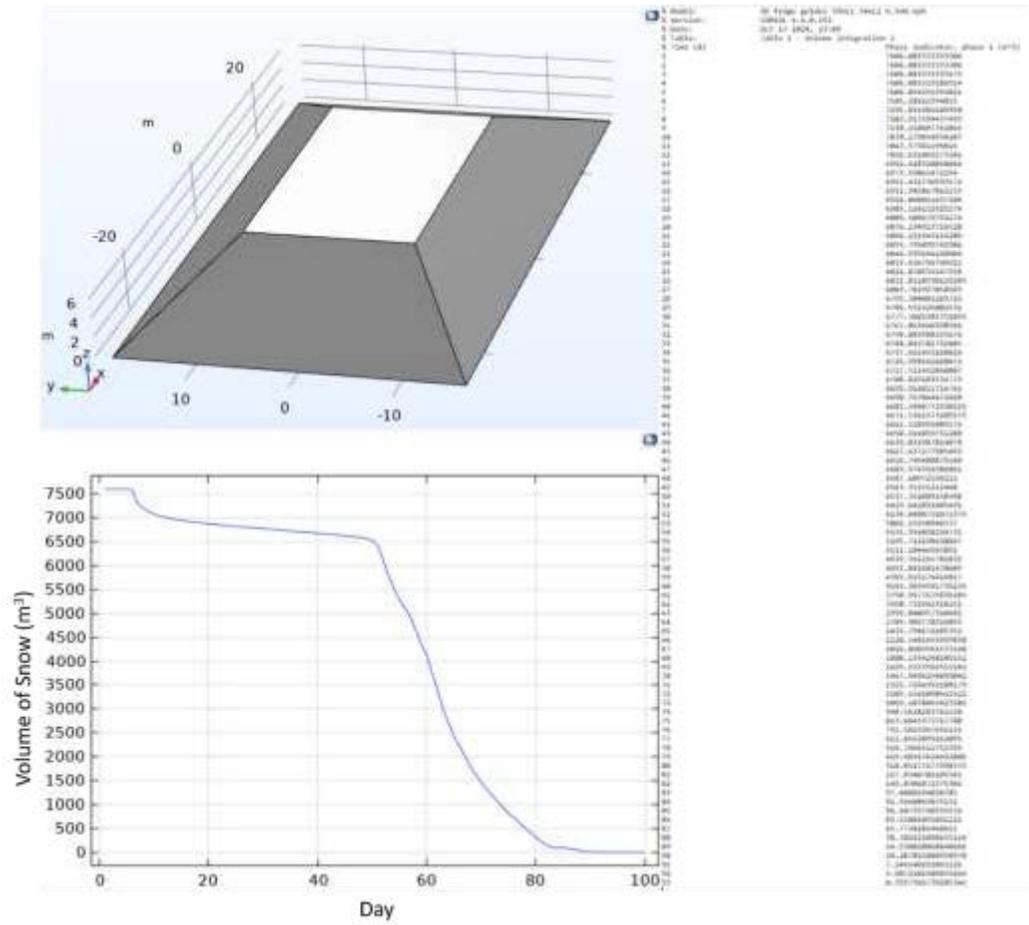


Figure E.25 Numerical modeling results for the ridge (6.5 m height, 34 m width, and 59 m length) SMP with 2022 weather function

Pile Number 26

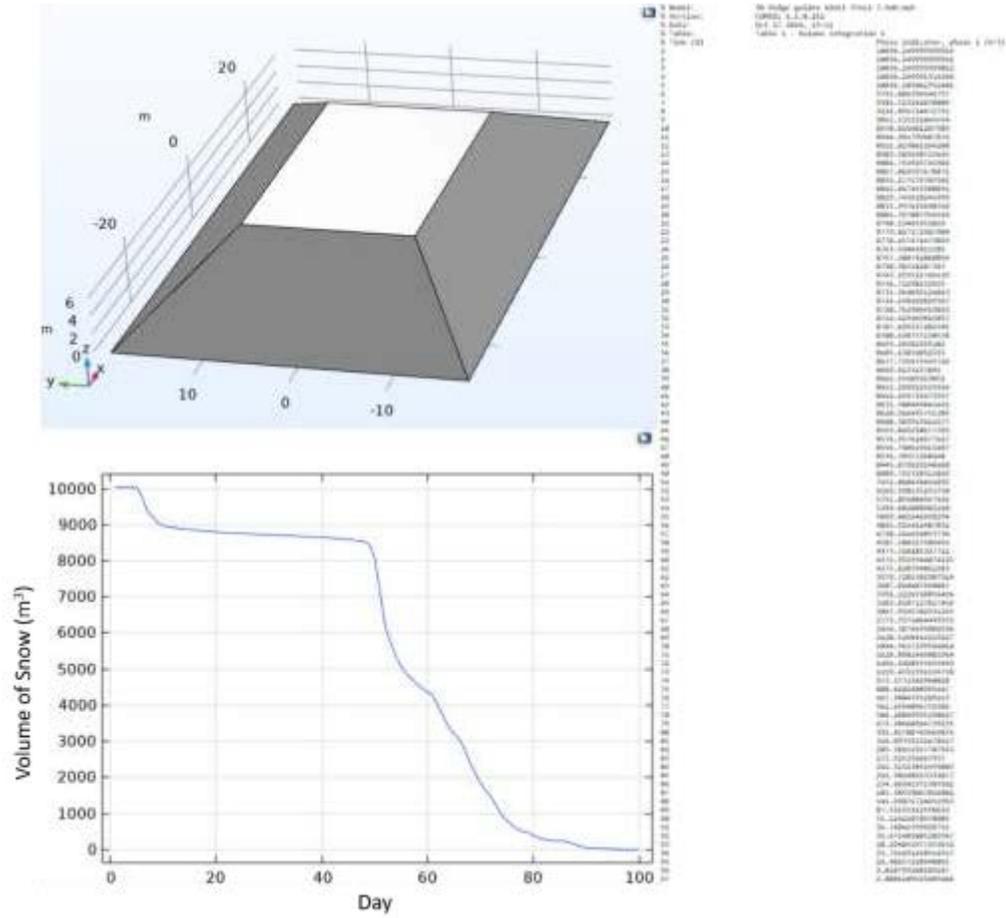


Figure E.26 Numerical modeling results for the ridge (7.5 m height, 37 m width, and 62 m length) SMP with 2022 weather function

Pile Number 27

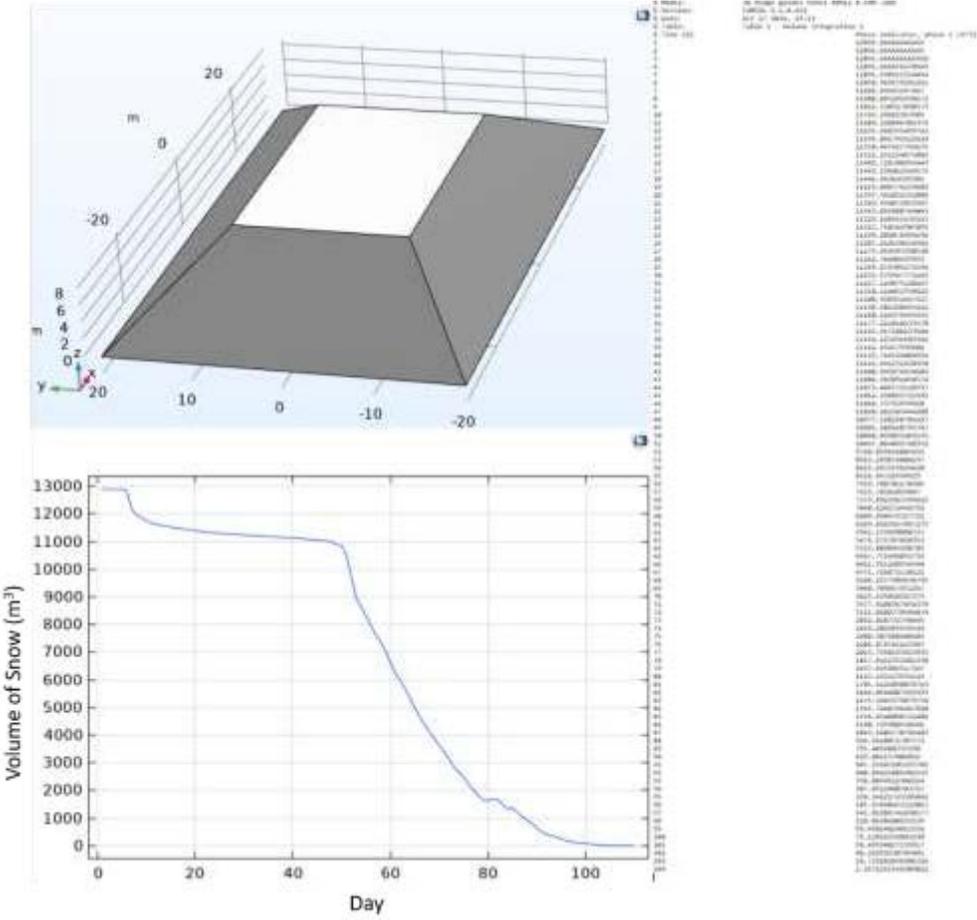


Figure E.27 Numerical modeling results for the ridge (8.5 m height, 40 m width, and 65 m length) SMP with 2022 weather function

Pile Number 28

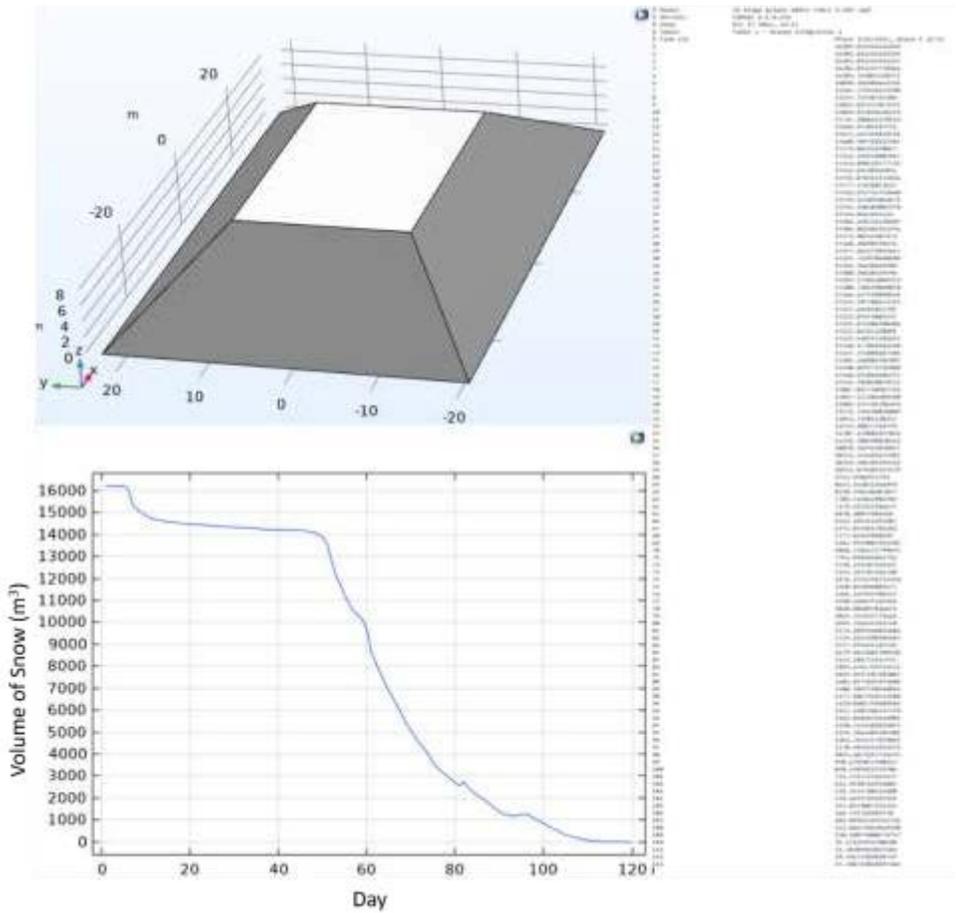


Figure E.28 Numerical modeling results for the ridge (9.5 m height, 43 m width, and 68 m length) SMP with 2022 weather function

Pile Number 29

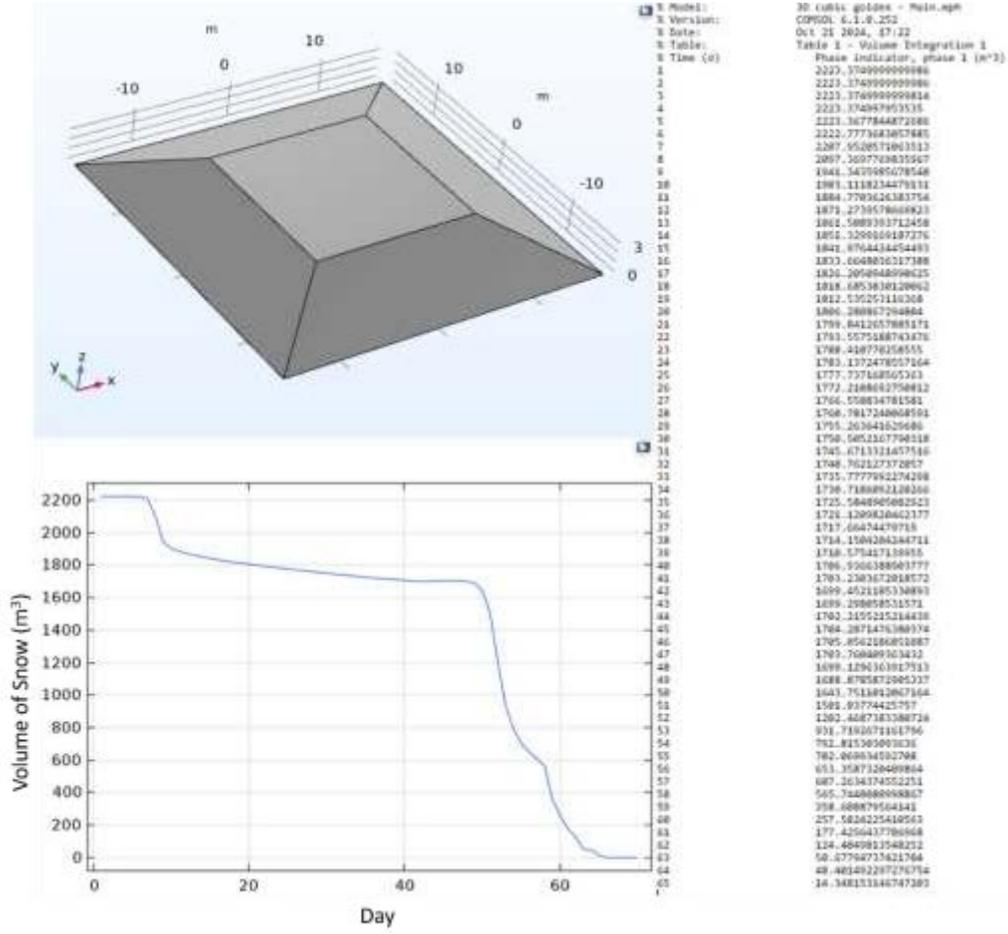


Figure E.29 Numerical modeling results for the cubic (3.5 m height, 33 m width, and 33 m length) SMP with 2022 weather function

Pile Number 30

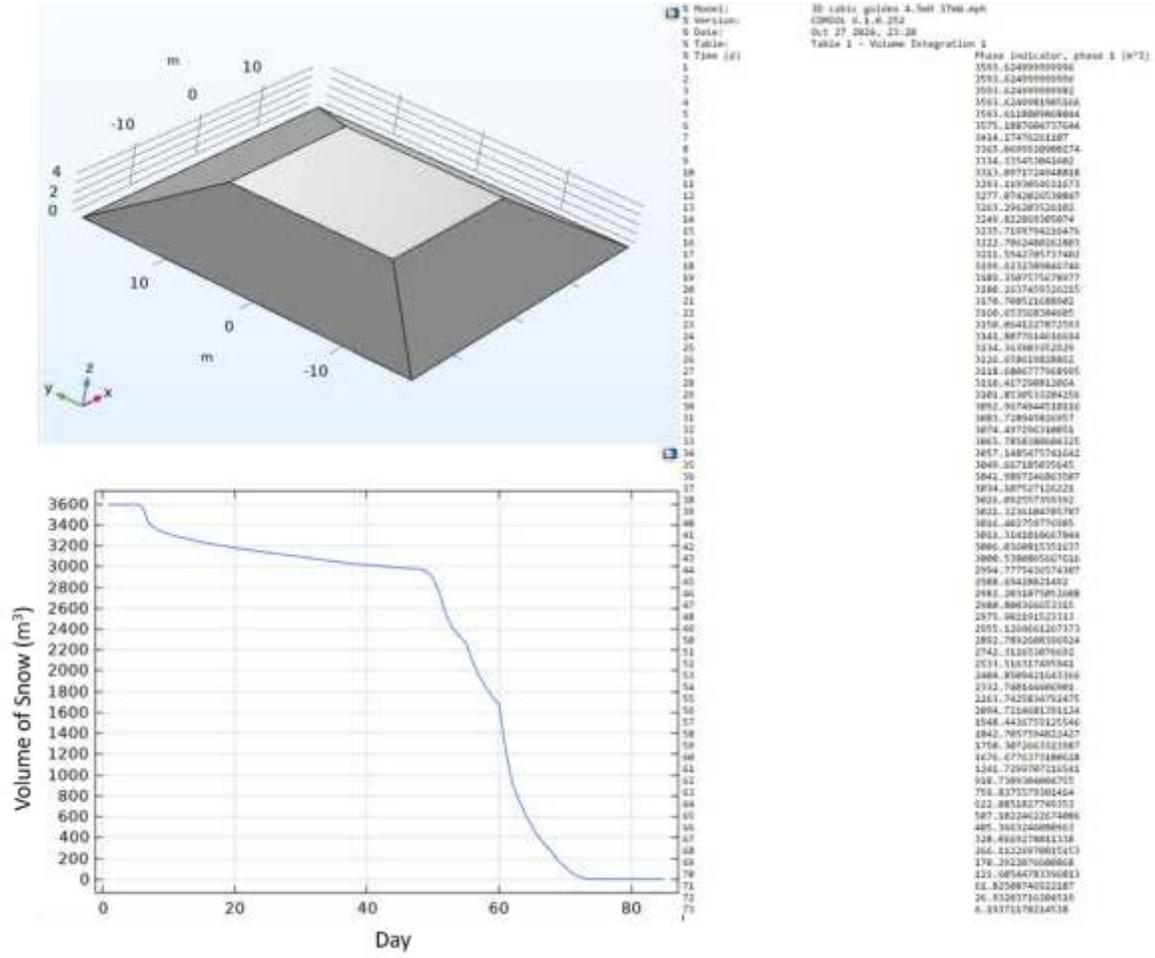


Figure E.30 Numerical modeling results for the cubic (4.5 m height, 37 m width, and 37 m length) SMP with 2022 weather function

Pile Number 31

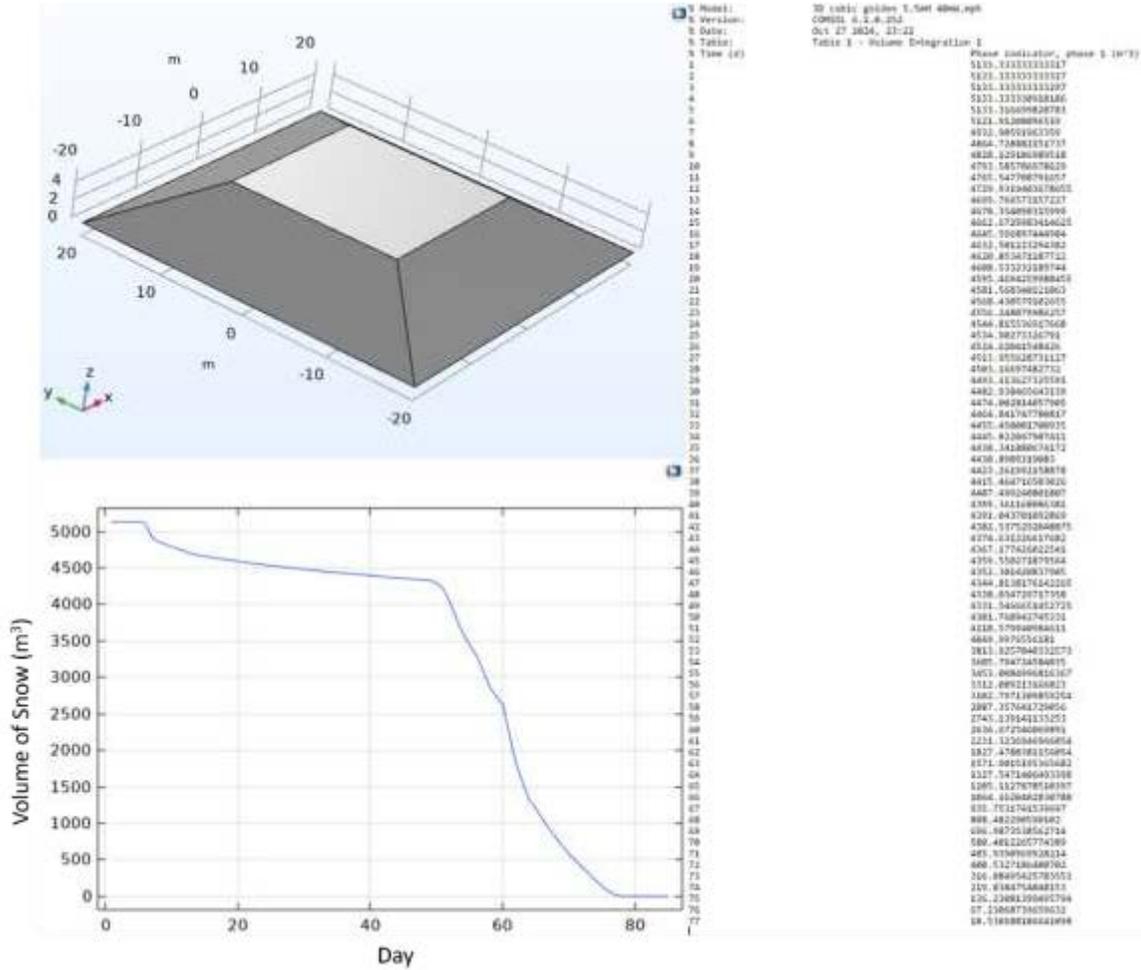


Figure E.31 Numerical modeling results for the cubic (5.5 m height, 40 m width, and 40 m length) SMP with 2022 weather function

Pile Number 32

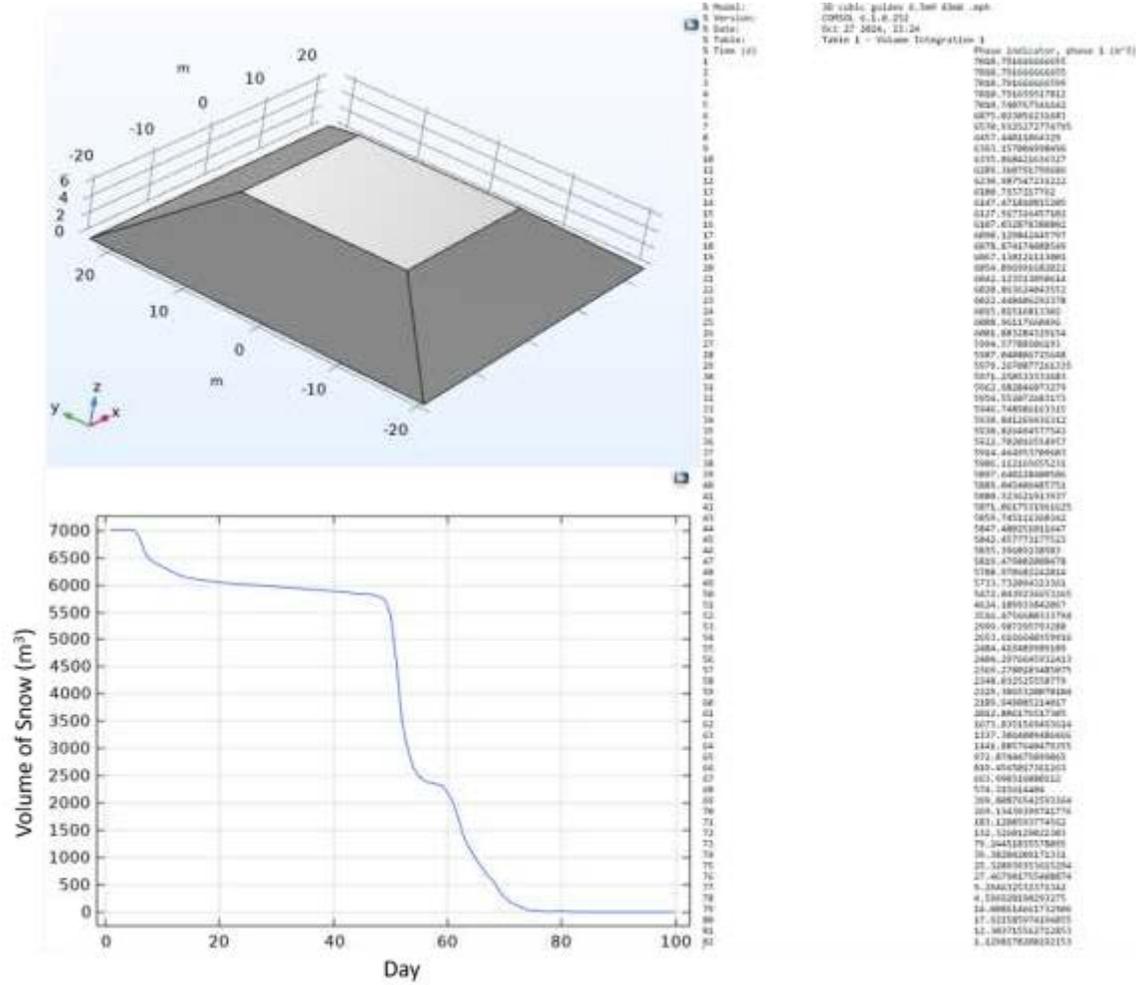


Figure E.32 Numerical modeling results for the cubic (6.5 m height, 43 m width, and 43 m length) SMP with 2022 weather function

Pile Number 33

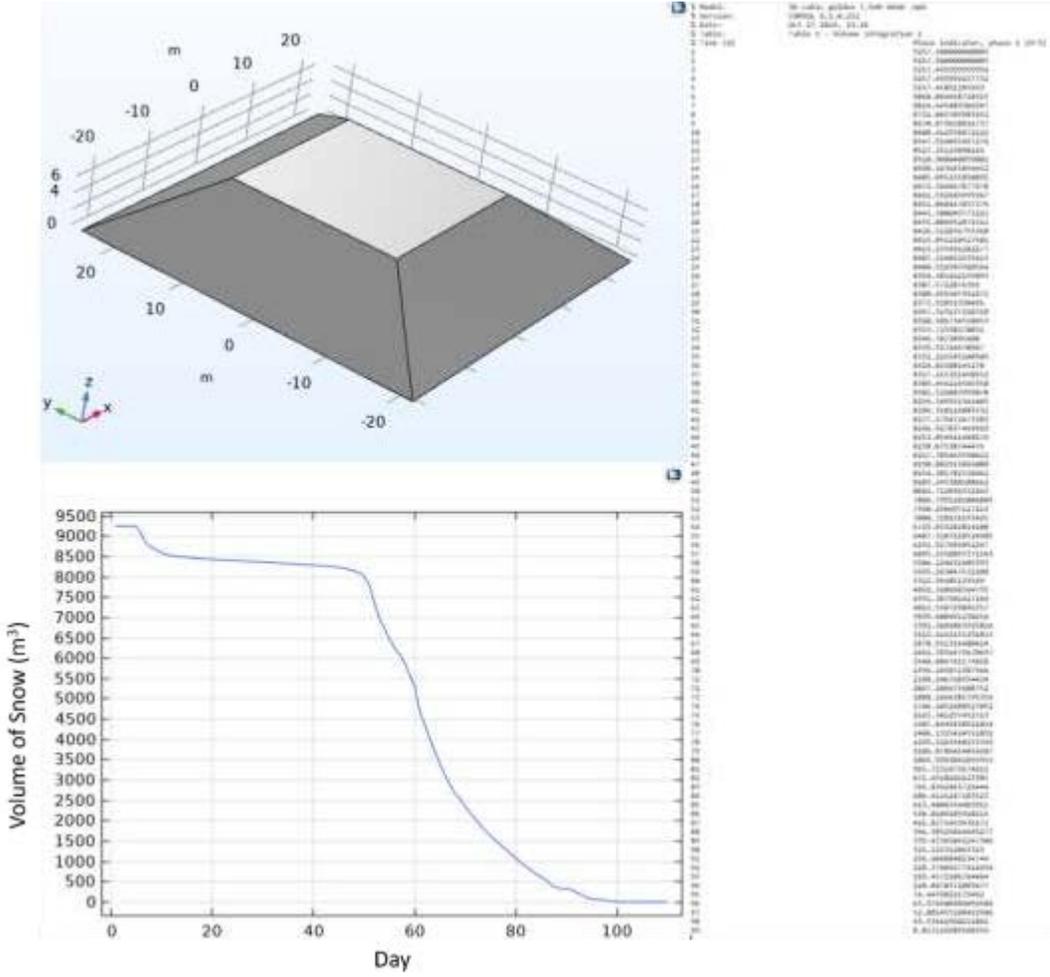


Figure E.33 Numerical modeling results for the cubic (7.5 m height, 46 m width, and 46 m length) SMP with 2022 weather function

Pile Number 34

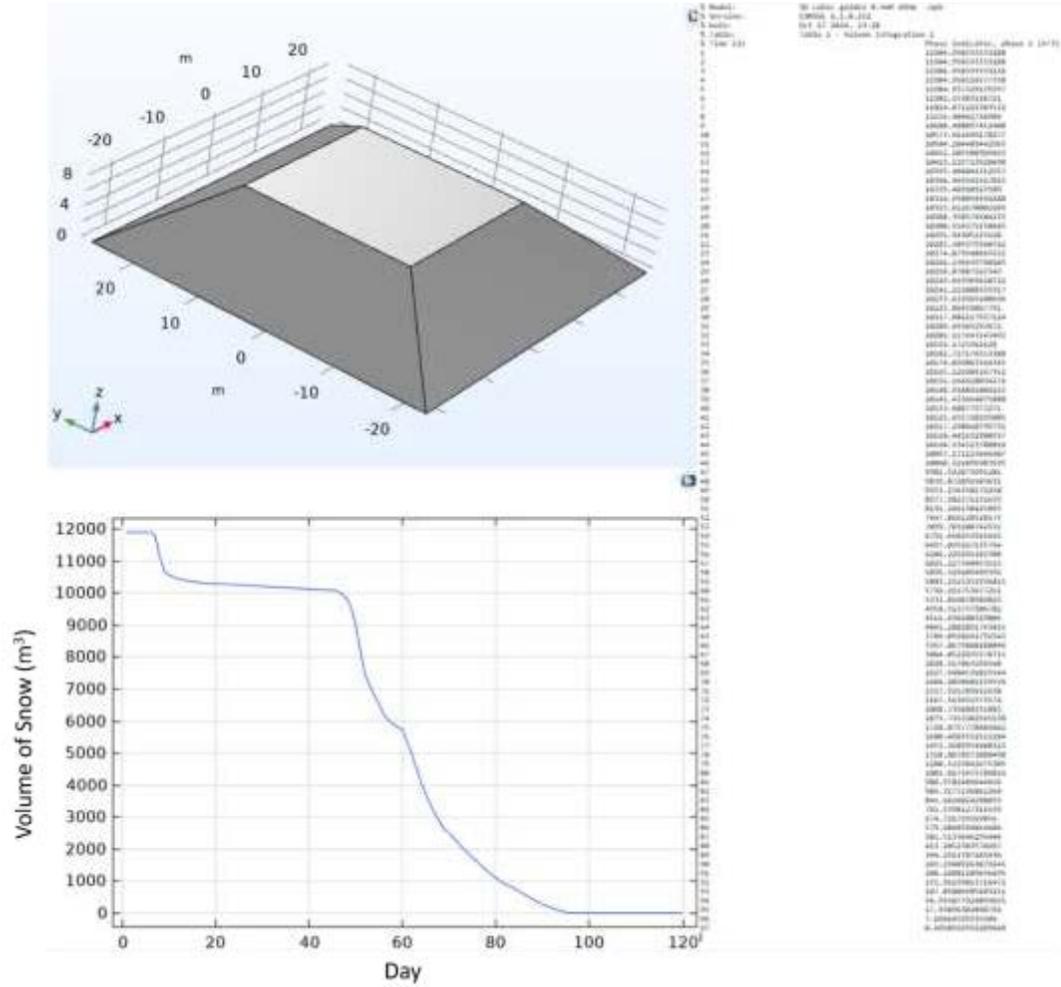


Figure E.34 Numerical modeling results for the cubic (8.5 m height, 49 m width, and 49 m length) SMP with 2022 weather function

Pile Number 35

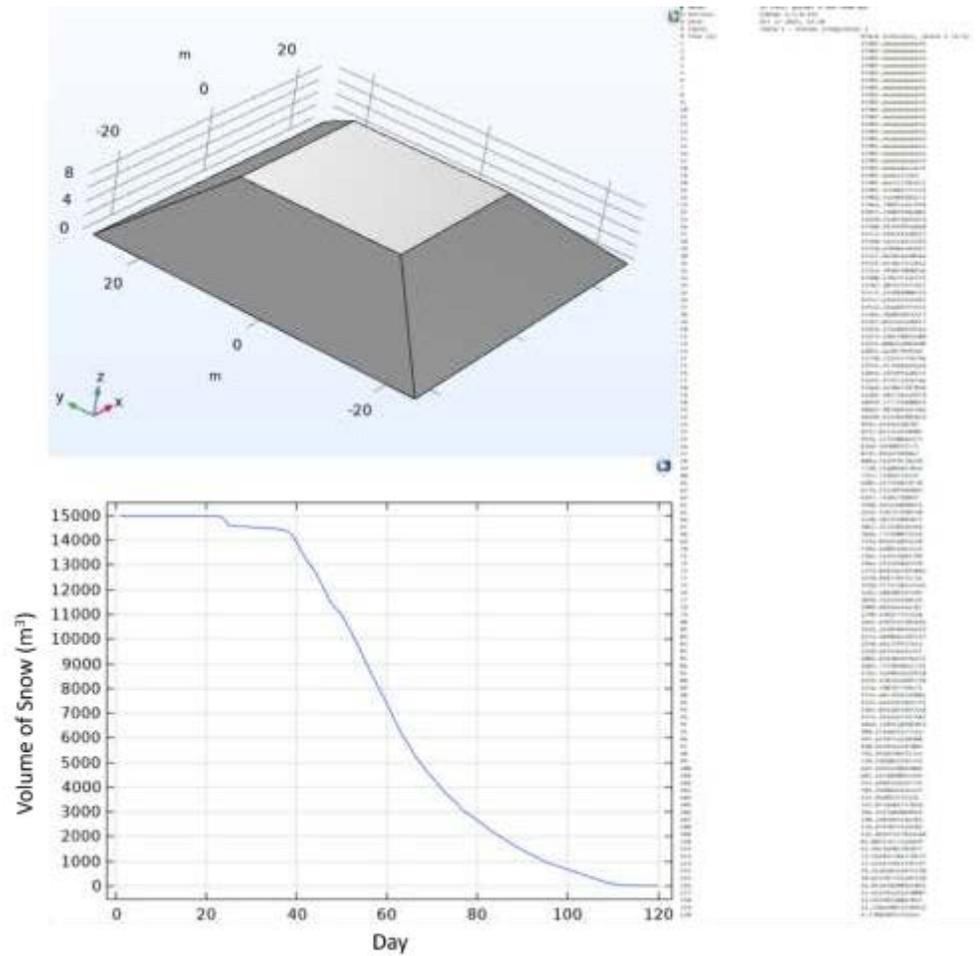


Figure E.35 Numerical modeling results for the cubic (9.5 m height, 52 m width, and 52 m length) SMP with 2022 weather function

Pile Number 36

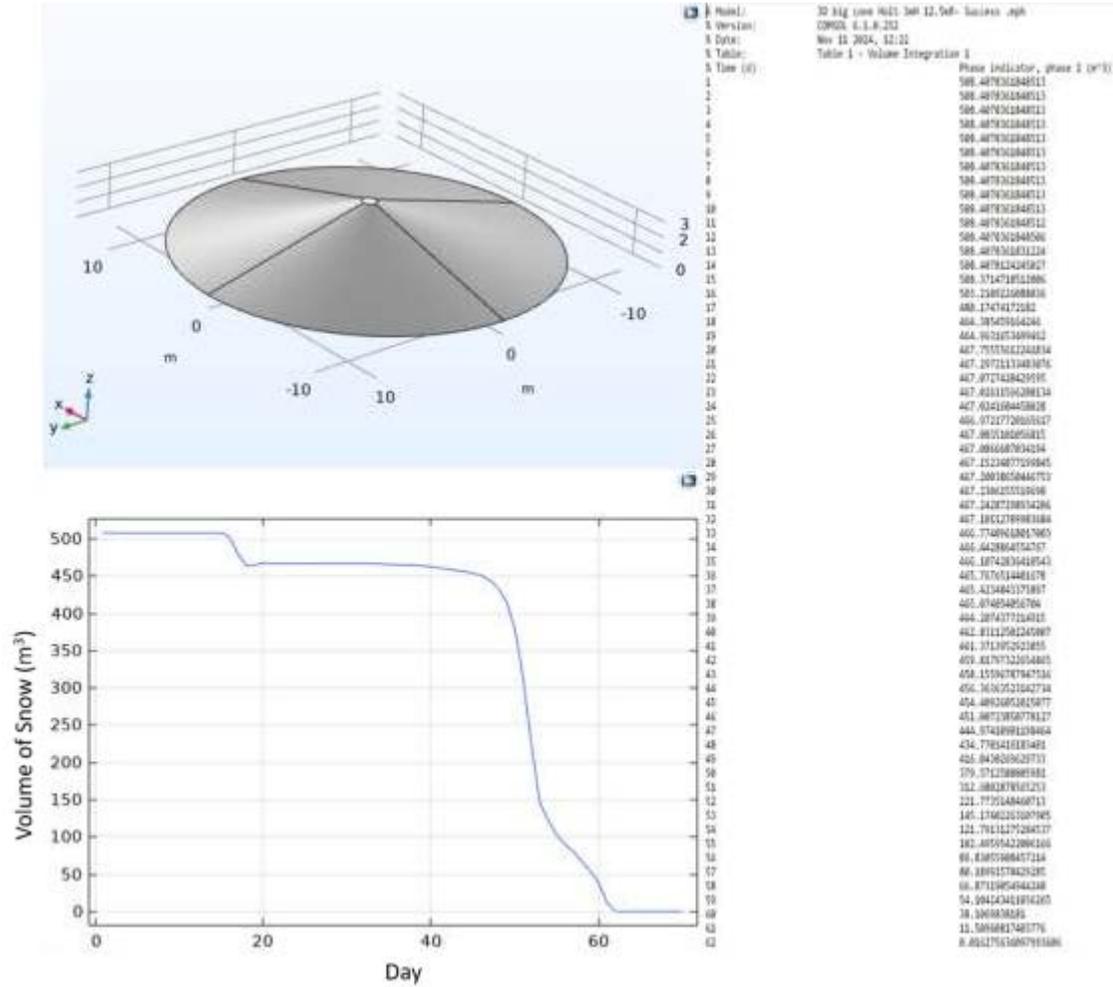


Figure E.36 Numerical modeling results for the cone (3 m height, and 12.5 m radius) SMP with 2022 weather function

Pile Number 38

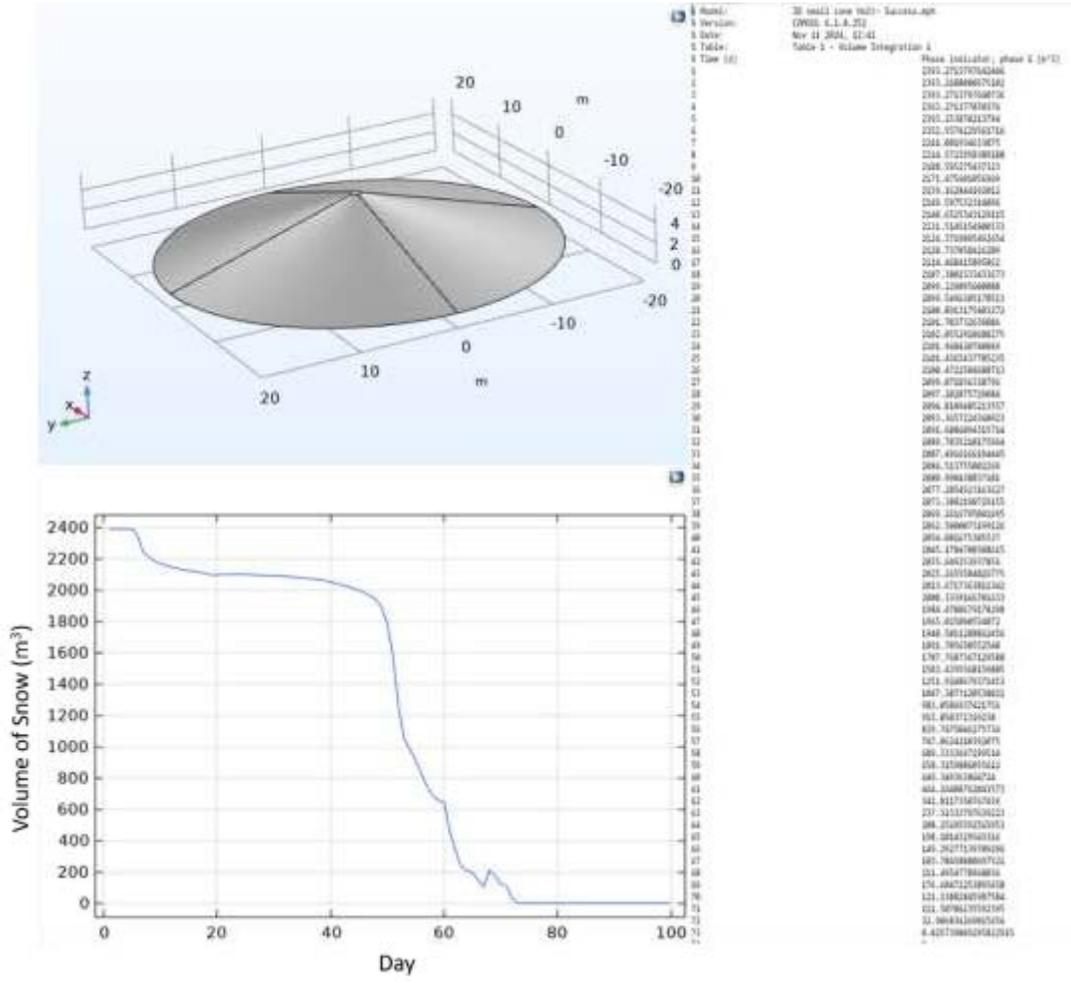


Figure E.38 Numerical modeling results for the cone (5.6 m height, and 20 m radius) SMP with 2022 weather function

Pile Number 39

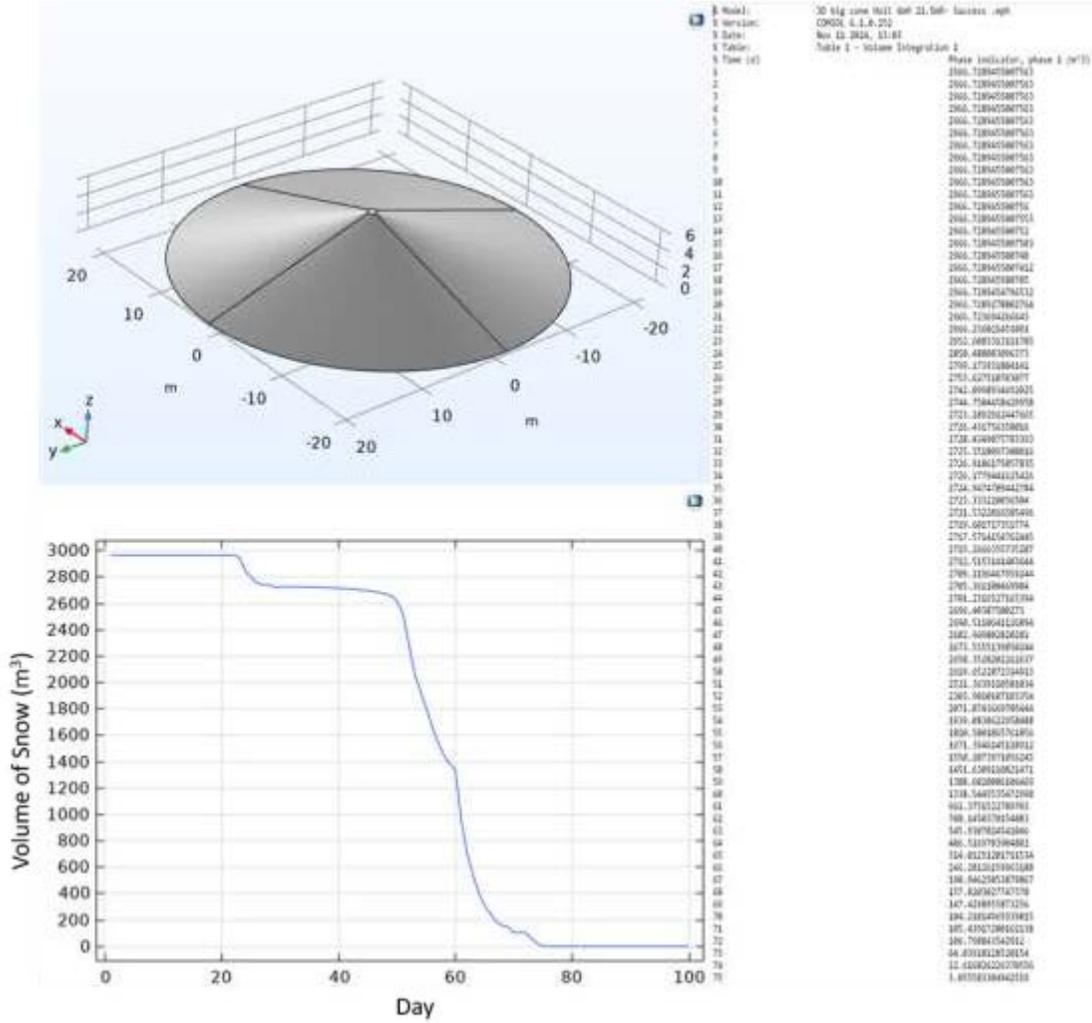


Figure E.39 Numerical modeling results for the cone (6 m height, and 21.5 m radius) SMP with 2022 weather function

Pile Number 40

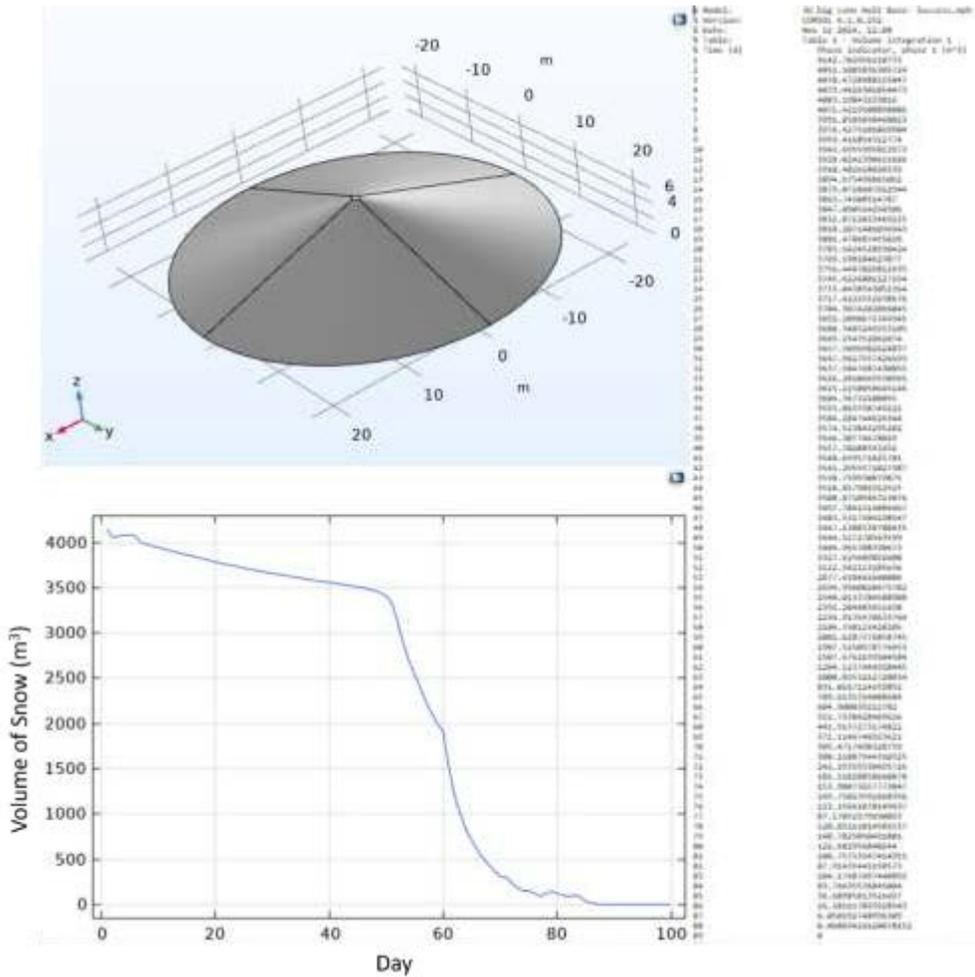


Figure E.40 Numerical modeling results for the cone (7.33 m height, and 23 m radius) SMP with 2022 weather function

Pile Number 41

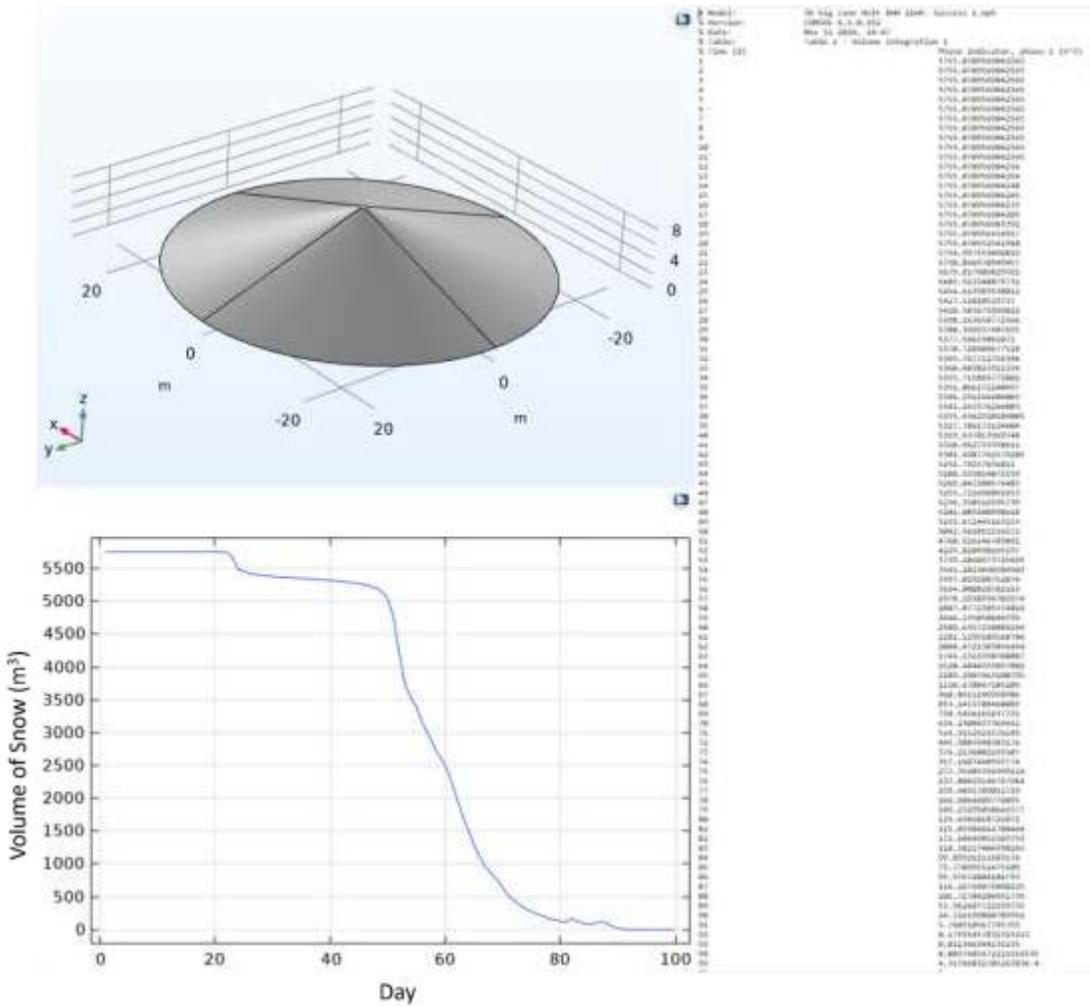


Figure E.41 Numerical modeling results for the cone (8 m height, and 26 m radius) SMP with 2022 weather function

Pile Number 42

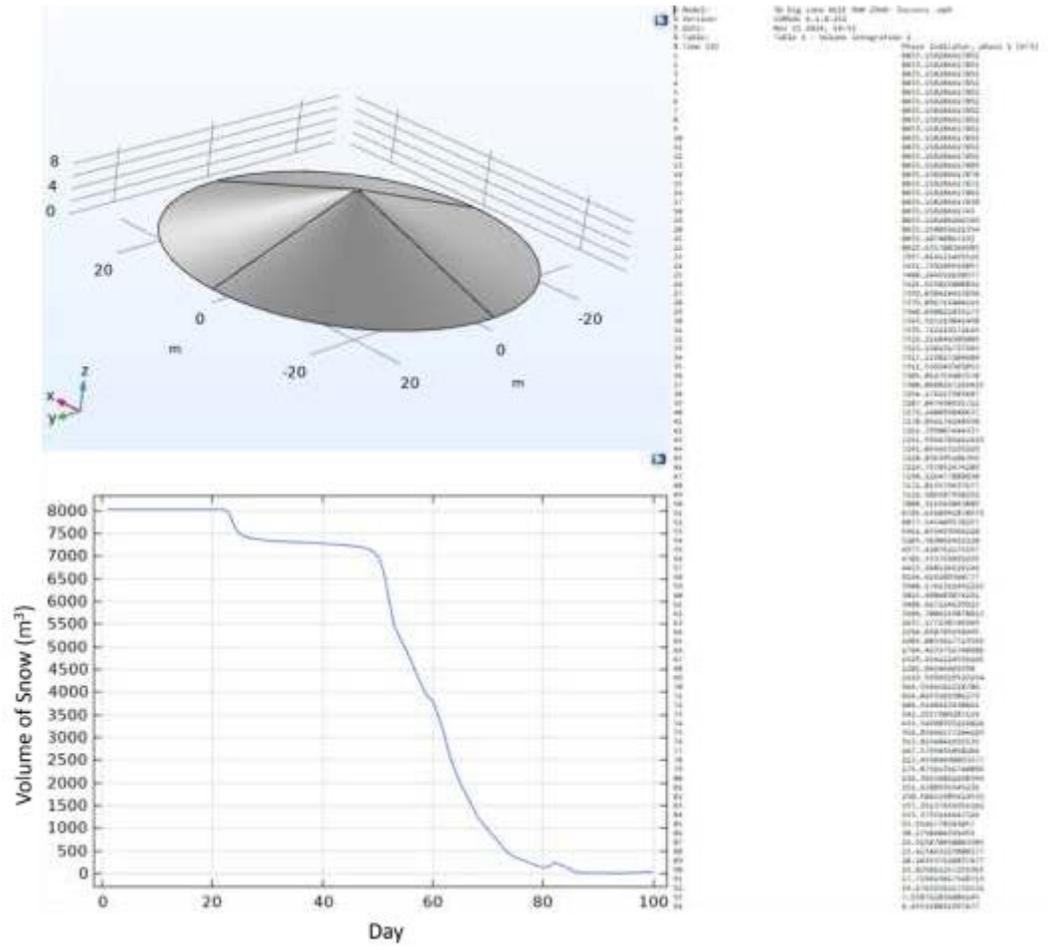


Figure E.42 Numerical modeling results for the cone (9 m height, and 29 m radius) SMP with 2022 weather function

Pile Number 43

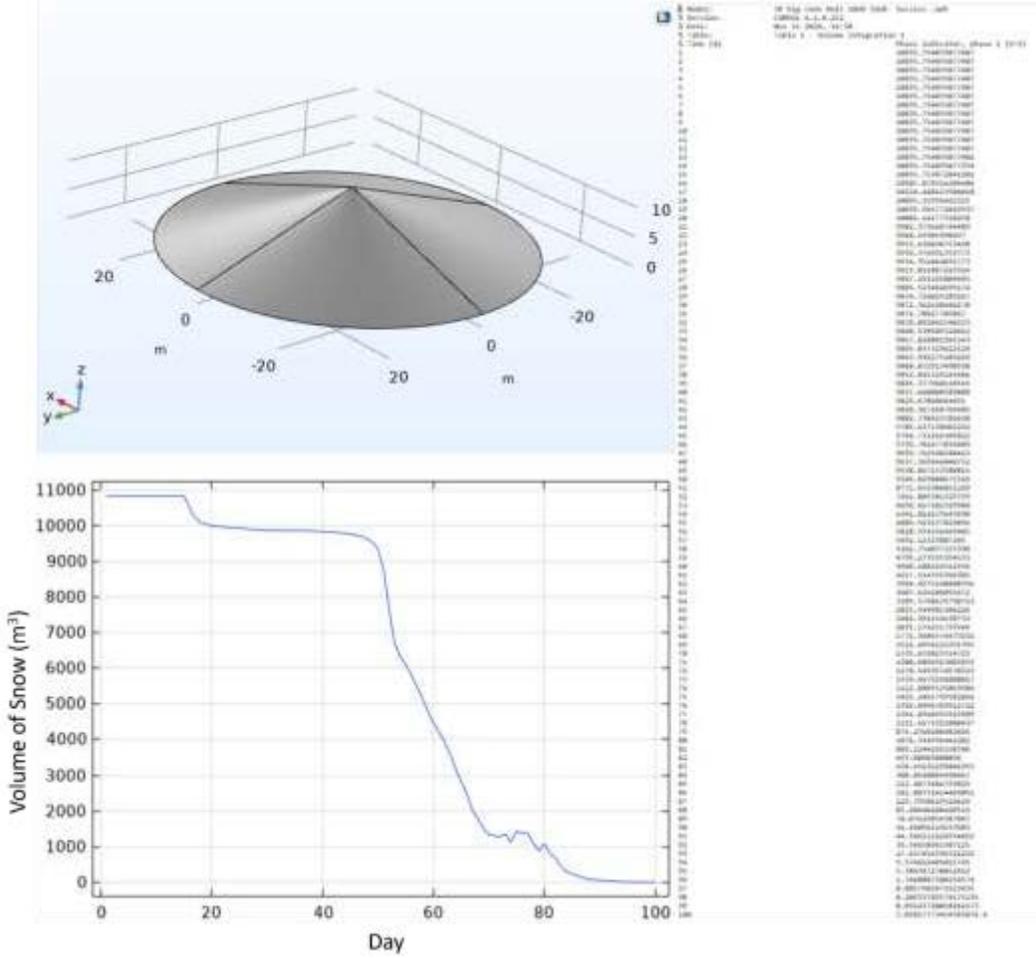


Figure E.43 Numerical modeling results for the cone (10 m height, and 32 m radius) SMP with 2022 weather function

Pile Number 44

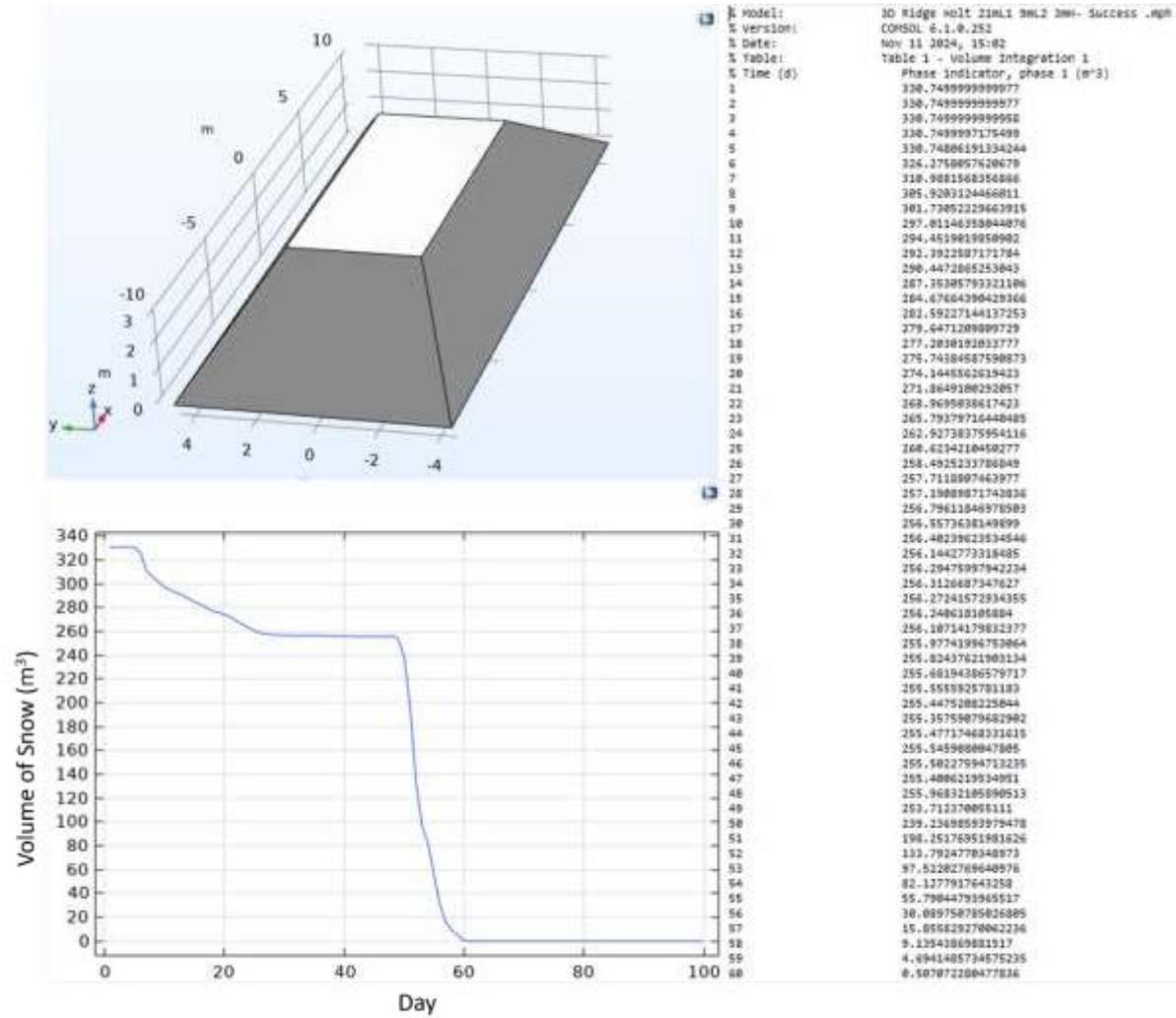


Figure E.44 Numerical modeling results for the ramp (3 m height, 9 m width, and 21 length) SMP with 2022 weather function

Pile Number 45

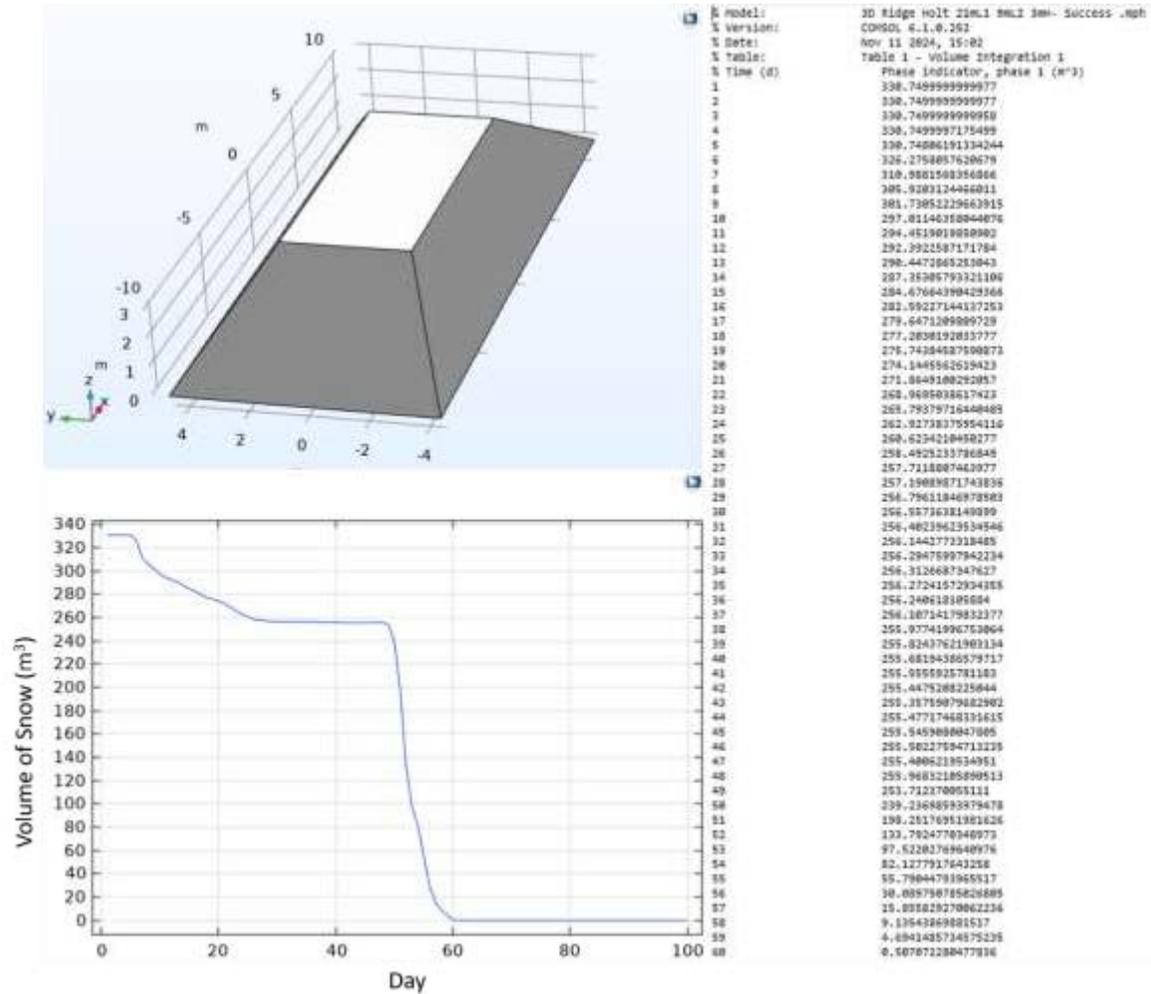


Figure E.45 Numerical modeling results for the ramp (4 m height, 12 m width, and 24 length) SMP with 2022 weather function

Pile Number 46

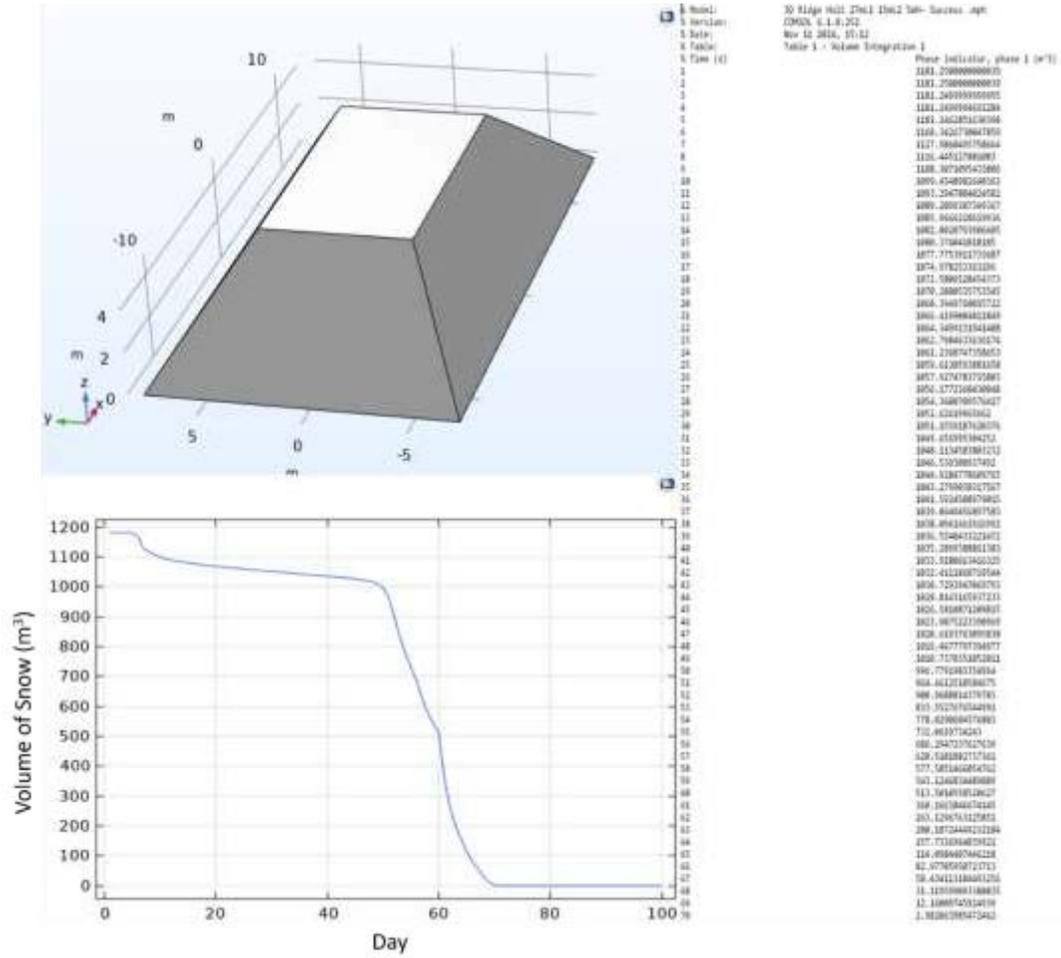


Figure E.46 Numerical modeling results for the ramp (5 m height, 15 m width, and 27 length) SMP with 2022 weather function

Pile Number 48

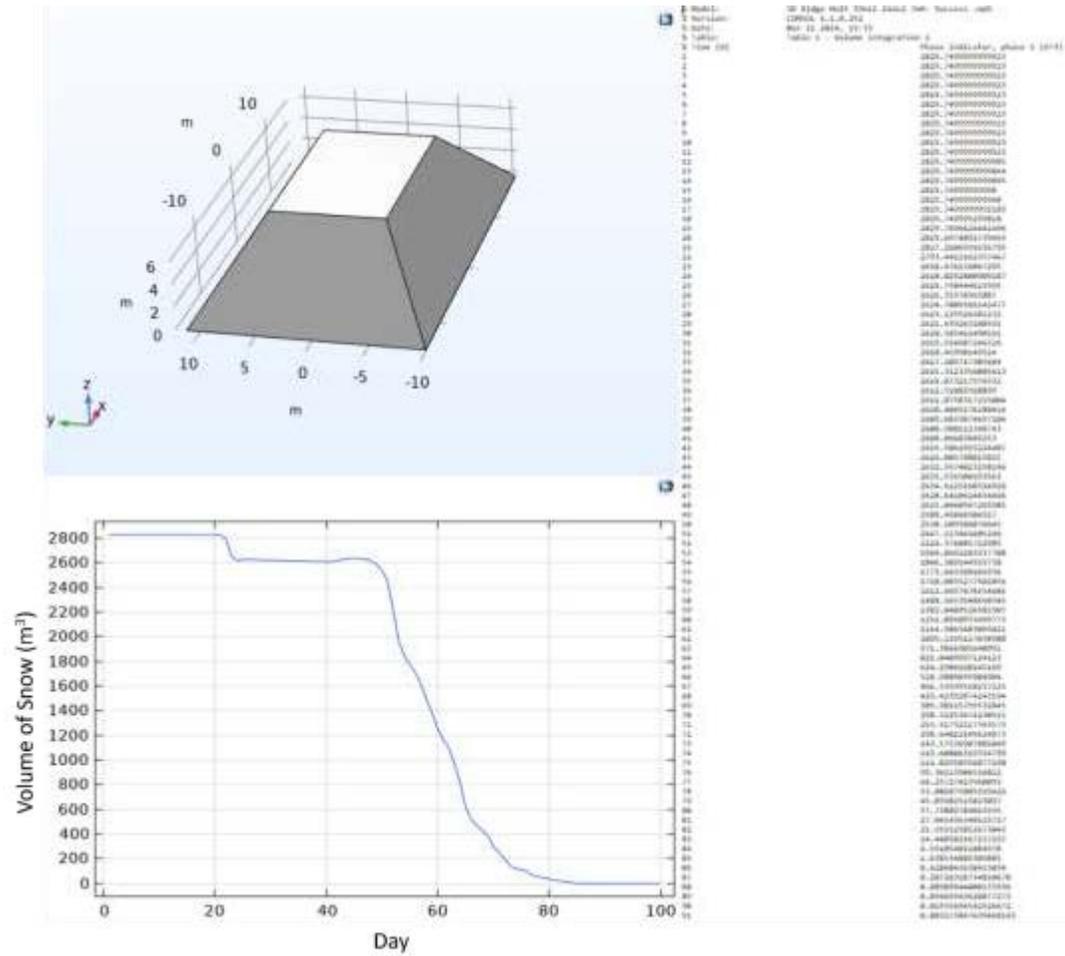


Figure E.48 Numerical modeling results for the ramp (7 m height, 21 m width, and 30=3 lenght) SMP with 2022 weather function

Pile Number 49

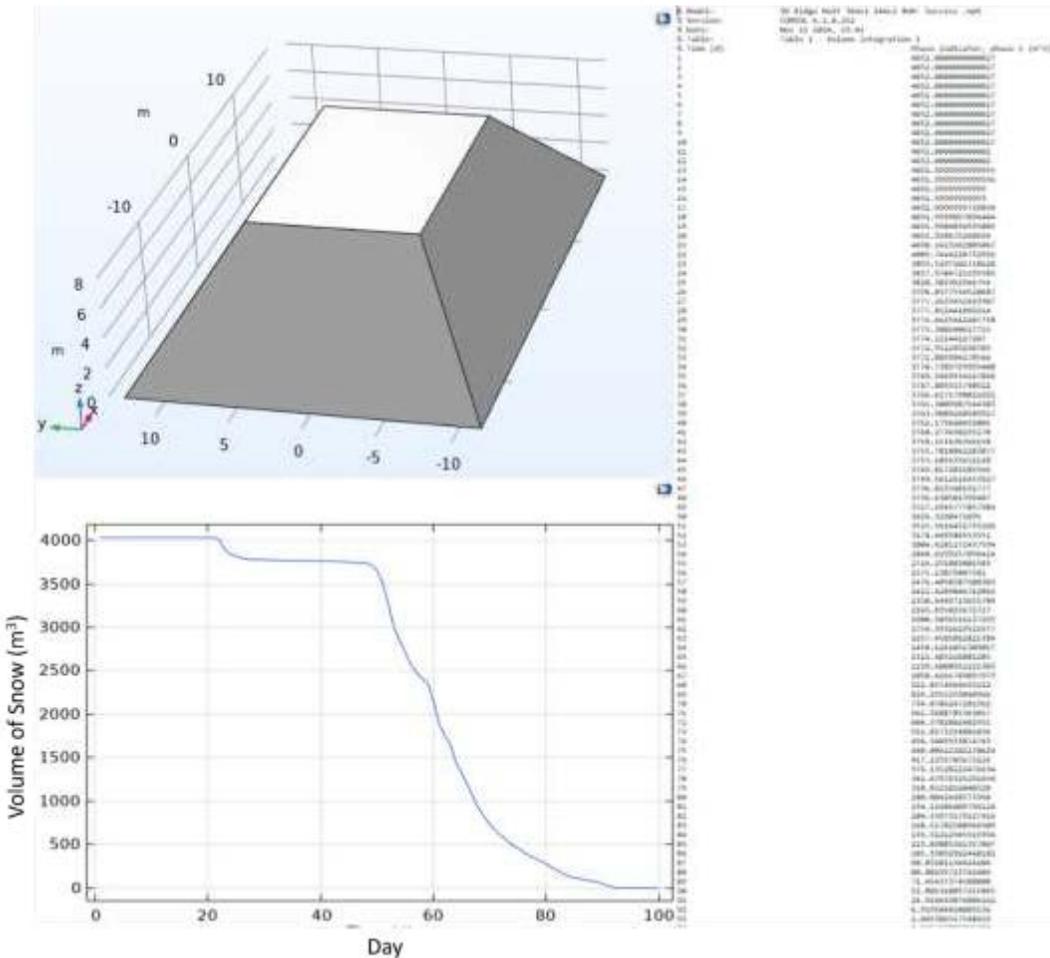


Figure E.49 Numerical modeling results for the ramp (8 m height, 24 m width, and 36 length) SMP with 2022 weather function

Pile Number 50

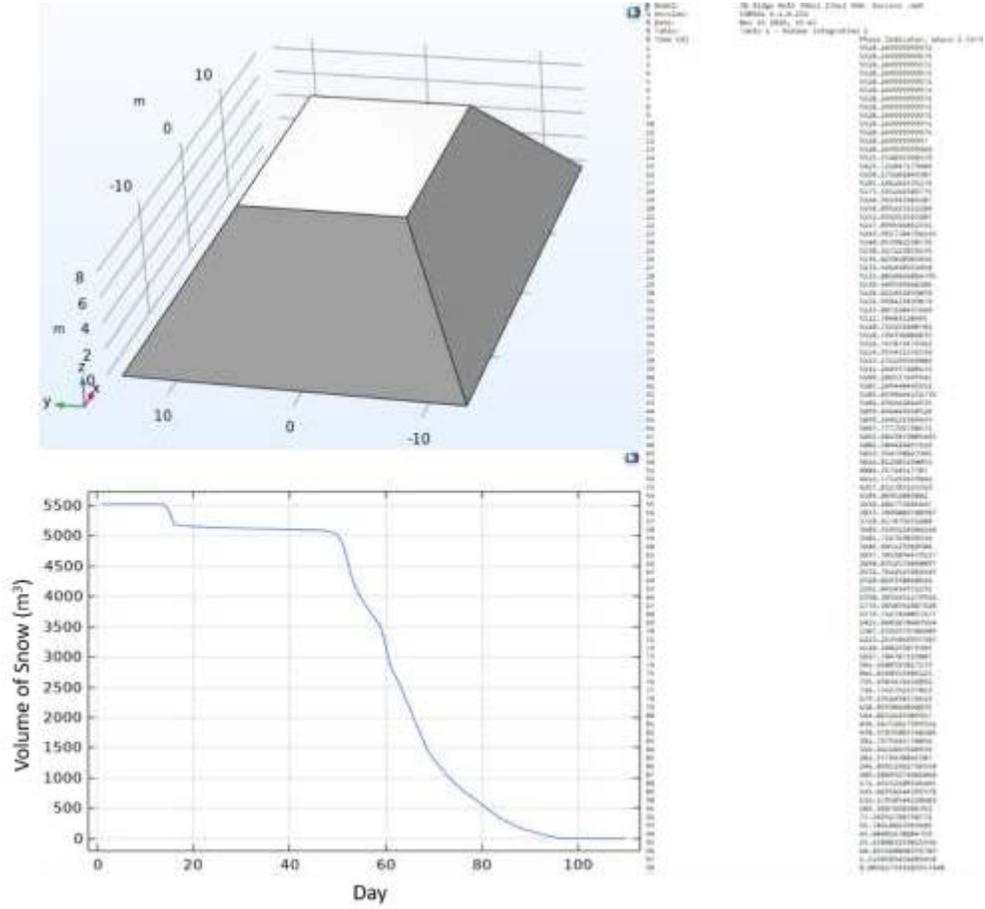


Figure E.50 Numerical modeling results for the ramp (9 m height, 27 m width, and 39 length) SMP with 2022 weather function

Pile Number 51

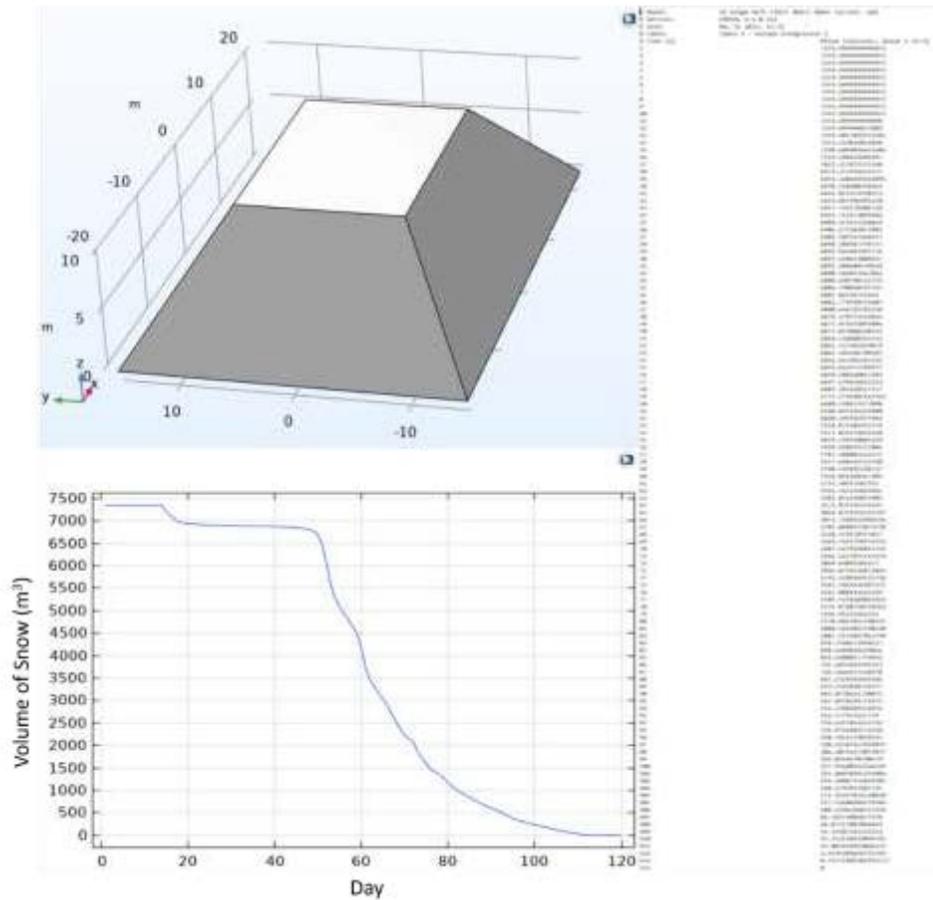


Figure E.51 Numerical modeling results for the ramp (10 m height, 30 m width, and 42 length) SMP with 2022 weather function

Pile Number 52

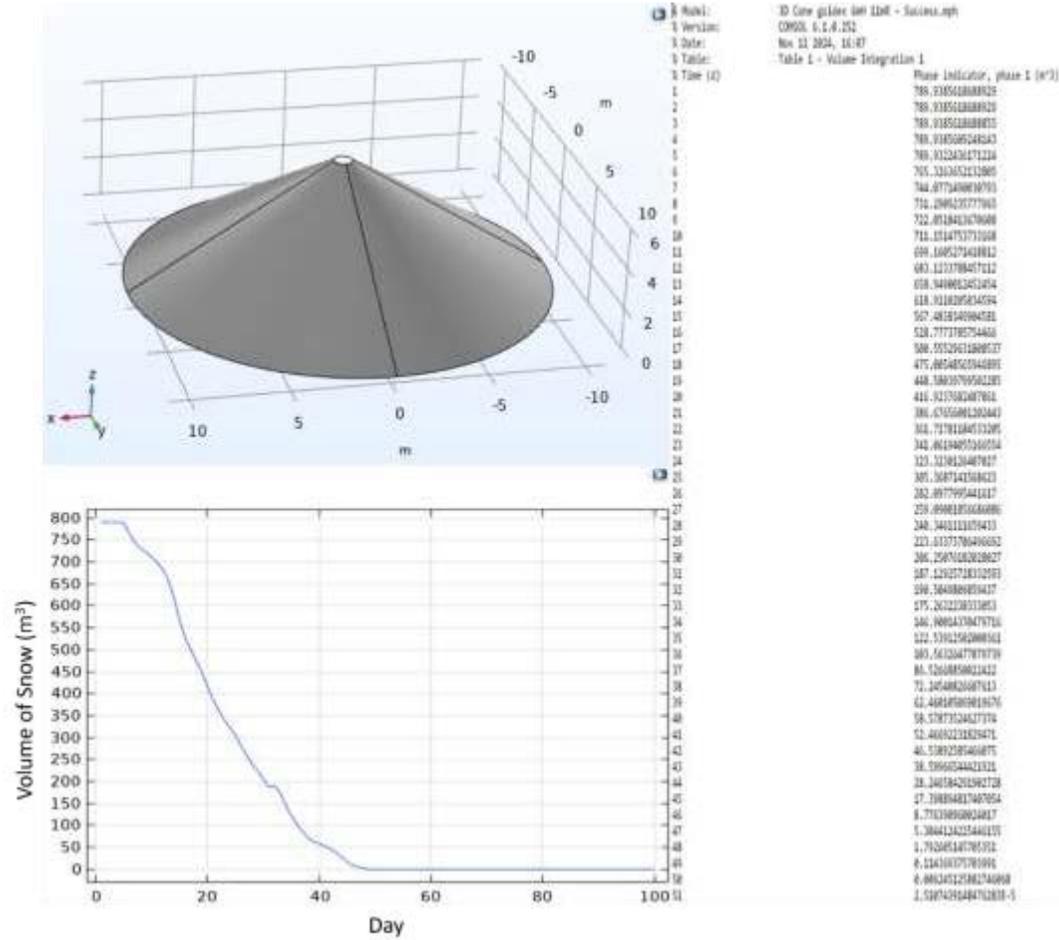


Figure E.52 Numerical modeling results for the cone (6 m height, and 11 m radius) SMP with 2023 weather function

Pile Number 53

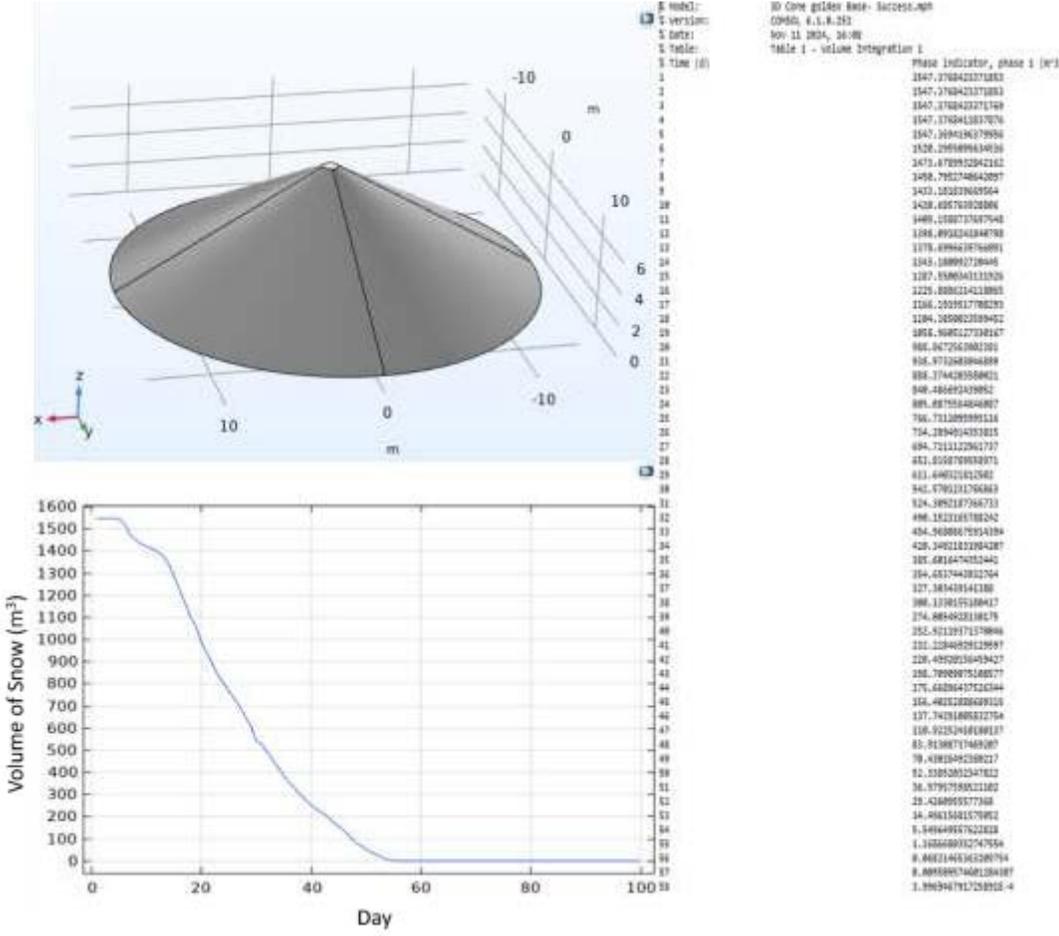


Figure E.53 Numerical modeling results for the cone (7.3 m height, and 14 m radius) SMP with 2023 weather function

Pile Number 55

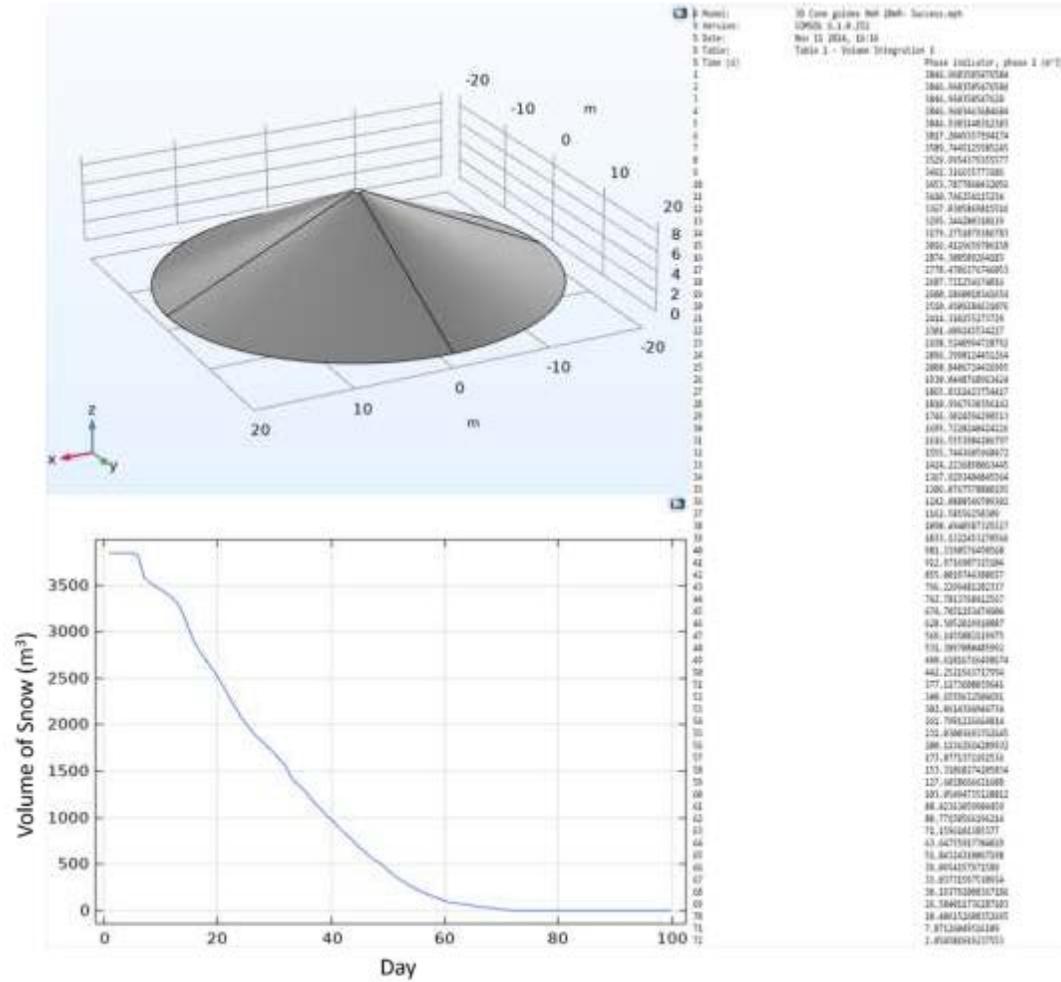


Figure E.55 Numerical modeling results for the cone (9 m height, and 20 m radius) SMP with 2023 weather function

Pile Number 56

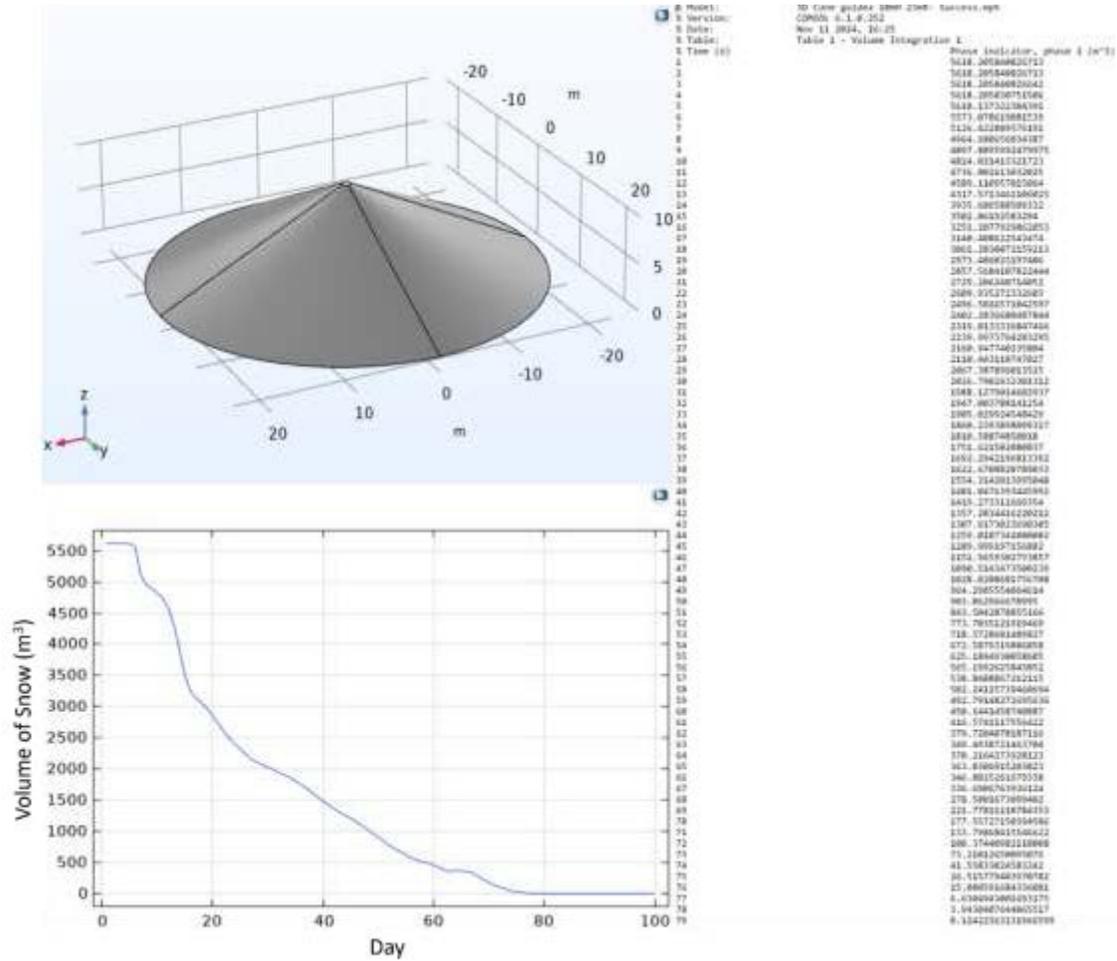


Figure E.56 Numerical modeling results for the cone (10 m height, and 23 m radius) SMP with 2023 weather function

Pile Number 57

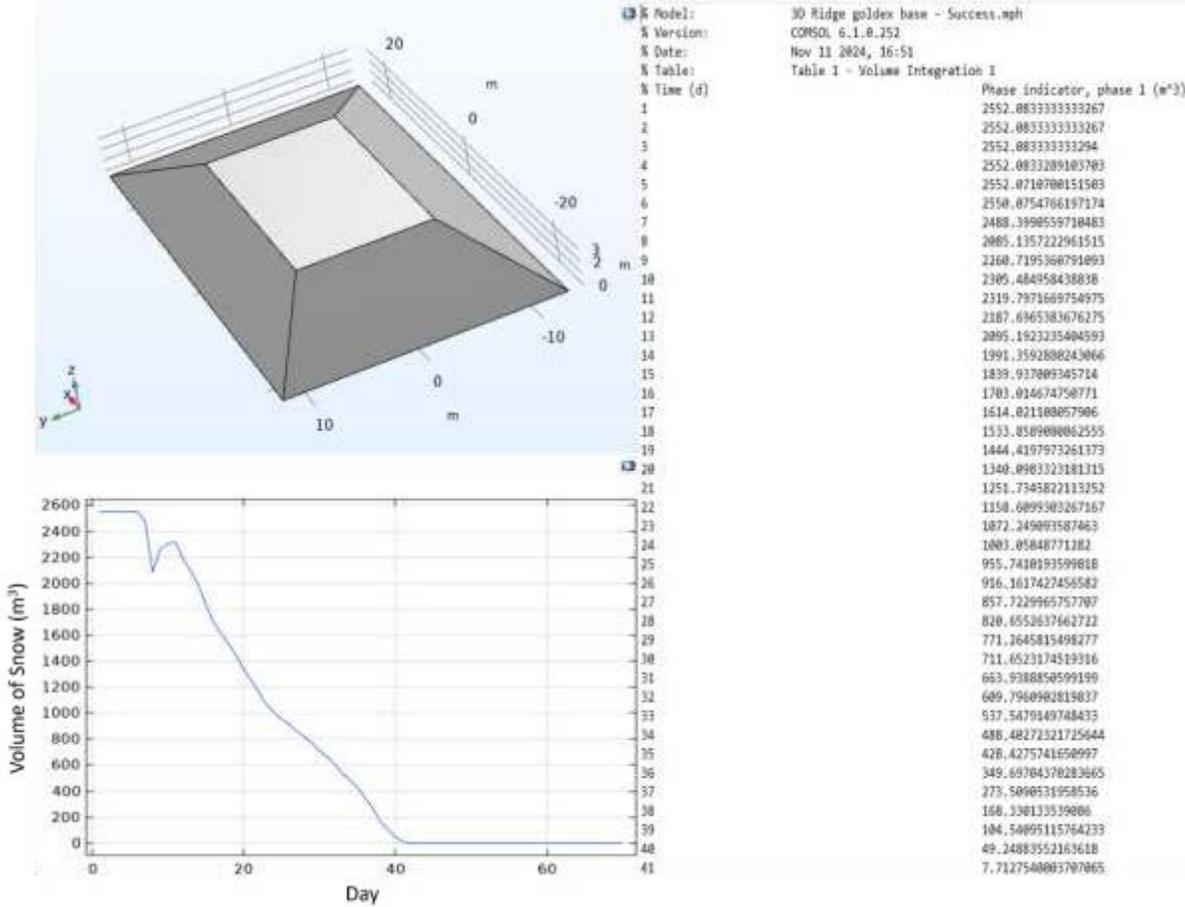


Figure E.57 Numerical modeling results for the ridge (3.5 m height, 25 m width, and 50 m length) SMP with 2023 weather function

Pile Number 58

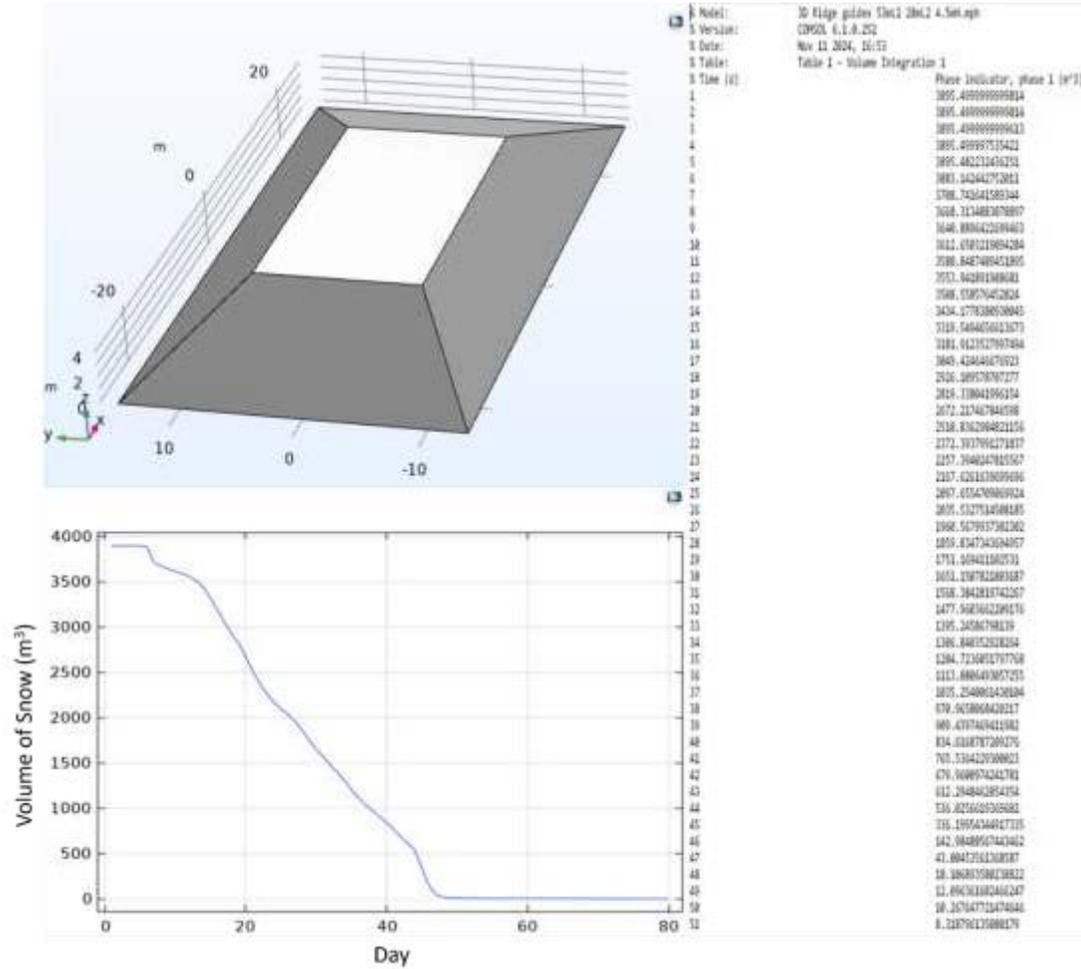


Figure E.58 Numerical modeling results for the ridge (4.5 m height, 28 m width, and 53 m length) SMP with 2023 weather function

Pile Number 59

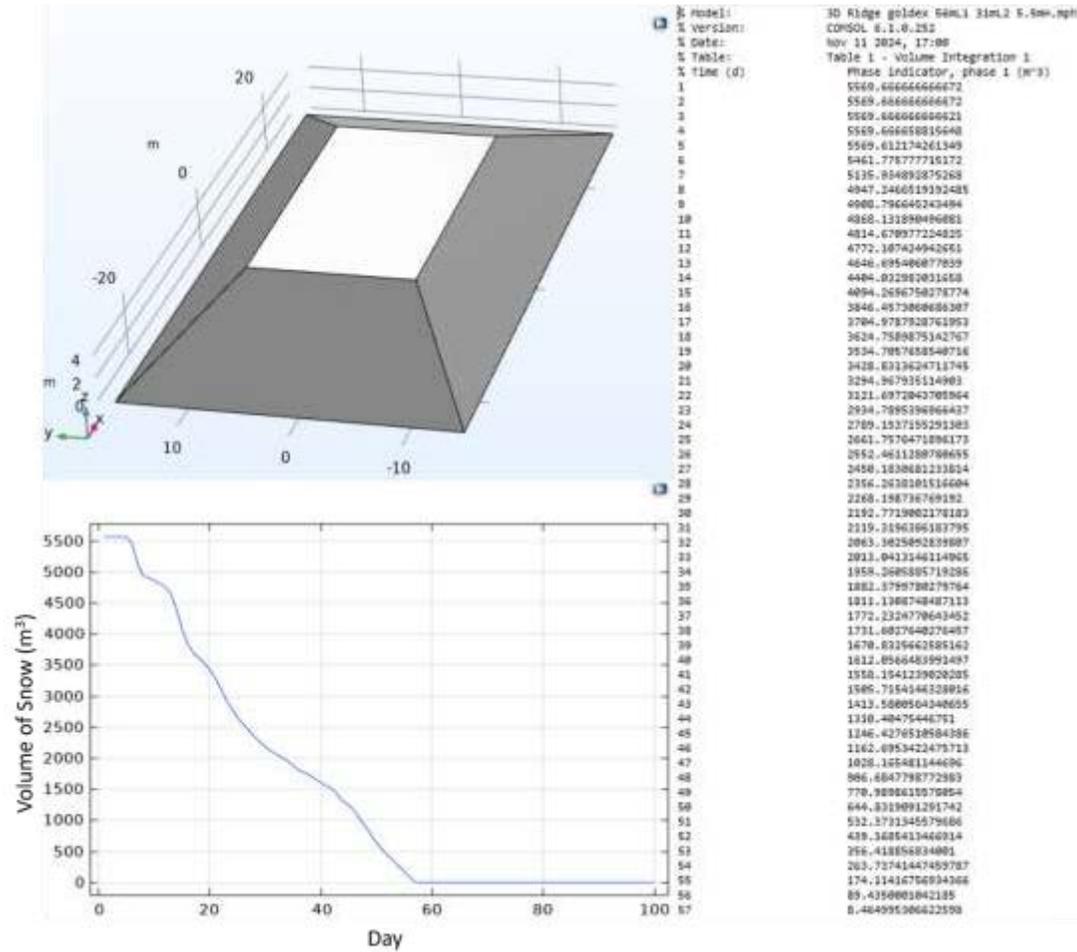


Figure E.59 Numerical modeling results for the ridge (5.5 m height, 31 m width, and 56 m length) SMP with 2023 weather function

Pile Number 60

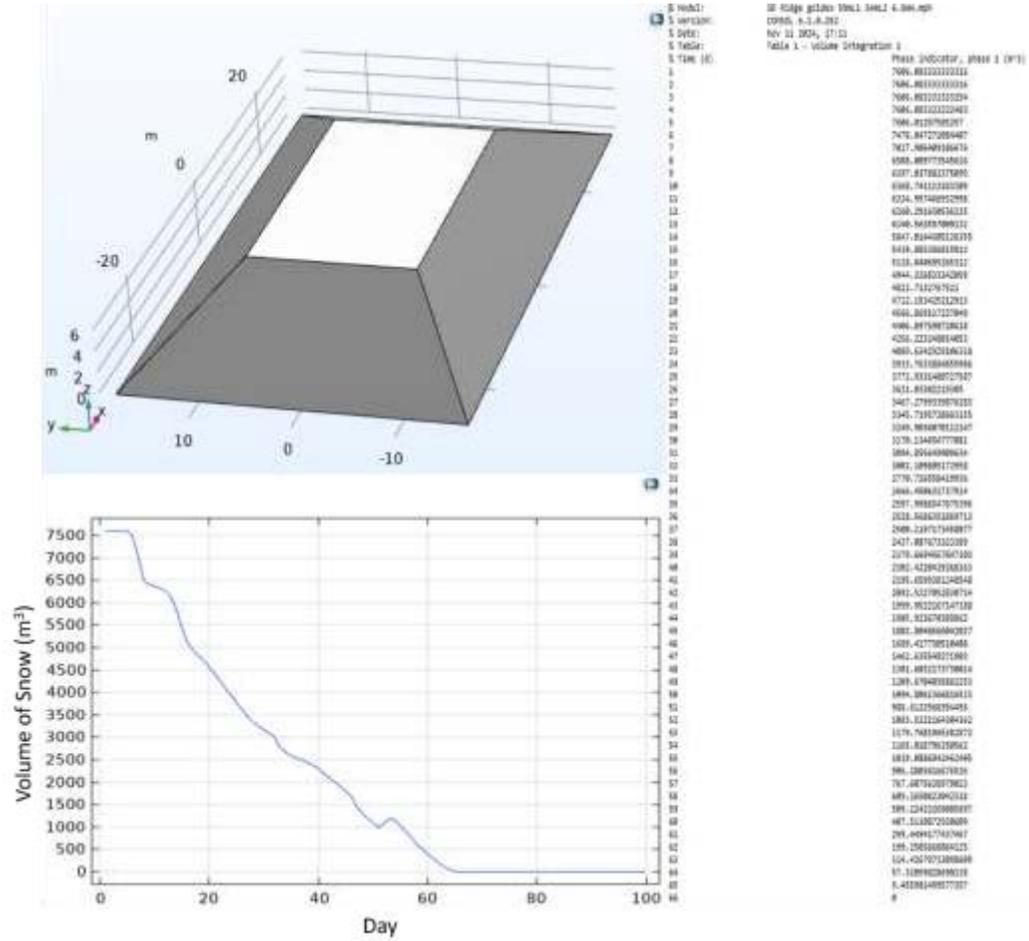


Figure E.60 Numerical modeling results for the ridge (6.5 m height, 34 m width, and 59 m length) SMP with 2023 weather function

Pile Number 62

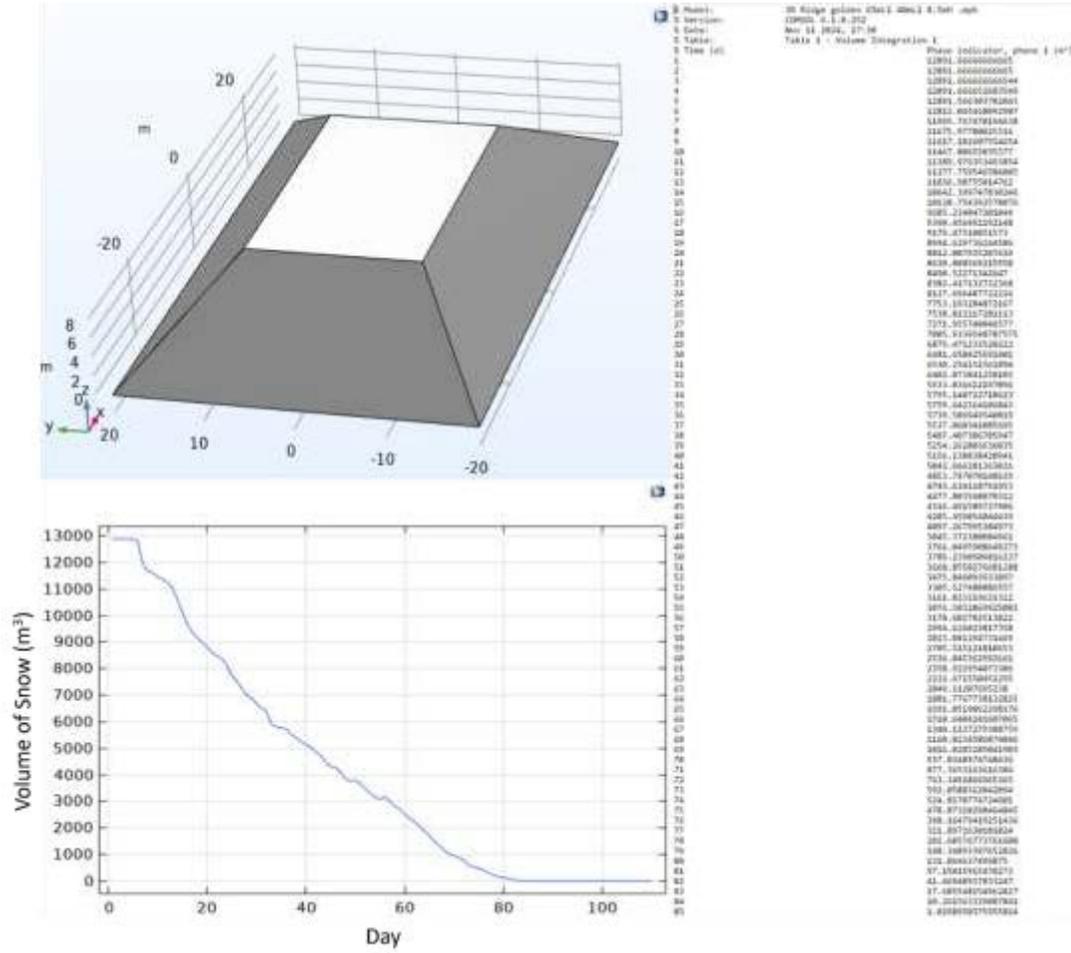


Figure E.62 Numerical modeling results for the ridge (8.5 m height, 40 m width, and 65 m length) SMP with 2023 weather function

Pile Number 63

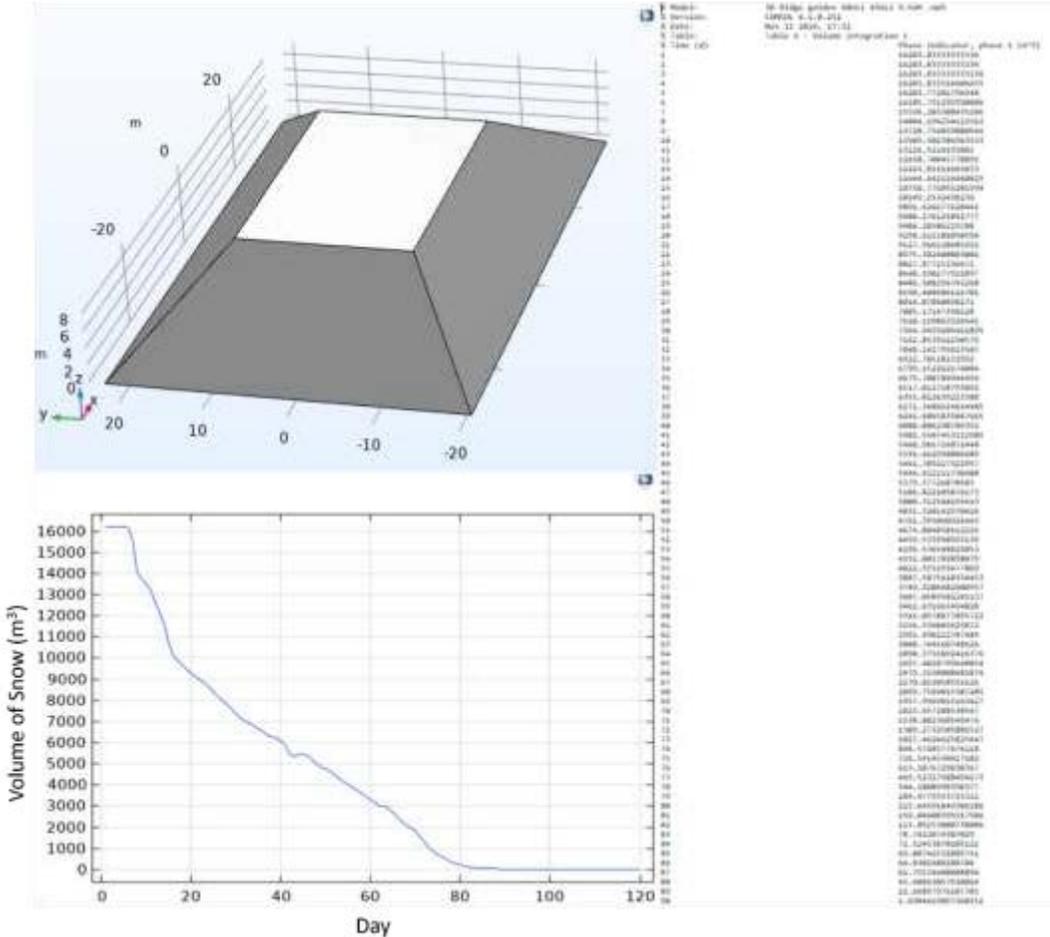


Figure E.63 Numerical modeling results for the ridge (9.5 m height, 43 m width, and 68 m length) SMP with 2023 weather function

Pile Number 64

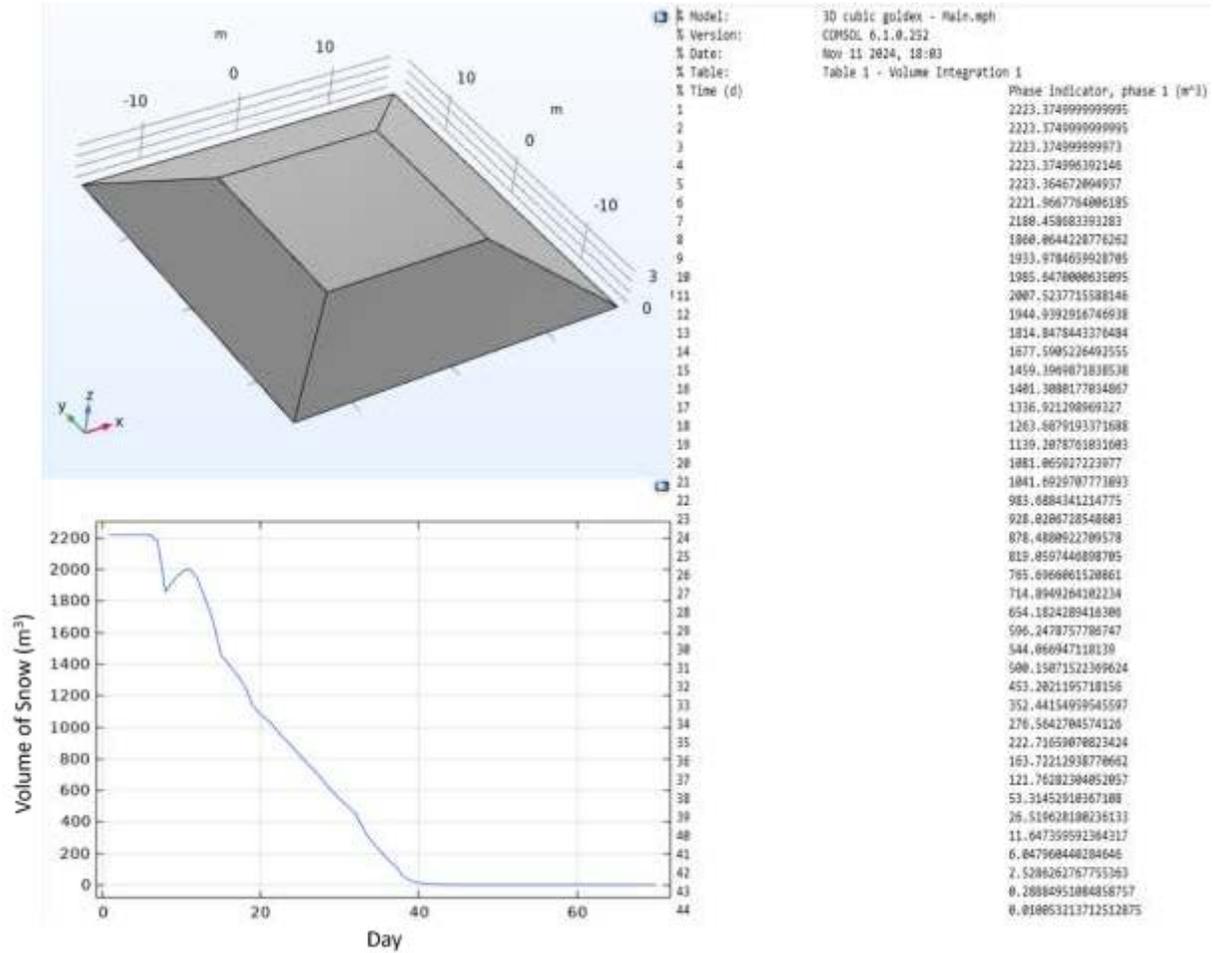


Figure E.64 Numerical modeling results for the cubic (3.5 m height, 33 m width, and 33 m length) SMP with 2023 weather function

Pile Number 65

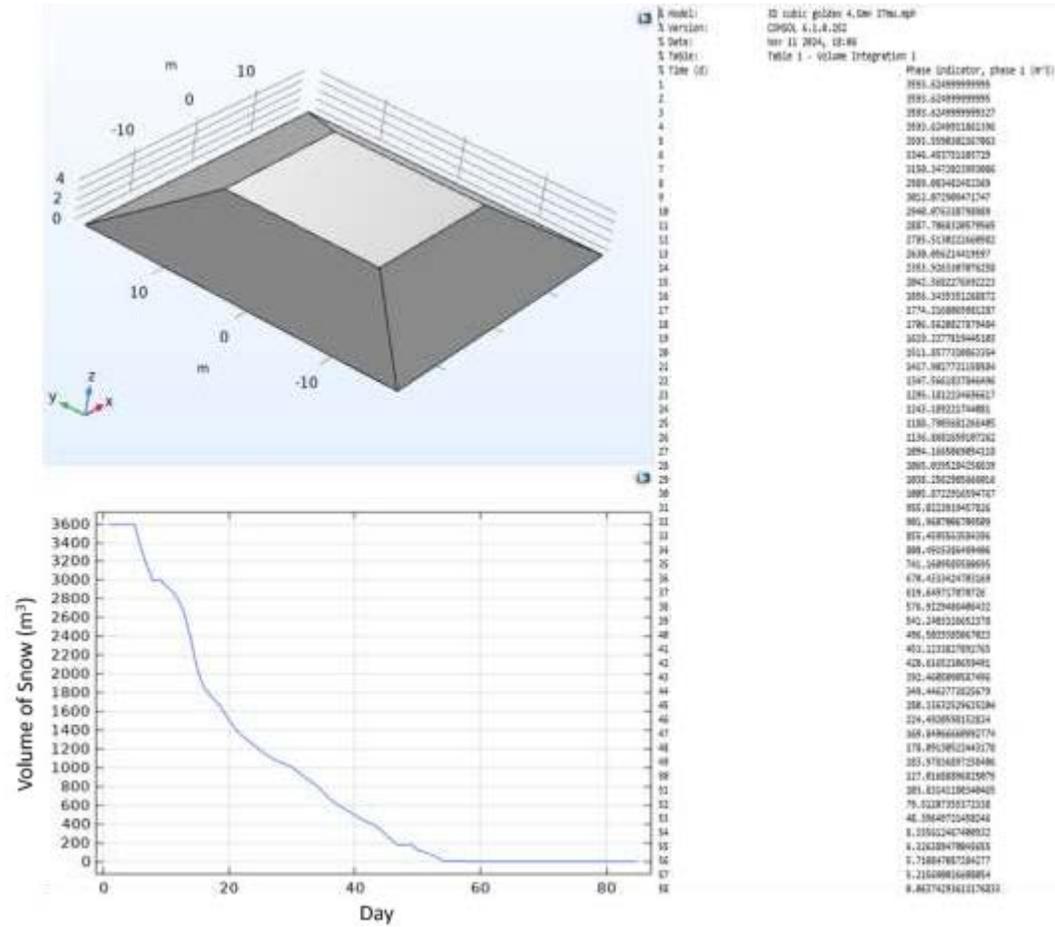


Figure E.65 Numerical modeling results for the cubic (4.5 m height, 37 m width, and 37 m length) SMP with 2023 weather function

Pile Number 66

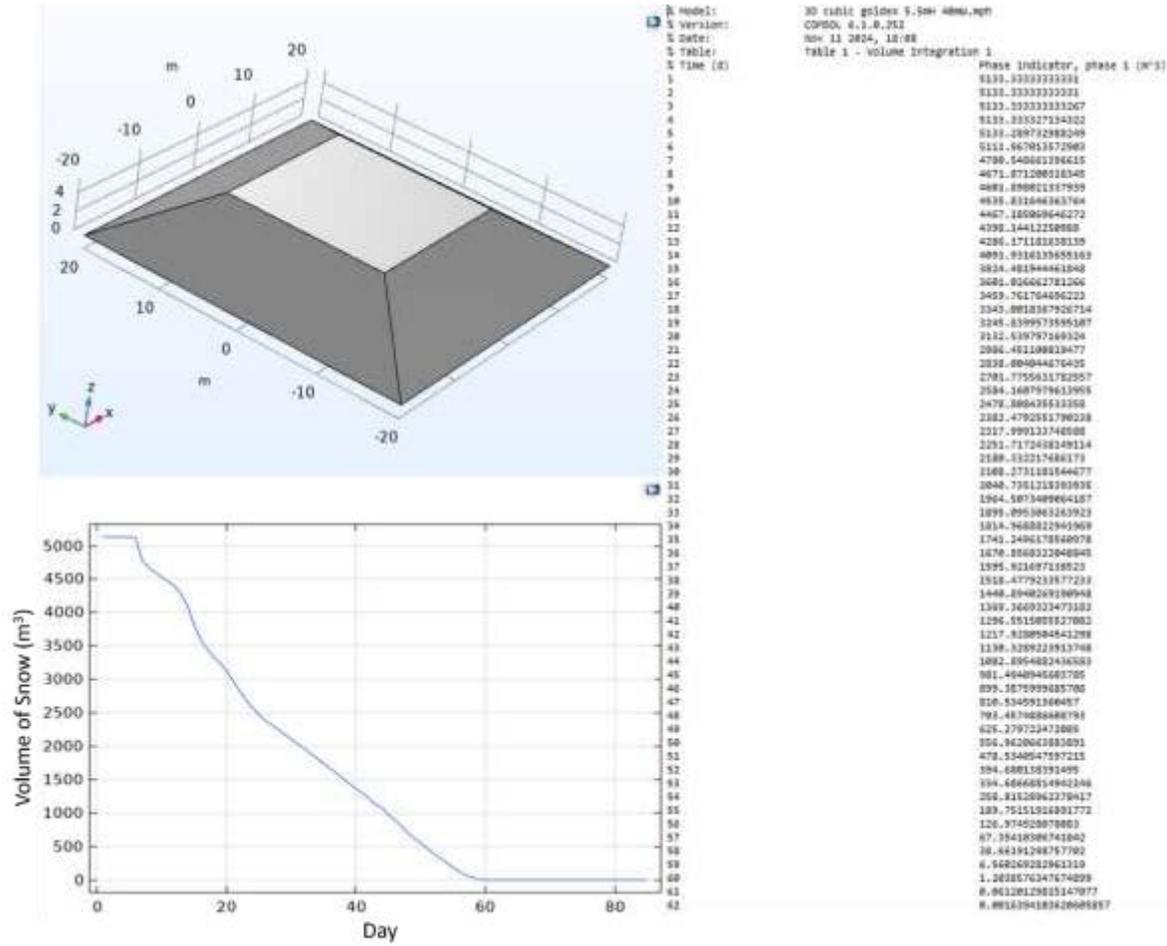


Figure E.66 Numerical modeling results for the cubic (5.5 m height, 40 m width, and 40 m length) SMP with 2023 weather function

Pile Number 67

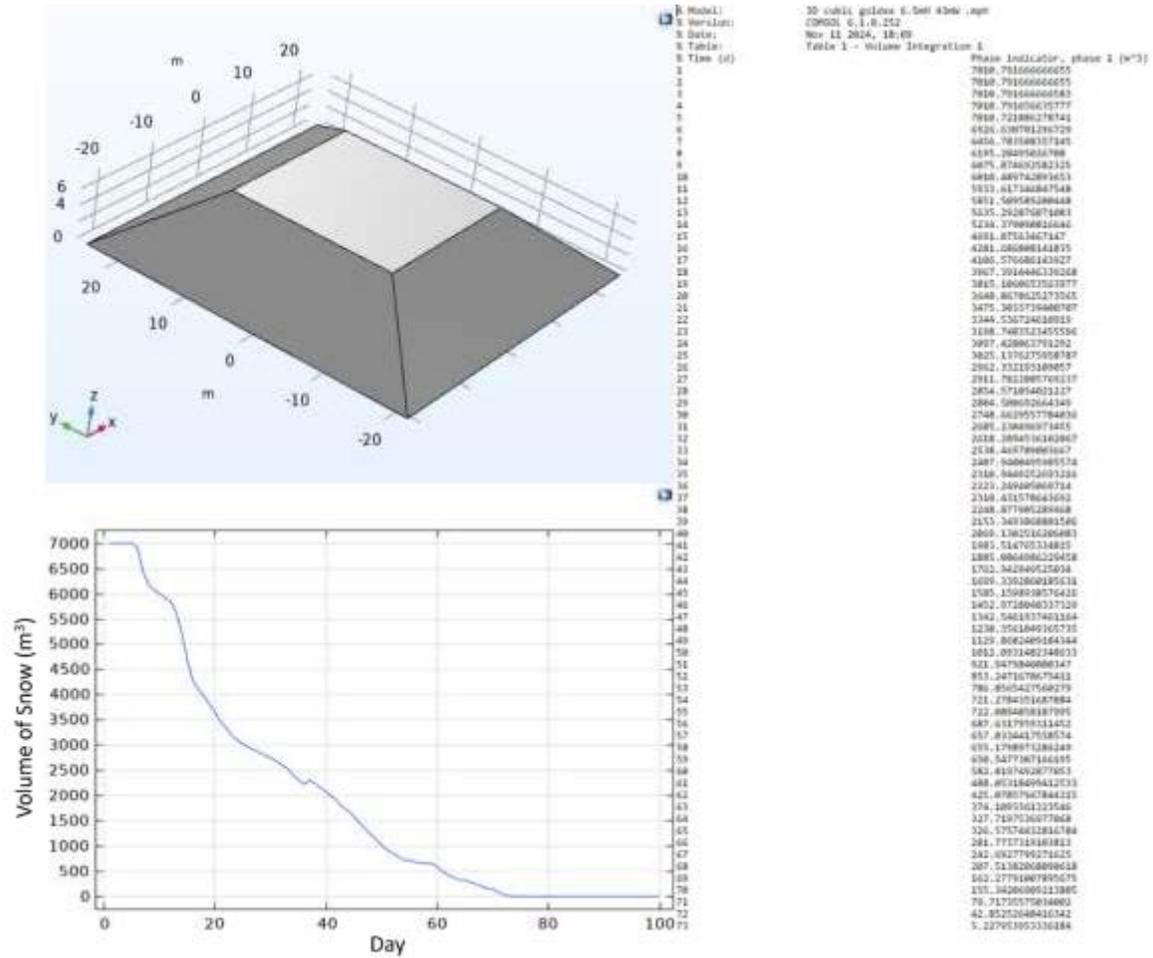


Figure E.67 Numerical modeling results for the cubic (6.5 m height, 43 m width, and 43 m length) SMP with 2023 weather function

Pile Number 68

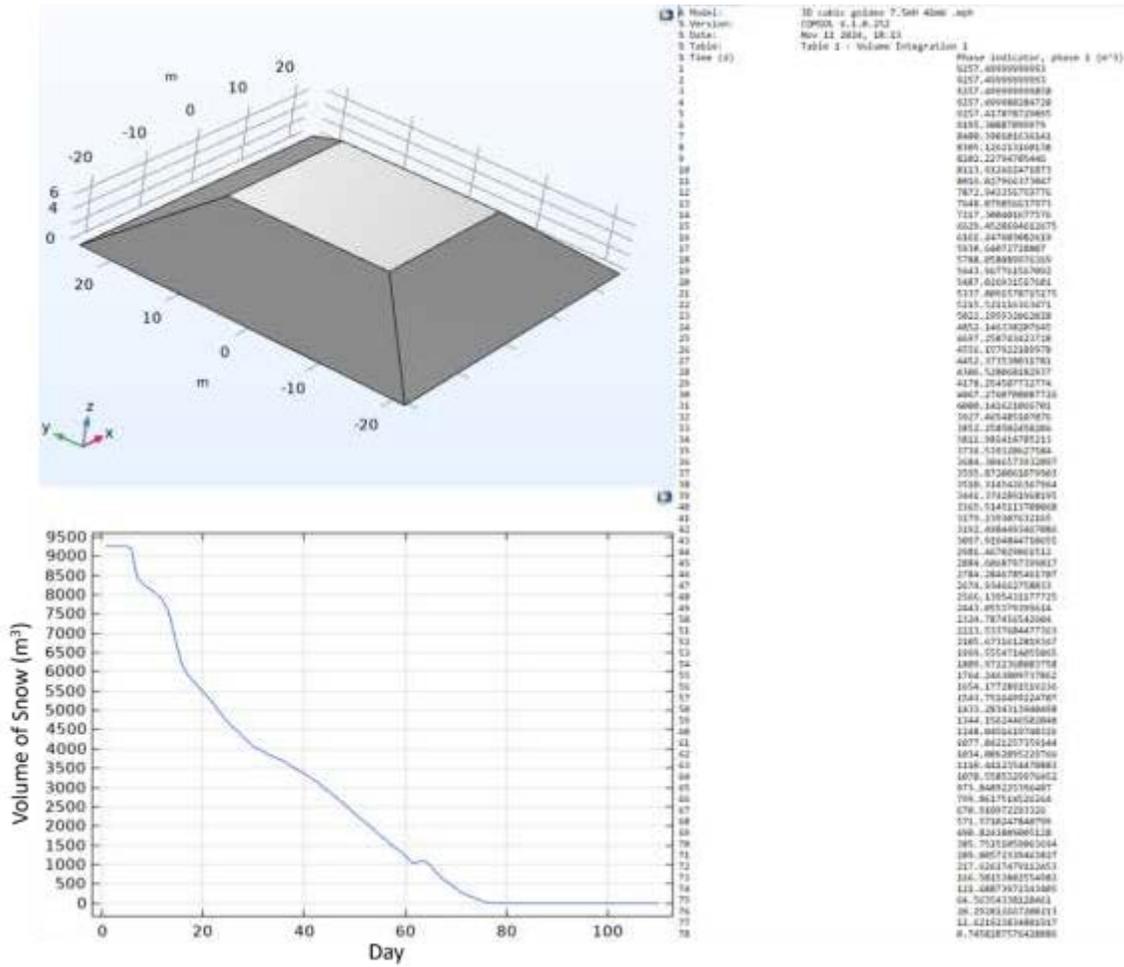


Figure E.68 Numerical modeling results for the cubic (7.5 m height, 46 m width, and 46 m length) SMP with 2023 weather functio

Pile Number 69

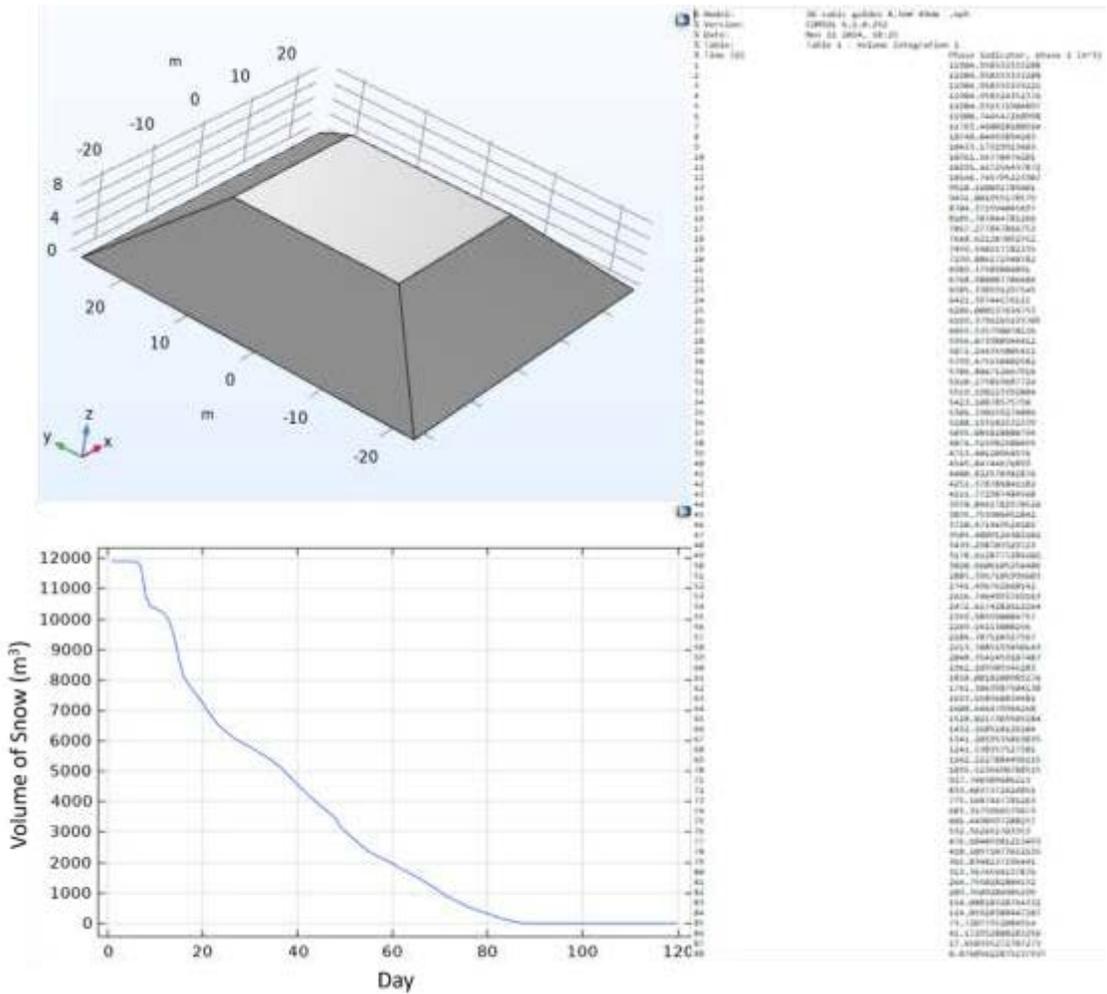


Figure E.69 Numerical modeling results for the cubic (8.5 m height, 49 m width, and 49 m length) SMP with 2023 weather function

Pile Number 70

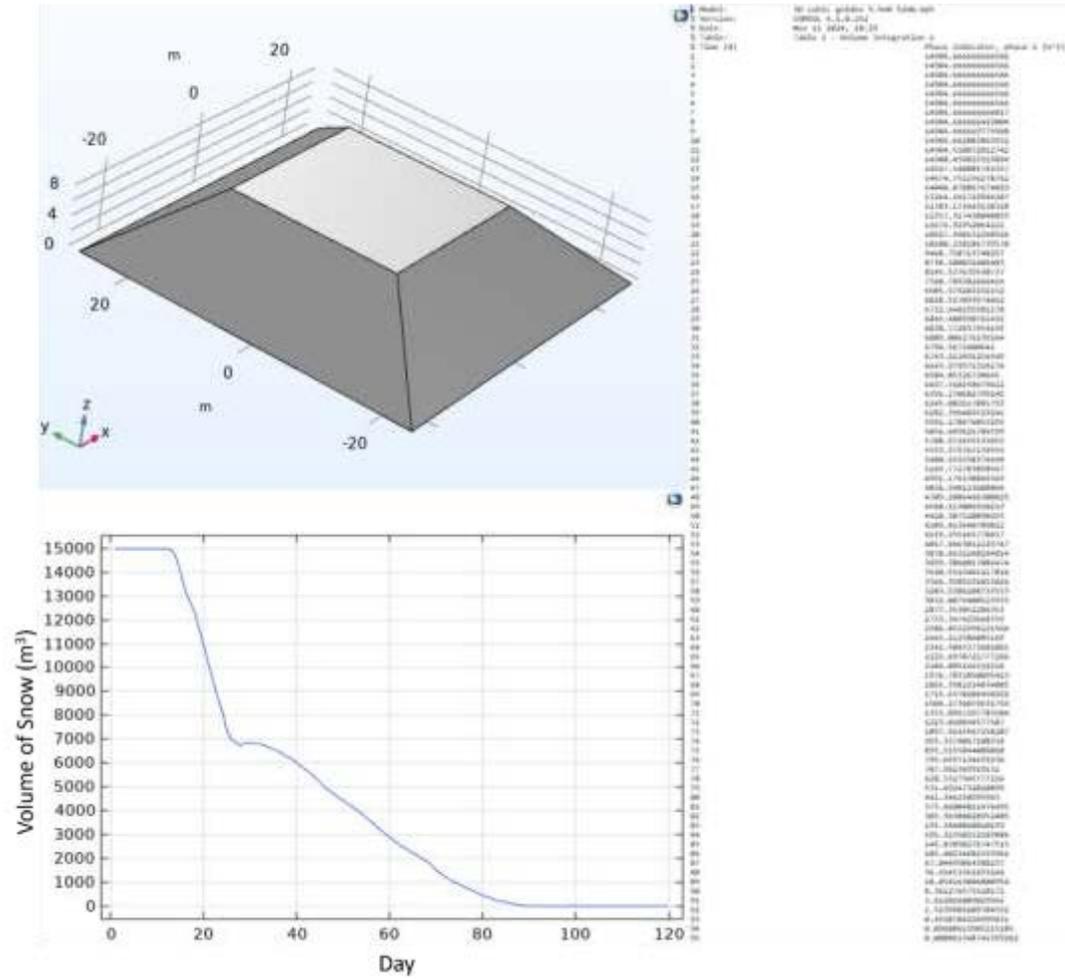


Figure E.70 Numerical modeling results for the cubic (9.5 m height, 52 m width, and 52 m length) SMP with 2023 weather function