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Multiphysics modeling of soil freezing and thawing processes: synthesis, validation, and outlook for soil-system science

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Abstract. Freezing and thawing transform soils through tightly coupled transfers of heat, water, vapor, solutes, and mechanical stress. These processes regulate frost heave, thaw settlement, infiltration, runoff generation, groundwater recharge, salinity redistribution, and the stability of cold-region infrastructure. Multiphysics models have advanced from empirical frost indices and thermal-hydraulic formulations to thermo-hydro-mechanical (THM) and thermo-hydro-mechanical-chemical (THMC) frameworks that represent phase change, cryosuction, unsaturated flow, vapor transport, ice segregation, poromechanical deformation, and damage. This review synthesizes freezing-soil modeling as a soil-system problem rather than only an engineering-design problem. We first organize the controlling mechanisms, including soil-freezing characteristic curves, soil-water retention behavior, generalized Clapeyron relations, frozen-fringe dynamics, ice-induced permeability reduction, and freeze-thaw damage. We then compare model families, primary variables, constitutive closures, numerical strategies, and validation requirements. Particular emphasis is placed on the gap between model complexity and data availability: temperature-only calibration can reproduce frost depth while failing to constrain water redistribution, deformation, and stress. We therefore argue that defensible THM/THMC modeling requires multi-observable calibration, conservation checks, out-of-sample validation, and explicit uncertainty propagation. The review concludes with a practical model-selection and reporting framework for soil scientists, hydrologists, and cold-region engineers. Priority needs include transferable closures for permeability and unfrozen water, shared benchmark datasets, uncertainty-aware inference, and hybrid continuum-discrete descriptions of ice lenses, interfaces, and damage.

1 Introduction

Freezing and thawing are among the most consequential transient processes in cold-region soils. They alter pore-water phase partitioning, hydraulic conductivity, thermal properties, suction, effective stress, soil fabric, and solute concentration. These changes affect not only frost heave and thaw settlement but also infiltration, runoff partitioning, groundwater recharge, active-layer development, slope stability, contaminant mobility, and the performance of infrastructure embedded in or founded on frozen ground (Walvoord and Kurylyk, 2016; Liu et al., 2024). Freezing-soil modeling is best viewed as an

https://doi.org/10.5194/egusphere-2026-4674
Preprint. Discussion started: 7 August 2026

integrative soil-system problem because freeze–thaw processes couple soil water storage, thermal regimes, solute redistribution, deformation, ecosystem function, and human infrastructure.

The physical couplings are strong and bidirectional. Thermal gradients govern freezing and melting, but the resulting phase change modifies heat capacity and thermal conductivity through latent heat and changes ice-water contents. Gradients in capillary pressure, cryogenic suction, chemical potential, and vapor density drive water movement toward or away from freezing fronts. Ice formation can reduce hydraulic conductivity by orders of magnitude, redirecting water from infiltration to runoff or restricting liquid supply to the freezing fringe. Deformation feeds back on porosity, permeability, storage, and stress, while repeated freeze-thaw cycles can damage soil structure and create irreversible changes in compressibility and hydraulic function.

Model development has evolved accordingly. Early tools estimated frost penetration using empirical or semi-empirical thermal indices. Coupled heat-and-water models then incorporated Richards-type flow, latent heat, and unfrozen-water curves. Segregation-potential and frozen-fringe theories provided macroscopic descriptions of frost heave and ice-lens growth (Konrad and Morgenstern, 1981; O'Neill and Miller, 1985; Rempel, 2010). Poromechanics introduced thermodynamic consistency and more rigorous effective-stress concepts for freezing porous media (Coussy, 2005). Recent models extend these foundations to variably saturated THM problems with liquid-vapor-ice interactions (Huang and Rudolph, 2021; Norouzi and Li, 2024), phase-field descriptions of ice-lens growth (Sweidan et al., 2020; Suh and Sun, 2022; Gao et al., 2023), and THMC formulations that account for solute exclusion and freezing-point depression (Huang and Rudolph, 2023; Mo et al., 2025).

Despite this progress, several barriers limit the routine use of thermo-hydro-mechanical (THM) and thermo-hydro-mechanical-chemical (THMC) models in soil-system studies. First, key closures, such as the soil-freezing characteristic curve (SFCC), ice-induced permeability reduction, and effective stress in partially frozen unsaturated soils, remain difficult to measure and transfer across soils and scales. Second, model calibration is often underdetermined: temperature data may constrain frost depth but not moisture redistribution, deformation, or stress. Third, numerical stiffness arising from phase change, permeability collapse, and mechanical feedback can obscure whether predictions arise from robust physics or from compensating numerical and parametric errors. Finally, many published studies report insufficient information on solver settings, conservation checks, and uncertainty propagation. Existing reviews have summarized freezing-soil mechanics, permafrost hydrology, or THMC model development (Kurylyk and Watanabe, 2013; Kurylyk et al., 2014; Li and Yin, 2025; Lemieux et al., 2025), but fewer have connected model complexity to soil-system decision variables, validation observables, and reproducibility requirements.

This review addresses these issues by synthesizing freezing-thawing models from a soil-system perspective. The goals are to (i) clarify the physical mechanisms that must be represented for different decision questions; (ii) compare model families, governing equations, primary variables, and constitutive closures; (iii) identify validation practices that distinguish credible

https://doi.org/10.5194/egusphere-2026-4674
Preprint. Discussion started: 7 August 2026

prediction from curve fitting; and (iv) provide a practical model-selection and reporting framework suitable for soil science, hydrology, permafrost, and cold-region engineering applications.

2 Review scope and organizing framework

This manuscript is a critical narrative review rather than a quantitative meta-analysis or bibliometric survey. The literature was organized around model function, process representation, and prediction reliability in freezing and thawing soils. We considered classical freezing-soil theory, unsaturated soil physics, poromechanics, continuum and phase-field descriptions of ice-lens formation, THM and THMC numerical formulations, laboratory and field validation studies, and applications in permafrost hydrology, artificial ground freezing, cold-region infrastructure, salinity, contaminant transport, and ground-source energy systems. Representative studies were selected because they contributed to one or more of the following themes: physical mechanism identification, governing-equation formulation, constitutive closure development, numerical implementation, validation strategy, uncertainty assessment, or translation of model outputs into hydrologic, environmental, or engineering decision metrics.

The purpose of the review is therefore not to catalog all freezing-soil studies exhaustively, but to synthesize the modeling choices that most strongly affect prediction credibility. Particular attention is given to the gap between model complexity and data availability. Modern THM and THMC formulations can include many interacting processes, but their reliability depends on whether key closures, such as the SFCC, soil-water retention curve (SWRC), ice-reduction of permeability, vapor transport, effective stress, and solute-dependent freezing-point depression, can be independently constrained by observations. Figure 1 presents the conceptual framework for this review, emphasizing how coupled thermal, hydraulic, and mechanical processes regulate soil water storage, infiltration, runoff generation, solute redistribution, deformation, and other soil-system outcomes. Studies were therefore interpreted not only in terms of the processes they include, but also in terms of the observations, assumptions, and numerical practices required to make their predictions defensible.

Four organizing questions guide the synthesis. First, what soil-system processes must the model resolve for the intended purpose: frost depth, water redistribution, infiltration and runoff partitioning, heave, settlement, stress, solute redistribution, or damage? Second, which constitutive closures connect measurable soil properties to phase change, flow, heat transfer, deformation, and chemical effects? Third, what observations are available to constrain and test these closures, including temperature, moisture, suction, pore pressure, deformation, ice content, solute concentration, geophysical data, or remote-sensing proxies? Fourth, how should uncertainty, verification, validation, and reproducibility be reported so that model complexity remains commensurate with the available data and the intended decision variable?

https://doi.org/10.5194/egusphere-2026-4674
Preprint. Discussion started: 7 August 2026

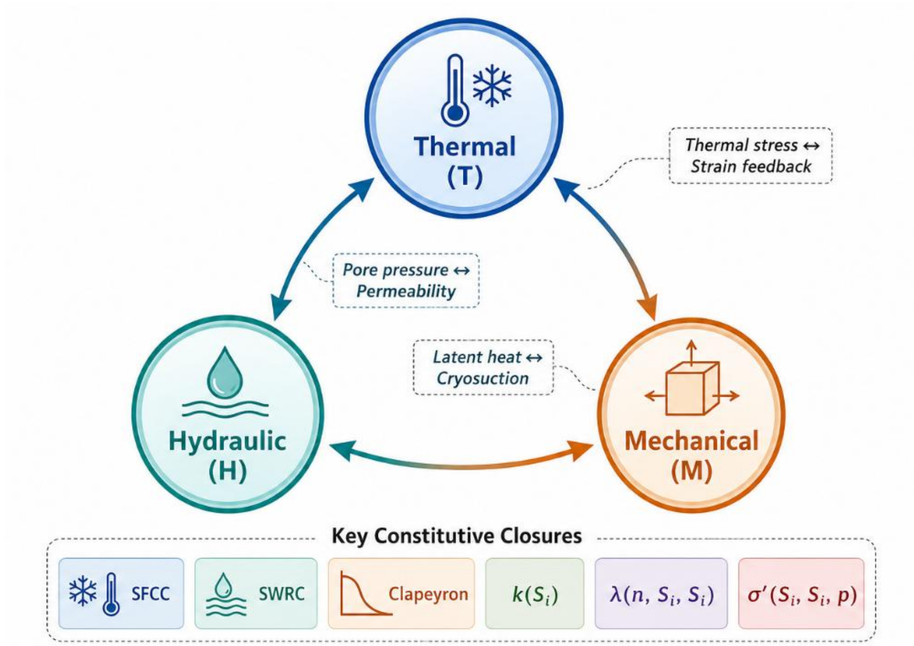

Figure 1. Conceptual coupling among thermal, hydraulic, and mechanical fields in variably saturated freezing soils. These couplings regulate soil water storage, infiltration, runoff generation, solute redistribution, deformation, and infrastructure response, highlighting why freezing and thawing should be treated as coupled soil-system processes rather than only as thermal or geotechnical problems.

3 Evolution of freezing-soil modeling

The evolution of freezing-soil modeling is best understood not as a simple replacement of older approaches by newer ones, but as a progressive expansion in the soil processes that models are able to represent (Table 1; Fig. 2). Empirical and semi-empirical methods remain useful for screening frost susceptibility and estimating frost penetration when data are limited. However, their predictive value is limited because they typically treat freezing as a primarily thermal process and cannot account for the coupled movement of heat, water, vapor, ice, solutes, and stress. As a result, they provide limited insight into why two soils with similar freezing indices may show different heave, infiltration recovery, thaw settlement, or hydrologic response.

Early thermal-hydraulic (TH) models marked an important transition from frost-depth estimation to process-based simulation. By coupling heat transfer with liquid-water flow and unfrozen-water content, these models enabled representation of latent heat release, snowmelt infiltration into frozen soil, and freezing-induced changes in soil hydraulic behavior (Harlan, 1973; Guymon and Luthin, 1974; Kane, 1980; Hansson et al., 2004). They remain valuable for predicting soil temperature, frost depth, and some hydrologic responses. Their main limitation is that soil is commonly treated as mechanically rigid, while vapor transport, hysteresis, and deformation feedbacks are simplified or neglected. Consequently,

https://doi.org/10.5194/egusphere-2026-4674
Preprint. Discussion started: 7 August 2026

a TH model may reproduce temperature profiles while still misrepresenting water redistribution, ice segregation, or settlement.

A second major line of development focused on frost heave and ice-lens formation. Segregation-potential theory provided a practical macroscopic description of heave rate, while frozen-fringe theory linked ice-lens growth to cryosuction, water supply, permeability, thermal gradients, and overburden stress (Konrad and Morgenstern, 1981; O'Neill and Miller, 1985; Rempel, 2010). These theories were crucial because they showed that frost heave is not caused only by the volumetric expansion of water upon freezing, but also by water migration toward freezing zones and the segregation of ice into lenses. Their continuing challenge is transferability: parameters describing water supply, permeability reduction, and lens initiation are difficult to measure directly and may vary with soil texture, saturation, stress state, salinity, and freezing rate.

Subsequently, poromechanical and thermodynamic formulations provided a more general framework for freezing porous media. In these models, temperature, pressure, saturation, ice content, deformation, and effective stress are treated as coupled state variables rather than independent processes (Coussy, 2005). This development enabled the representation of feedback from deformation to porosity, permeability, storage, and stress. Modern THM models extend this framework to variably saturated freezing soils by including liquid-water flow, vapor transport, cryosuction, phase change, and mechanical response within a single coupled formulation (Li et al., 2024a; Norouzi and Li, 2024). These models are powerful but also parameter-intensive. Their credibility depends strongly on whether temperature, water content, suction, deformation, and stress can be jointly constrained.

Recent developments have further expanded the modeling hierarchy. Phase-field, discrete, and hybrid continuum-discrete approaches have been introduced to describe the initiation of localized ice lenses, interface migration, cracking, and damage (Sweidan et al., 2020; Suh and Sun, 2022; Gao et al., 2023). THMC models have added solute transport, freezing-point depression, solute exclusion from ice, and osmotic effects, which are essential for saline soils, road salt, coastal and submarine permafrost, and cold-region contaminant transport (Huang and Rudolph, 2023; Mo et al., 2025). At the same time, open-source tools, benchmark studies, and multi-observable monitoring are beginning to shift attention from model formulation alone toward verification, validation, uncertainty quantification, and reproducible reporting (Pekinasova et al., 2025a, 2025b).

This historical progression highlights a central message of this review: increasing model complexity is useful only when it resolves processes that matter for the target question and when the additional parameters can be constrained. Empirical and TH models may be adequate for predicting frost depth or soil temperature. In contrast, THM models are needed for heave, settlement, stress, and slope stability, and THMC models are needed when solutes or freezing-point depression materially alter phase change and flow. The major unresolved challenge is therefore not simply to include more physics, but to align the model structure, constitutive closures, observations, and uncertainty analysis with the intended soil-system prediction.

https://doi.org/10.5194/egusphere-2026-4674
Preprint. Discussion started: 7 August 2026

Table 1. Evolution and practical role of freezing-soil model families.

Model family	Main soil processes represented	Typical strengths	Main limitations
Empirical frost-susceptibility and frost-index methods	Frost penetration risk, frost-susceptible textures, screening-level heave potential	Simple, code-compatible, low data demand	Cannot resolve water migration, ice lenses, stress, hysteresis, or climate-driven feedbacks
Thermal-hydraulic (TH) models	Heat transfer, phase change, liquid water flow, unfrozen water content	Useful for frost depth, soil temperature, infiltration/runoff partitioning	Usually, no deformation or stress feedback; vapor and hysteresis are often simplified
Segregation-potential and frozen-fringe models	Cryosuction, water supply to ice lenses, frost heave	Mechanistic heave prediction with practical parameterizations	Parameter transferability and unsaturated extensions remain challenging
Poromechanical THM models	Phase change, water/vapor flow, stress, strain, porosity-permeability feedbacks	Directly connects soil hydrology to deformation and effective stress	Parameter-intensive; requires multi-observable calibration and robust solvers
Phase-field, discrete, and hybrid models	Ice-lens initiation, interface migration, cracking, and damage	Promising for localized processes and interfaces	Computationally expensive and difficult to validate at the field scale
THMC models	Solute transport, freezing-point depression, solute exclusion, osmotic effects	Essential for saline soils, road salt, remediation, coastal, and submarine permafrost	Limited validation datasets; chemistry-mechanics coupling remains immature

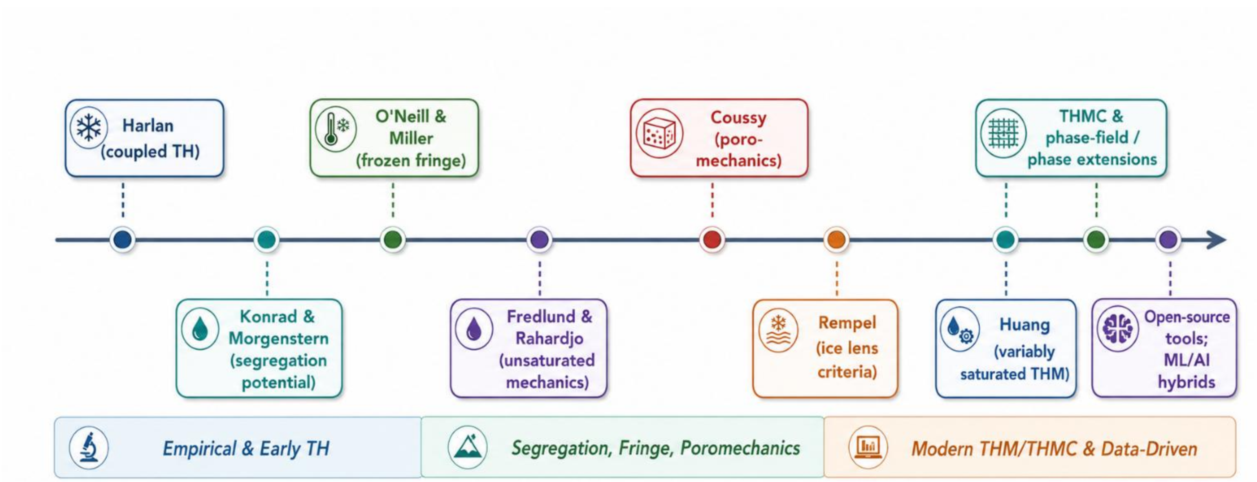

Figure 2. Timeline of major modeling milestones, from empirical and thermal-hydraulic approaches to modern THM, THMC, phase-field, and data-aware frameworks.

4 Physical mechanisms controlling soil freezing and thawing processes

Freezing and thawing of soils involve more than a thermal phase transition. They reorganize liquid water, ice, vapor, pore space, solutes, stress, and soil structure. The relative importance of these processes depends on the prediction target. Frost

https://doi.org/10.5194/egusphere-2026-4674
Preprint. Discussion started: 7 August 2026

depth is controlled primarily by surface energy exchange, thermal properties, latent heat, and the SFCC. Water redistribution depends additionally on capillary and cryogenic suction, hydraulic conductivity, vapor pathways, and boundary water supply. Heave, settlement, and stress require mechanical coupling, while salinity and contaminant redistribution require chemical coupling. This section summarizes the physical mechanisms that most directly determine which model complexity is warranted.

4.1 Unfrozen water, SFCC, SWRC, and cryosuction

A defining feature of frozen soils is the persistence of unfrozen water below 0 °C. This water is retained by capillarity in small pores, adsorption on mineral and organic surfaces, and solute-induced freezing-point depression. The SFCC, which relates unfrozen water content to temperature, is therefore one of the central closures in freezing-soil models. It controls the distribution of latent heat, the availability of mobile liquid water, the strength of cryosuction, the reduction of permeability by ice, and the shape and speed of the freezing front (Kurylyk and Watanabe, 2013; Devoie et al., 2022; Wang et al., 2025). A model can often reproduce temperature profiles with a simplified SFCC, but predictions of water redistribution, heave, and thaw recovery are much more sensitive to its shape, hysteresis, and residual unfrozen-water content.

The SFCC is thermodynamically connected to the SWRC. Under local equilibrium, the generalized Clapeyron relation links the depression in temperature to pressure differences between ice and liquid water, thereby connecting cryogenic suction to capillary suction. This relationship provides a useful way to interpret freezing as a suction-controlled process rather than simply as a temperature threshold. However, the SFCC–SWRC connection is not universal. It may be altered by freezing rate, hysteresis, salinity, air entrapment, pore-structure change, organic matter, and nonequilibrium ice formation. Consequently, directly transferring an unfrozen SWRC into a freezing model, or deriving an SFCC from an SWRC without sensitivity testing, can introduce substantial uncertainty.

Cryosuction is the main driver of water migration toward colder, partially frozen zones. In saturated or nearly saturated fine-grained soils, liquid flow toward the freezing front may dominate. In unsaturated soils, cryosuction interacts with capillary gradients and vapor-density gradients, producing redistribution patterns that can differ from those predicted by saturated frozen-fringe theories. This distinction matters for soil-system predictions: a model may capture frost penetration while still misrepresenting soil water storage, infiltration capacity after thaw, runoff generation, or groundwater recharge. Thus, the need for a detailed SFCC, SWRC hysteresis, and explicit vapor treatment should be judged based on the target variable, not solely on the desired physical completeness.

4.2 Ice segregation, frozen fringe, permeability collapse, and vapor pathways

Frost heave is controlled not only by the approximately 9% volume expansion of water upon freezing, but also by the migration of water toward freezing zones and the segregation of ice into lenses. The frozen fringe is the partially frozen zone between unfrozen soil and an ice lens or more completely frozen region (Fig. 3). Within this zone, decreasing temperature

https://doi.org/10.5194/egusphere-2026-4674
Preprint. Discussion started: 7 August 2026

reduces unfrozen water content, and ice increasingly blocks pore throats. Hydraulic conductivity can therefore decline by several orders of magnitude over a narrow temperature interval. This permeability collapse is one of the strongest nonlinearities in freezing-soil modeling and often controls water supply, ice-lens growth, heave rate, and infiltration/runoff partitioning.

Ice-lens initiation and growth depend on the balance among cryosuction, hydraulic supply, thermal gradient, overburden stress, effective stress, pore geometry, and soil fabric (O'Neill and Miller, 1985; Style and Peppin, 2012; Peppin and Style, 2013; Rempel, 2010; Kjelstrup et al., 2021). Fine-grained soils often sustain high suction and can support strong ice segregation. In contrast, coarse-grained soils may be limited by weaker capillary retention but can still experience vapor-assisted or localized ice formation under certain conditions (Teng et al., 2022). The practical implication is that ice-lens prediction requires more than a correct thermal field. It requires a defensible representation of water supply, permeability reduction, stress state, and the criterion used for lens initiation. These quantities are difficult to measure directly, which explains why frost-heave predictions often remain less transferable than frost-depth predictions.

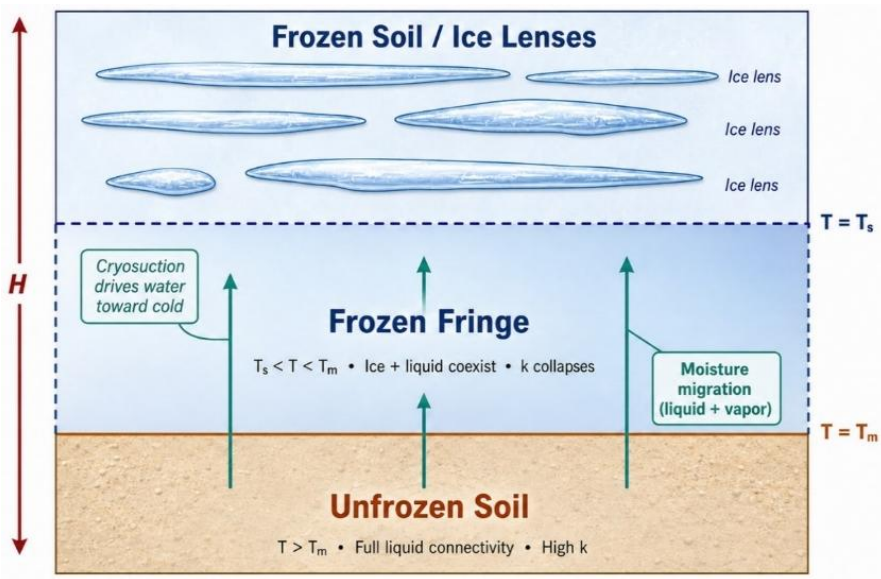

Figure 3. Frozen fringe, ice-lens formation, and cryosuction-driven water migration. Permeability collapse within the partially frozen fringe controls the supply of water to the freezing zone and is one of the least transferable but most influential closures in freezing-soil THM models.

Vapor transport provides an additional pathway for water redistribution when liquid connectivity is weak. It can be important in coarse-textured soils, dry near-surface layers, soils with strong thermal gradients, or partially frozen regions where ice blockage restricts liquid flow. Vapor fluxes also interact with energy conservation through evaporation, condensation, sublimation, and deposition. Explicit vapor models can improve predictions of moisture redistribution in partially saturated freezing soils (Teng et al., 2022; Wang et al., 2026), but they require additional parameters, including gas-filled porosity, tortuosity, gas permeability, and effective vapor diffusivity. For this reason, vapor transport should not be included automatically. It is most justified when the target outcome is moisture redistribution, near-surface water storage, drying–freezing interaction, or ice formation in coarse or partially saturated soils. For frost-depth prediction in near-saturated soils, a simpler liquid-dominated formulation may be adequate.

4.3 Mechanical response, soil-structure change, and freeze–thaw damage

Mechanical coupling is required when the prediction target includes frost heave, thaw settlement, stress redistribution, bearing capacity, slope stability, cracking, or soil–structure interaction. Ice formation can increase stiffness and strength by cementing particles and filling pores, but it can also increase brittleness and promote localized stress concentration. During thawing, the loss of ice bonding, drainage limitations, and the generation of excess pore pressure can reduce strength and cause settlement. These processes are especially important in ice-rich soils, organic soils, fine-grained frost-susceptible materials, and layered deposits where differential deformation controls field-scale impacts.

Repeated freeze–thaw cycles can cause irreversible changes in soil fabric. Aggregates may break down, pores may collapse or reorganize, cracks may form, and hydraulic conductivity and compressibility may change from one cycle to the next. Such path-dependent behavior cannot be represented by purely elastic THM models with fixed parameters. Depending on the application, models may need elasto-plasticity, creep, damage variables, evolving porosity–permeability relationships, or interface/fracture descriptions (Gawin et al., 2020; Wu et al., 2025). This is particularly relevant for long-term infrastructure performance, active-layer evolution, slope stability, and soil-water flow paths that are modified by repeated freezing and thawing.

Effective stress remains one of the most uncertain aspects of partially saturated frozen-soil mechanics. Stress may be shared among the soil skeleton, liquid water, ice, and gas, and different stress partitions can lead to different deformation predictions even when temperature and water-content predictions are similar. Bishop-type effective stress, net-stress formulations, and thermodynamically derived poromechanical stresses each make different assumptions about how suction, ice pressure, and saturation contribute to skeleton stress. The chosen effective-stress definition should therefore be treated as a model assumption that requires explicit reporting and, where possible, validation against deformation, pore-pressure, or stress data.

Across these mechanisms, the most transferable predictions are usually thermal, while the least transferable predictions involve ice segregation, permeability collapse, deformation, and damage. This hierarchy has practical consequences for model selection. A thermal model (TH) may be defensible for frost depth, whereas heave, settlement, stress, and solute redistribution require additional closures that are harder to measure and more prone to overfitting. The next section, therefore, links these mechanisms to model families, governing equations, primary variables, and constitutive closures.

https://doi.org/10.5194/egusphere-2026-4674
Preprint. Discussion started: 7 August 2026

5 Model families, equations, primary variables, and closures

The mechanisms summarized above can be represented at different levels of complexity. The appropriate model is not necessarily the most complete, but the simplest that resolves the processes controlling the target variable and can be constrained by available observations. A model designed to predict frost depth has different requirements from one designed to predict heave, settlement, solute redistribution, or soil-structure interaction. This section links process requirements to model hierarchy, governing equations, primary variables, constitutive closures, numerical implementation, and calibration strategy.

5.1 Model hierarchy and primary variables

Model selection should begin with the decision question. If the target is soil temperature or frost depth, a thermal or thermal-hydraulic (TH) model with credible thermal properties and an appropriate soil-freezing characteristic curve may be sufficient. If the target includes infiltration, runoff partitioning, groundwater recharge, or active-layer water storage, the model must also represent freezing-dependent hydraulic conductivity, water redistribution, and boundary water supply. If the target includes frost heave, thaw settlement, stress, bearing capacity, slope stability, or soil-structure interaction, THM coupling is required. If salinity, contaminant redistribution, road salt, or freezing-point depression materially alter phase change and flow, THMC coupling becomes necessary.

Table 2. Model hierarchy based on the target decision question.

Decision question	Minimum useful model	Essential observations	Main risk if oversimplified
Frost depth or soil temperature	Thermal or TH	Temperature profiles; snow/surface forcing	Correct temperature, but wrong water redistribution
Infiltration, runoff, recharge, and active-layer water storage	TH with freezing-dependent conductivity	Temperature, water content, water table, or fluxes	Misrepresentation of permeability collapse and thaw recovery
Frost heave, thaw settlement, bearing capacity, slope stability	THM	Temperature, moisture/suction, displacement, stress, or pore pressure	Temperature fits with unconstrained deformation and stress
Salinity, road salt, and contaminant redistribution	THMC	Temperature, water content, concentration, ice/unfrozen fraction	Ignoring freezing-point depression and solute exclusion
Cracking, interfaces, localized ice lenses	THM plus phase-field, cohesive-zone, peridynamic, or discrete approach	High-resolution deformation, imaging, fracture, or interface observations	Continuum smoothing of localized failure

Primary variables determine how phase change, flow, deformation, and chemistry are represented numerically. Common choices include temperature-liquid pressure-displacement, temperature-capillary pressure-displacement, temperature-total water content-displacement, and temperature-chemical potential-displacement. Pressure-based formulations are intuitive and align well with many hydrological and geotechnical measurements. Total-water formulations can be robust when phase partitioning is treated through an SFCC. Chemical-potential formulations can provide a thermodynamically unified

https://doi.org/10.5194/egusphere-2026-4674
Preprint. Discussion started: 7 August 2026

description of liquid and vapor transport, but they are less familiar in practice and may require careful scaling. A useful primary-variable set should remain well behaved near full saturation, near dry conditions, and across the freezing interval, and correspond to variables that can be measured or inferred for calibration.

5.2 Conservation equations and phase partitioning

Most freezing-soil models are built from conservation of mass, energy, and momentum over a representative elementary volume. The following equations are intended as compact schematic forms rather than a single prescriptive formulation. Individual implementations differ in sign convention, primary variables, phase partitioning, deformation measures, and treatment of phase equilibrium (Harlan, 1973; Guymon and Luthin, 1974; Hansson et al., 2004; Nishimura et al., 2009; Thomas et al., 2009; Kurylyk and Watanabe, 2013; Li and Yin, 2025).

A compact total-water balance can be written as

$$\frac{\partial}{\partial t}\left[n\left(S_l\rho_l + S_i\rho_i + S_g\rho_v\right)\right] + \nabla\cdot\left(\rho_l q_l + j_v\right) = Q_w \, , \tag{1}$$

where n is porosity; S_l, S_i, and S_g are liquid, ice, and gas saturations; ρ_l, ρ_i, and ρ_v are liquid-water, ice, and vapor densities; q_l is the liquid Darcy flux; j_v is the vapor mass flux; and Q_w represents sources and sinks. Ice is commonly treated as an immobile phase whose amount evolves through phase change. More detailed multiphase formulations may solve separate balances for liquid water, water vapor, dry air, and ice. Total-water formulations are compact, but they make the phase-partitioning rule especially important (Hansson et al., 2004; Kurylyk and Watanabe, 2013; Stuurop et al., 2021).

Liquid flux is usually represented by a Darcy-type law,

$$q_l = -\frac{k k_{rl}}{\mu_l}\left(\nabla p_l - \rho_l g\right), \tag{2}$$

where k is intrinsic permeability, k_{rl} is relative permeability, μ_l is liquid viscosity, p_l is liquid pressure, and g is the gravitational vector. In frozen soils, the effective liquid conductivity depends not only on saturation but also on ice content, pore blockage, and, in some cases, deformation-induced porosity changes. Vapor flux may be represented by a diffusive or advective-diffusive expression such as

$$j_v = -D_{v,eff}\nabla\rho_v + \rho_v q_g \, , \tag{3}$$

where $D_{v,eff}$ is the effective vapor diffusivity and q_g is the gas-phase velocity. Some models neglect gas advection and assume vapor diffusion under constant gas pressure, whereas others explicitly solve for gas pressure. Vapor transport formulations originate from non-isothermal porous-media theory and have been extended in freezing-soil models to account

https://doi.org/10.5194/egusphere-2026-4674
Preprint. Discussion started: 7 August 2026

for moisture redistribution under partially saturated conditions (Philip and de Vries, 1957; Thomas et al., 2009; Huang and Rudolph, 2021, 2023).

Energy conservation may be written in terms of an enthalpy-like variable H:

$$\frac{\partial H}{\partial t}+\nabla\cdot\left(\rho_l c_l T q_l + c_v T j_v\right)-\nabla\cdot\left(\lambda_{eff}\nabla T\right)=Q_T\,, \tag{4}$$

where T is temperature, c_l and c_v are heat capacities, λ_{eff} is the effective thermal conductivity, and Q_T denotes heat sources or boundary exchange. The enthalpy H includes sensible heat of the soil matrix and pore phases, plus latent heat associated with freezing and melting. Apparent heat-capacity methods embed latent heat within an effective heat capacity over a finite freezing interval, whereas source-term methods compute latent heat from explicit phase-change rates. Apparent heat-capacity methods are often numerically smoother, but the selected freezing interval and latent-heat conservation should be reported because they can affect freezing-front timing (Hansson et al., 2004; Kurylyk and Watanabe, 2013; Jan et al., 2020)

Momentum balance is usually treated as quasi-static:

$$\nabla\cdot\sigma+\rho_b g=0\,, \tag{5}$$

where σ is the total stress and ρ_b is the bulk density. Mechanical coupling is introduced through constitutive relations that link total stress, effective stress, strain, temperature, pore pressures, ice pressure, suction, and porosity. A schematic effective-stress relation can be expressed as

$$\sigma' = \sigma-\alpha \mathrm{P}_{eff}\mathrm{I}\,, \tag{6}$$

where σ′ is the effective stress, α is a Biot-type coefficient, I is the identity tensor, and P_{eff} is an effective pore pressure or stress-partition variable. The definition of P_{eff} is model-dependent. In partially saturated frozen soils, it may include contributions from liquid pressure, gas pressure, ice pressure, capillary suction, cryosuction, and saturation-dependent weighting functions. Because different effective-stress choices can produce similar thermal and hydraulic predictions but different deformation predictions, the stress partition should always be stated explicitly (Coussy, 2005; Nishimura et al., 2009; Gawin et al., 2020; Li et al., 2024a; Norouzi and Li, 2024).

The thermodynamic link between temperature and pressure is commonly expressed through a generalized Clapeyron-type relation. In simplified form,

$$p_l-p_i\approx\rho_l L_f\left(T-T_m\right)/T_m\,, \tag{7}$$

where p_i is ice pressure, L_f is the latent heat of fusion, and T_m is the reference melting temperature. The sign convention varies among formulations, but the physical role is the same: temperature depression below the melting point corresponds to

https://doi.org/10.5194/egusphere-2026-4674
Preprint. Discussion started: 7 August 2026

a pressure difference between liquid water and ice, generating cryosuction. In saline soils, T_m is further depressed by solute concentration, which motivates THMC formulations (Coussy, 2005; Kurylyk and Watanabe, 2013; Cui et al., 2024; Mo et al., 2025).

A typical permeability-reduction closure can be written as

$$k_{eff} = k_0 k_{rl}(S_l) f_i(S_i, n), \tag{8}$$

where k_0 is unfrozen intrinsic permeability and f_i is an ice-impedance function, often represented using a power law or exponential function such as $f_i = (1-S_i)^b$ or $f_i = \exp(-aS_i)$. This closure is often one of the most influential and least transferable components of THM models, because small differences in assumed ice blockage can strongly affect water supply, infiltration recovery, and frost-heave prediction (Kurylyk and Watanabe, 2013; Stuurop et al., 2021; Li et al., 2024b).

If solute transport is included, a liquid-phase transport equation may be added:

$$\frac{\partial(nS_l c)}{\partial t} + \nabla \cdot \left(q_l c - nS_l D_{eff} \nabla c\right) = Q_c + R_c, \tag{9}$$

where c is solute concentration, D_{eff} is effective dispersion-diffusion, Q_c represents solute sources and sinks, and R_c represents reactions or phase-partitioning effects. Coupling to freezing occurs through freezing-point depression, solute exclusion from ice, and concentration changes in the residual liquid phase. These terms should be explicitly stated in THMC models because different phase-partitioning assumptions can yield different concentration and freezing-front predictions even when the thermal field is similar (Cui et al., 2024; Mo et al., 2025; Li and Yin, 2025).

5.3 Thermodynamic and constitutive closures

The governing equations are not predictive without constitutive closures. These closures determine how measurable or inferable soil properties are translated into phase change, water retention, hydraulic conductivity, heat transfer, deformation, and chemical redistribution. The most important closures are the SFCC, SWRC, generalized Clapeyron relation, permeability reduction by ice, thermal-property mixing law, mechanical constitutive law, effective-stress definition, and, for THMC models, solute-phase partitioning and freezing-point depression.

A recurring problem is that several closures interact nonlinearly. For example, the SFCC controls liquid availability, but the permeability-reduction function controls whether that liquid can move. The SWRC controls capillary suction, but the Clapeyron relation modifies suction under freezing. Mechanical deformation changes porosity and permeability, which feed back into flow and heat transfer. Therefore, calibrating one closure while arbitrarily fixing another can create compensating errors. This is especially problematic when calibration is based only on temperature.

https://doi.org/10.5194/egusphere-2026-4674
Preprint. Discussion started: 7 August 2026

Table 3. Key closures in freezing-soil THM and THMC models and their implications.

Closure	Common representation	What it matters	Practical recommendation
SFCC	Power law, exponential, pore-size/Gibbs-Thomson, dynamic curves	Controls unfrozen water, latent heat, liquid connectivity, permeability, and cryosuction	Measure when possible; report freezing/thawing branch, residual water, and hysteresis assumptions
SWRC	van Genuchten or Brooks-Corey, with or without hysteresis	Controls capillary suction and unsaturated flow before, during, and after freezing	Do not assume the unfrozen SWRC transfers unchanged to freezing conditions without sensitivity testing
Clapeyron relation	Pressure-temperature equilibrium relation	Links cryosuction to temperature depression and phase equilibrium	State pressure convention, reference temperature, local-equilibrium assumption, and salinity correction if used
Permeability reduction	Power-law or exponential function of ice saturation or unfrozen water	Often dominates the heave rate, infiltration limitation, and runoff generation	Treat as uncertain; calibrate jointly with SFCC and moisture/deformation data
Thermal properties	Geometric mean, de Vries, Johansen, organic-soil variants	Control frost depth, phase-change timing, and thermal-memory effects	Use soil-specific parameterization for organic-rich, peat, or strongly layered horizons
Effective stress and mechanics	Bishop-type, net-stress, poromechanical, elastic, plastic, viscoplastic, or damage laws	Control heave, settlement, bearing capacity, cracking, and stress transfer	Validate with deformation, pore-pressure, or stress data, not temperature alone
Vapor transport	Diffusion or advective-diffusive gas-phase transport	Controls moisture redistribution when liquid connectivity is weak	Include explicitly when dry, coarse, or near-surface soils are important
Solute coupling	Advection-dispersion with freezing-point depression and solute exclusion	Controls saline soils, road salt, remediation, and osmotic effects	Use THMC only when concentration data or strong salinity effects can constrain the model

5.4 Parameter transferability and scale dependence

Freezing-soil parameters are strongly scale dependent. Laboratory specimens are usually more homogeneous, better constrained, and more carefully prepared than field soils. Field soils contain layering, roots, organic horizons, macropores, cracks, ice-rich lenses, variable salinity, and lateral heterogeneity. Hydraulic conductivity, thermal conductivity, and stiffness may be anisotropic and change with freeze–thaw history. Consequently, parameters measured at the specimen scale should not be assumed to transfer directly to field simulations without uncertainty analysis.

A practical hierarchy can be used. Thermal conductivity and volumetric heat capacity are often moderately transferable if soil type, water content, and ice content are known, although organic soils and peat require special treatment. SFCC parameters are less transferable because they depend on pore-size distribution, mineralogy, organic matter, solutes, and thermal history. Permeability-reduction parameters are often the least transferable because they depend on pore blockage and ice morphology, which are rarely measured directly. Mechanical stiffness, strength, creep, and damage parameters are highly

https://doi.org/10.5194/egusphere-2026-4674
Preprint. Discussion started: 7 August 2026

consequential only when deformation or stress is a target, but they can dominate predictions of heave, settlement, and infrastructure response.

Parameter provenance should therefore be reported explicitly. Each parameter should be identified as directly measured, estimated from literature, inferred by inverse calibration, or assumed. Sensitivity analysis should then identify which parameters control the target output. Without this information, differences among models may reflect hidden parameter choices rather than genuine differences in physical formulation.

5.5 Numerical implementation, coupling strategy, and verification

Freezing-soil simulations are numerically challenging because several nonlinearities occur over narrow temperature and saturation ranges. Latent heat produces sharp changes in apparent heat capacity. The SFCC may have steep slopes near the freezing interval. Hydraulic conductivity can collapse by orders of magnitude as ice forms. Mechanical deformation can feed back into porosity, permeability, and stress. These nonlinearities make time-step control, robustness of the nonlinear solver, and conservation checks central to model credibility.

Finite element and finite volume methods are most common, although finite difference, finite-discrete element, phase-field, and peridynamic approaches are used for specific problems. Mesh resolution must be sufficient near freezing fronts, frozen fringes, ice lenses, interfaces, and structural contacts. Time-step refinement is often needed when temperature crosses the phase-change interval or when permeability changes rapidly. Numerical diffusion can smear freezing fronts, whereas overly sharp phase-change functions can cause convergence failure. Both problems should be assessed through grid and time-step convergence tests.

Coupling strategies can be monolithic, staggered, or hybrid (Table 4). Monolithic approaches solve all coupled unknowns simultaneously and are generally more robust when thermal, hydraulic, and mechanical feedbacks are strong. Their disadvantages are larger linear systems, stronger scaling requirements, and more demanding preconditioning. Staggered approaches solve the thermal, hydraulic, chemical, and mechanical subproblems sequentially, which is easier to implement and can reuse existing solvers, but they may converge slowly or fail during rapid phase change, permeability collapse, or strong mechanical feedback. Hybrid approaches use iterative coupling among physics with nonlinear subproblem solves and can provide a practical compromise.

Verification should be performed before validation. Minimum verification includes mass and energy conservation checks, grid- and time-step convergence, and comparisons with analytical or benchmark problems, such as Stefan or Neumann freezing solutions, where appropriate (Xiang & Rudloph, 2022; Nicolsky et al., 2026). Manufactured solutions are valuable when exact freezing solutions are unavailable. Cross-code intercomparison, such as freeze–thaw transport benchmark studies, remains limited but is essential for building community confidence. Agreement with laboratory or field data is not sufficient

https://doi.org/10.5194/egusphere-2026-4674
Preprint. Discussion started: 7 August 2026

if the model has not demonstrated conservation, convergence, and numerical robustness; apparent agreement can result from compensating errors in parameters, discretization, or boundary conditions.

Table 4. Comparison of numerical coupling strategies for freezing-soil simulations.

Coupling strategy	Main features	Strengths	Limitations	Most appropriate use
Monolithic	Simultaneous solution of thermal, hydraulic, mechanical, and chemical unknowns	Robust for strong coupling; captures cross-derivatives consistently	High implementation complexity; requires scaling and preconditioning	Rapid freezing, strong heave, permeability collapse, tightly coupled THM/THMC problems
Staggered	Sequential solution of subproblems with information exchange	Easier to implement; can reuse existing solvers; lower memory per subproblem	May require many outer iterations; can fail under strong coupling	Mildly coupled problems, large 3-D simulations, exploratory applications
Hybrid	Iterative coupling with nonlinear subproblem solves or partial monolithic blocks.	Balance between robustness and implementation effort	Performance depends on relaxation, convergence criteria, and coupling order	Practical engineering and field-scale studies with moderate to strong coupling

5.6 Calibration, validation, identifiability, and uncertainty

Calibration is often the limiting step in THM and THMC modeling. Many parameter combinations can reproduce soil temperature while producing substantially different predictions of water redistribution, ice content, heave, settlement, stress, or solute concentration. This non-uniqueness is especially severe when the SFCC, permeability-reduction function, boundary water supply, and mechanical parameters are calibrated simultaneously. A model calibrated only to temperature should not be used to make strong claims about heave, stress, moisture redistribution, or solute transport unless these variables are independently validated or their uncertainty is explicitly propagated.

Temperature-only calibration may be adequate when the intended output is temperature or frost depth. It is not adequate when the model is used to infer hydrologic or mechanical outcomes. For TH applications, temperature should be complemented by water content, suction, water table, infiltration, runoff, or recharge data, where possible. For THM applications, temperature, moisture, suction, and deformation form a practical minimum-observable set. For THMC applications, concentration data are also needed because solute exclusion and freezing-point depression can otherwise remain weakly constrained. Calibration should distinguish between assigned and estimated parameters and report the objective functions used.

Laboratory directional-freezing tests are valuable because boundary conditions can be controlled, and internal variables can be measured. Open-system tests constrain water supply and ice segregation, closed-system tests isolate volumetric effects, and cyclic tests reveal hysteresis and damage. Field validation is more difficult because surface temperature, snow, vegetation, groundwater, soil layering, and lateral flow are often uncertain. Distributed temperature sensing, soil-moisture networks, pore-pressure sensors, electrical resistivity tomography, seismic methods, fiber-optic strain sensing, and InSAR-

https://doi.org/10.5194/egusphere-2026-4674
Preprint. Discussion started: 7 August 2026

derived deformation can provide complementary constraints. The most convincing validation tests model predictions under boundary conditions or cycles not used for calibration.

Uncertainty should be propagated to decision-relevant outputs rather than reported only for internal parameters. For soil-system applications, relevant outputs may include frost depth, thaw depth, infiltration capacity, runoff ratio, groundwater recharge, active-layer water storage, solute concentration, settlement, or probability of exceeding a deformation threshold. Sensitivity analysis can identify whether soil parameters, boundary forcing, numerical choices, or model structure dominate uncertainty. Bayesian calibration, ensemble simulation, and surrogate modeling can support uncertainty propagation, but their usefulness depends on the availability of observations that actually constrain the uncertain parameters.

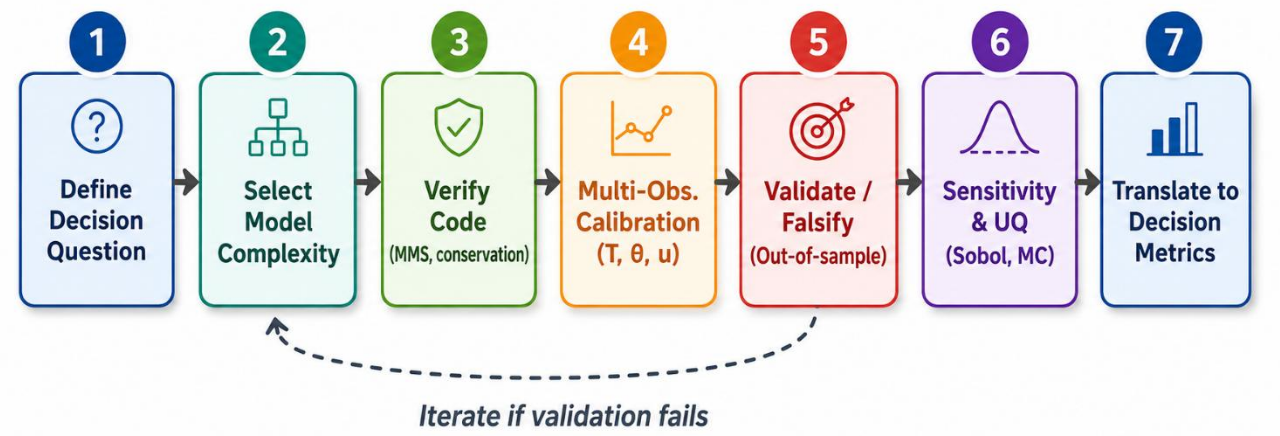

Figure 4. The workflow emphasizes multi-observable calibration, out-of-sample validation, conservation checks, and translation from state variables to decision-relevant soil-system or engineering metrics.

Table 5. Validation pathways and the types of evidence they provide.

Validation level	Typical observations	What can be tested	Main limitation
Analytical/benchmark verification	Known solution, conservation residuals, grid convergence	Implementation correctness and numerical robustness	Usually simplified physics and geometry
Laboratory columns	Temperature, water content, suction, displacement, ice content	SFCC, permeability reduction, ice segregation, heave, hysteresis	Scale and boundary conditions may differ from field soils
Controlled artificial ground freezing.	Temperature, deformation, water migration, and overburden response	Strong thermal gradients, engineered boundaries, and thaw response	Often site-specific and engineering-oriented
Field monitoring	Borehole temperature, moisture, water table, geophysics, InSAR, settlement	Boundary uncertainty, heterogeneity, and long-term performance	Sparse observations and uncertain forcing
Infrastructure or ecosystem response	Pipe strain, pavement roughness, slope movement, runoff/recharge, solute loads	Translation from soil states to impacts	Requires coupling to structural, hydrologic, or ecological models

https://doi.org/10.5194/egusphere-2026-4674
Preprint. Discussion started: 7 August 2026

The credibility of a freezing-soil model, therefore, depends on the full chain from governing equations to closure selection, parameter estimation, numerical verification, validation, and uncertainty propagation. Stronger physics does not automatically produce stronger predictions. Model complexity becomes useful only when it is matched to the decision question and supported by observations that constrain the additional processes introduced.

6 Application domains and soil-system implications

The practical value of freezing-soil models lies in their ability to translate coupled thermal, hydraulic, mechanical, and chemical processes into outcomes relevant to soil science, hydrology, environmental management, energy systems, and infrastructure (Fig. 5). These applications differ in their target variables and therefore in the level of model complexity that is justified. For some questions, such as seasonal frost depth or soil-temperature evolution, thermal models may be sufficient. For others, such as heave, settlement, salinity redistribution, or soil-structure interaction, THM or THMC coupling becomes necessary. This section groups the main applications by soil-system function rather than by discipline, and highlights how modeling choices affect the credibility of predictions.

Figure 5. Application domains in which THM and THMC freezing-soil models connect soil processes to hydrologic, environmental, energy, and infrastructure outcomes.

6.1 Permafrost soils, hydrology, and climate-boundary uncertainty

Permafrost degradation changes soil thermal regimes, active-layer thickness, water storage, hydrologic connectivity, and ground stability. Thaw can deepen flow paths, increase groundwater-surface water exchange, alter drainage networks, mobilize previously frozen water and solutes, and induce settlement in ice-rich soils. These processes link frozen-soil physics directly to catchment hydrology and landscape evolution (Walvoord and Kurylyk, 2016; Lemieux et al., 2025). THM models are therefore needed when thermal projections must be translated into hydrologic or mechanical consequences rather than into thaw depth alone.

A central challenge in permafrost applications is uncertainty in boundary conditions. Snow cover, vegetation, surface organic layers, rainfall timing, water table depth, wildfire disturbance, and lateral drainage can strongly affect the ground thermal and hydraulic regime. For example, snow insulation can reduce winter cooling, while changes in vegetation and surface organic layers can alter both thermal conductivity and near-surface moisture storage. Climate-driven changes in precipitation phase and timing further affect antecedent soil moisture and water availability during freezing. These boundary uncertainties may be as important as internal soil parameters in controlling future thaw, active-layer hydrology, and thaw settlement.

Recent permafrost modeling studies illustrate the need to combine mechanistic representation with uncertainty-aware prediction. Sun et al. (2022) simulated thaw settlement and permafrost change along the Qinghai–Tibet Engineering Corridor, linking thermal evolution to deformation. Xavier et al. (2024) used mechanistic modeling to assess future permafrost degradation in a central Siberian catchment under climate change scenarios. Streletskiy et al. (2025) synthesized observations of thaw subsidence across the Northern Hemisphere, emphasizing that ice-rich permafrost can undergo substantial surface lowering. Zhou et al. (2025) further highlighted that uncertainty in soil properties can be comparable to, or even exceed, uncertainty in climate forcing for some permafrost projections. These studies show that THM-informed permafrost assessment must consider both internal parameter uncertainty and external boundary forcing.

For soil-system studies, the strongest contribution of THM modeling is not only predicting thaw depth but linking thaw to soil-water storage, infiltration capacity, runoff generation, groundwater recharge, solute transport, and deformation. Large-scale land-surface and Earth-system models generally use simplified freeze–thaw parameterizations, which are computationally necessary but may miss feedbacks among permeability collapse, water redistribution, ice-rich settlement, and lateral hydrologic connectivity (Zhang et al., 2007; Jan et al., 2020; Walvoord and Kurylyk, 2016; Lemieux et al., 2025). A key research direction is therefore to develop reduced-order or upscaled THM closures that preserve the dominant freeze–thaw feedbacks while remaining practical for catchment- to regional-scale applications.

6.2 Cold-region infrastructure and soil–structure interaction

Infrastructure applications remain important because they provide clear decision metrics, including differential heave, thaw settlement, pipe bending strain, pavement roughness, bearing capacity, slope factor of safety, and frozen-wall closure time.

https://doi.org/10.5194/egusphere-2026-4674
Preprint. Discussion started: 7 August 2026

Transportation corridors, buried lifelines, foundations, piles, and embankments are often damaged where soil processes are spatially heterogeneous. Variations in soil texture, water supply, snow redistribution, drainage, shading, and thermal exposure can create differential freezing and thawing, producing deformation that is more damaging than uniform movement. Transportation infrastructure has motivated many recent THM studies because roads, railways, and airstrips are sensitive to frost heave, thaw weakening, and long-term settlement. Liu et al. (2024) developed a THM model for unsaturated frozen soils considering both frost heave and thaw settlement. Zhang et al. (2024a) combined experiments and numerical modeling to investigate THM behavior under freeze–thaw cycles. Chen et al. (2025) analyzed coupled THM processes affecting slopes in seasonally frozen regions. These studies demonstrate that mechanically coupled models can provide insight into deformation mechanisms, but their reliability depends on whether water content, suction, deformation, and boundary conditions are constrained in addition to temperature.

Buried lifelines illustrate the need to translate soil states into infrastructure-relevant metrics. Frost heave can impose differential displacement along pipes, while lateral and vertical frost pressures can change the stress state at soil－pipe interfaces. Huang et al. (2022) linked THM ground response to water-main vulnerability by translating frost-induced ground stress and deformation into pipe-related failure metrics. Such studies are valuable because they demonstrate how freezing-soil models can move beyond reproducing soil temperature and instead support risk-informed maintenance and adaptation. Similarly, Hao et al. (2025) investigated coupled THM responses in pile–soil systems under freezing conditions, highlighting the importance of material contrast and soil–structure interaction.

In soil-system interpretation, infrastructure applications should not be viewed solely as engineering case studies. They are also controlled experiments in how soil texture, water supply, phase change, and boundary forcing interact (Cai et al., 2024; Yu et al., 2020; Nikolaev et al., 2025). The most useful infrastructure studies are those that connect observed damage or deformation to specific soil processes and that validate predictions against variables not used for calibration.

6.3 Artificial ground freezing as a controlled validation environment

Artificial ground freezing (AGF) is widely used for temporary ground support and groundwater control during shaft sinking, tunneling, and underground construction. AGF creates strong thermal gradients, rapid phase change, and large changes in permeability and strength. Because freezing is intentionally imposed and boundary conditions are often better controlled than in natural permafrost systems, AGF provides a valuable environment for testing THM models.

Several recent studies illustrate the role of AGF in both application and validation settings. Zhelnin et al. (2022) developed a coupled THM model to simulate frost heave and water migration during artificial freezing for mineshaft construction. Sweidan et al. (2022) combined experiments and numerical modeling to examine THM processes under different frost-penetration directions. Joudieh et al. (2024, 2025) provided experimental evidence on soil deformation during freeze–thaw cycles and on the role of overburden pressure in AGF conditions. Saberi and Meschke (2024) investigated freezing–thawing processes in tunnel construction, while Hong et al. (2025) analyzed the influence of horizontal freezing on existing

https://doi.org/10.5194/egusphere-2026-4674
Preprint. Discussion started: 7 August 2026

underground structures. These studies provide useful datasets and test cases because thermal boundaries, overburden, and deformation can often be measured more directly than in field permafrost systems.

However, AGF results should be transferred cautiously to natural seasonal or permafrost soils. AGF commonly involves engineered cooling, relatively strong thermal gradients, and saturated or near-saturated conditions. Natural soils may be more heterogeneous, partially saturated, affected by snow and vegetation, and subject to long-term climate variability. Therefore, AGF is most useful as a controlled validation environment for specific THM processes, such as freezing-front advance, water migration, heave, and thaw settlement, rather than as a complete analog for all cold-region soil systems.

6.4 Salinity, solutes, remediation, and THMC extensions

Solutes alter freezing soils through several coupled mechanisms. Dissolved salts depress the freezing point, increase unfrozen water content at a given sub-temperature, concentrate in residual liquid as ice forms, generate osmotic gradients, and may alter soil structure and permeability. These processes are important for saline soils, road-salt-affected transportation corridors, and cold-region contaminant remediation. In such settings, THMC modeling may be required because purely TH or THM models cannot represent concentration-dependent phase change or solute exclusion from ice.

THMC models extend THM formulations by coupling heat transfer, water and vapor flow, deformation, solute advection–dispersion, phase partitioning, and freezing-point depression. Huang and Rudolph (2023) simulated the coupled water and vapor flow, heat transfer, and solute transport in variably saturated deformable soils during freeze–thaw cycles. Cui et al. (2024) developed an approach to calculate the SFCC of saline soils, highlighting how solute concentration affects freezing behavior. Mo et al. (2025) further advanced THMC modeling of solidification and solute separation in saturated freezing soils. These studies show that chemical effects can materially alter freezing dynamics and should not be treated as a minor correction when salinity is high or when solute redistribution is the target variable.

The main limitation of THMC modeling is validation. Concentration, temperature, water content, ice content, suction, and deformation are rarely measured together during freezing and thawing. Solute concentrations may vary sharply over small spatial scales due to exclusion from ice and concentration in unfrozen films or pore water. Sampling can disturb the phase distribution, and non-destructive measurements of both ice and solute are difficult. Boundary conditions are also challenging because salt input, groundwater chemistry, evaporation, and thaw drainage may vary through time. As a result, THMC models can easily become underdetermined if concentration data and phase-partitioning assumptions are weakly constrained. A practical recommendation is to use THMC only when salinity, contaminants, or osmotic effects materially affect the decision question and when concentration data or well-defined chemical boundary conditions are available.

6.5 Ground-source energy systems

Ground-source energy systems in cold regions provide another application in which freezing-soil models connect soil physics to practical decision-making. Ground-source heat pump systems may cool the surrounding soil during operation. If

https://doi.org/10.5194/egusphere-2026-4674
Preprint. Discussion started: 7 August 2026

heat extraction exceeds natural thermal recharge, progressive freezing can occur around heat exchangers, altering thermal and hydraulic conductivities, ground deformation potential, and system efficiency. In permafrost regions, a warming climate can also thaw the ground around infrastructure designed under colder historical conditions, creating interacting thermal and mechanical risks.

Norouzi et al. (2024) numerically evaluated ground-source heat pump performance in a thawing permafrost region, underscoring the need to account for coupled thermal, hydraulic, and mechanical effects for long-term system assessment. For many energy-system questions, a thermal model may be sufficient to estimate heat-extraction performance, but TH or THM coupling becomes important when freezing changes hydraulic conditions, induces settlement, or affects the stability of foundations and borehole infrastructure. This application area is more specialized than permafrost hydrology or infrastructure, but it is useful because it shows how freezing-soil models can support sustainable energy-system design while accounting for soil thermal memory and climate change.

6.6 Cross-application guidance for model selection and reporting

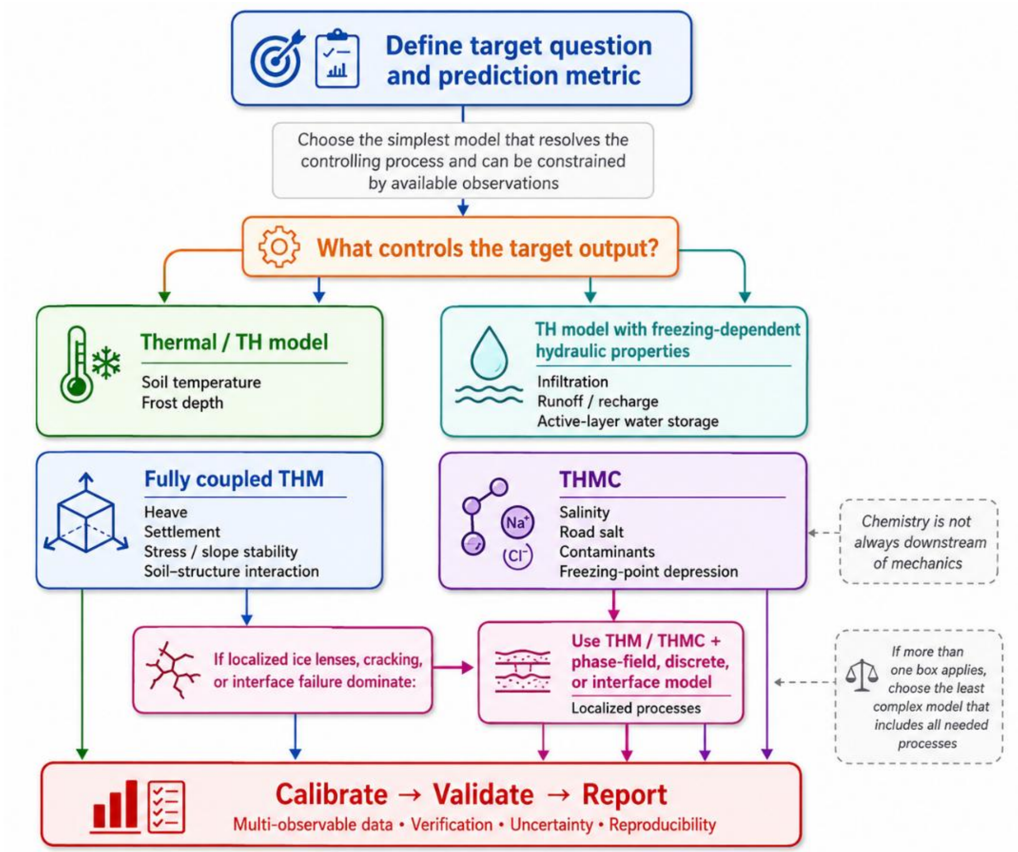

Figure 6. Model-selection framework for freezing-soil problems. Model complexity should align with the target decision variable and the available observations, rather than the desire to include every possible process.

https://doi.org/10.5194/egusphere-2026-4674
Preprint. Discussion started: 7 August 2026

This guidance also applies to validation. A temperature-calibrated model should not be used to make strong claims about heave, stress, water redistribution, or solute transport unless those variables are independently validated or their uncertainty is explicitly propagated. Similarly, a THMC model is not automatically superior to a THM model if solute data are unavailable. For many practical problems, the most defensible approach is to begin with a simpler model, identify which processes control the target output through sensitivity analysis, and add complexity only when the added process can be constrained by observations.

For reproducible reporting, freezing-soil model studies should provide enough information for readers to trace predictions back to governing equations, closures, parameters, boundary conditions, numerical choices, and calibration data. Table 6 summarizes a minimum reporting checklist. The checklist is intentionally practical: it helps distinguish whether differences among studies arise from physical assumptions, parameter choices, boundary forcing, numerical implementation, or validation data. Wider adoption of such reporting standards would improve comparability across TH, THM, and THMC studies and support future benchmark development.

Table 6. Minimum reporting checklist for freezing-soil THM/THMC studies.

Reporting item	Minimum information to provide
Model purpose	Target decision variable and reason for choosing thermal, TH, THM, or THMC complexity
Primary variables	Temperature, pressure/capillary pressure/chemical potential, water content, displacement, concentration
Phase treatment	Instantaneous or kinetic phase equilibrium; SFCC form; freezing/thawing hysteresis
Hydraulic closures	SWRC, saturated conductivity, relative permeability, ice-reduction function, vapor model
Thermal closures	Thermal conductivity and heat capacity models; apparent heat-capacity interval or phase-change source term
Mechanical closures	Effective stress definition, constitutive law, strain assumption, damage or creep treatment
Boundary and initial conditions	Surface temperature/energy balance, snow, water table, fluxes, loads, salinity, initial temperature and water content
Numerics	Mesh, time step, nonlinear solver, coupling scheme, preconditioner, tolerances, convergence failures
Verification	Mass and energy conservation, grid/time-step convergence, analytical or benchmark comparisons
Calibration and validation	Data sets, objective functions, calibrated versus assigned parameters, out-of-sample tests
Uncertainty	Sensitivity analysis and uncertainty propagation to decision-relevant outputs
Reproducibility	Code or software version, input files, parameter tables, figure data, and repository links where possible

Taken together, the application domains reviewed here show that freezing and thawing should be modeled as coupled soil-system processes. The same underlying physics, including phase change, cryosuction, permeability reduction, water redistribution, deformation, and solute concentration, can produce different outcomes depending on whether the problem concerns permafrost hydrology, infrastructure performance, artificial ground freezing, salinity, remediation, or energy systems. A robust modeling workflow, therefore, requires matching the model hierarchy to the target outcome, validating against relevant observables, and reporting uncertainty in a way that supports comparison and reuse.

7 Research priorities

The preceding sections show that freezing and thawing of soils are now represented by increasingly sophisticated TH, THM, and THMC models. However, progress in model formulation has outpaced progress in transferable parameterization, multi-observable validation, uncertainty reporting, and scale integration. Future advances should therefore focus not only on adding more physical processes, but also on making coupled freeze–thaw models more measurable, transferable, reproducible, and useful across scales. Six research priorities are especially important.

7.1 Transferable closures for unfrozen water, permeability, and effective stress

The first priority is to develop closures that are transferable across soil types, saturation states, thermal histories, and spatial scales. The SFCC, SWRC, permeability-reduction function, vapor-transport formulation, thermal-property model, and effective-stress relation largely determine model behavior. Among these, the SFCC and permeability-reduction function are especially influential because they control latent heat release, liquid availability, cryosuction, hydraulic connectivity, water supply to ice lenses, and infiltration recovery after thaw (Kurylyk and Watanabe, 2013; Devoie et al., 2022; Wang et al., 2025). Effective stress is similarly critical when deformation, heave, settlement, or slope stability is the target, but its formulation remains uncertain in partially saturated frozen soils (Coussy, 2005; Yin et al., 2023; Li et al., 2024a; Norouzi and Li, 2024).

Current parameterizations are often soil-specific and weakly constrained. SFCCs measured in the laboratory may not represent field soils with aggregation, organic matter, roots, cracks, salinity, or freeze–thaw history. Permeability reduction by ice is even harder to transfer because it depends on pore blockage, ice morphology, pore-size distribution, and flow-path connectivity, and is rarely measured directly (O'Neill and Miller, 1985; Rempel, 2010; Kjelstrup et al., 2021). Effective stress in partially saturated frozen soils remains uncertain because liquid water, ice, gas, and the soil skeleton share stress in ways that are difficult to observe directly (Coussy, 2005; Gawin et al., 2020; Yin et al., 2023).

A productive path forward is to connect pore-scale observations with continuum closures. Micro-computed tomography, nuclear magnetic resonance, calorimetry, neutron imaging, pore-network modeling, and phase-field simulations can help reveal how pore geometry and ice morphology control unfrozen water, permeability, and lens initiation. Phase-field and micro-poromechanical models have already shown promise for resolving ice-lens growth and interface evolution at scales not captured by standard continuum formulations (Sweidan et al., 2020; Suh and Sun, 2022; Gao et al., 2023). These insights should then be distilled into reduced closure forms that can be calibrated with realistic field or laboratory data. For closure

https://doi.org/10.5194/egusphere-2026-4674
Preprint. Discussion started: 7 August 2026

development, a useful near-term outcome would be an open, soil-type-indexed library of SFCC, permeability-reduction, vapor-transport, thermal, and mechanical parameterizations, with uncertainty ranges and metadata describing measurement conditions.

7.2 Shared benchmark datasets for multi-observable validation

The second priority is to build shared benchmark datasets for model validation. Many freezing-soil models are tested primarily against temperature profiles. This is insufficient for evaluating hydrologic, mechanical, or chemical predictions. A model calibrated only to temperature can reproduce frost depth while producing incorrect water redistribution, heave, stress, or solute concentration. Multi-observable validation should therefore become the standard for THM and THMC studies (Huang and Rudolph, 2021; Fu et al., 2024; Wu et al., 2025).

Useful benchmarks should include controlled laboratory column tests, artificial ground-freezing experiments, and well-instrumented field sites. Laboratory datasets should report temperature, water content, suction or pore pressure, displacement, ice content, and boundary fluxes. Directional-freezing and freeze–thaw experiments provide particularly valuable constraints because they can isolate water migration, frost heave, thaw settlement, and hysteresis under controlled conditions (Sweidan et al., 2022; Zhang et al., 2024a; Joudieh et al., 2024, 2025; Zhang et al., 2025). THMC benchmarks should also include solute concentration and phase-partitioning information, because solute exclusion and freezing-point depression can otherwise remain unconstrained (Cui et al., 2024; Mo et al., 2025).

Field benchmarks should include borehole temperature, soil moisture, water table or hydraulic gradients, snow and surface forcing, deformation, geophysical observations, and possible remote-sensing products, such as InSAR-derived settlement. Permafrost and cold-region hydrology studies have shown that field-scale predictions are strongly affected by boundary forcing, heterogeneity, groundwater exchange, and ground-ice distribution (Walvoord and Kurylyk, 2016; Sun et al., 2022; Xavier et al., 2024; Streletskiy et al., 2025; Lemieux et al., 2025). These data should be accompanied by complete soil characterization, initial and boundary conditions, metadata, and uncertainty estimates.

Benchmark design should deliberately test model falsifiability. Open-system freezing tests constrain water supply and ice segregation; closed-system tests isolate volumetric freezing and permeability reduction; cyclic tests evaluate hysteresis and damage; saline tests evaluate freezing-point depression and solute exclusion; layered or heterogeneous tests evaluate scale transfer and preferential flow. Verification benchmarks are also needed to ensure mass and energy conservation, grid convergence, and consistency across codes, building on existing intercomparison efforts for heat and water transport with freezing and thawing (Grenier et al., 2018). For benchmarking, the community would benefit from curated datasets that combine standardized input files, reference simulations, descriptions of uncertainty, and evaluation metrics for TH, THM, and THMC models.

https://doi.org/10.5194/egusphere-2026-4674
Preprint. Discussion started: 7 August 2026

7.3 Upscaling multiphysics freeze–thaw processes to land-surface and Earth-system models

The third priority is the upscaling of multiphysics freeze–thaw processes to land-surface and Earth-system models. This is a key research frontier because many large-scale models still represent freezing and thawing primarily through simplified parameterizations of soil temperature, ice content, or hydraulic impedance. Such simplifications are computationally necessary, but they may miss important feedbacks among cryosuction, permeability collapse, water redistribution, active-layer hydrology, thaw settlement, solute mobilization, and surface–subsurface connectivity (Zhang et al., 2007; Walvoord and Kurylyk, 2016; Stuurop et al., 2021; Lemieux et al., 2025).

The challenge is not to embed full THM or THMC solvers directly into global models. That would usually be computationally impractical and difficult to parameterize. Instead, the goal should be to extract reduced-order closures from detailed THM/THMC simulations and observations. These closures should represent the dominant effects of freezing on infiltration, runoff generation, groundwater recharge, active-layer water storage, thermal conductivity, porosity change, and surface deformation. Detailed THM models can be used to derive effective freezing-dependent hydraulic conductivity, thaw-settlement functions, ice-rich-layer collapse rules, or subgrid parameterizations for soil-water redistribution during freeze–thaw transitions (Sun et al., 2022; Li et al., 2024b; Huang et al., 2025; Norouzi and Li, 2024; Qiu et al., 2026).

Upscaling must also address landscape heterogeneity. Permafrost landscapes contain organic horizons, mineral soils, ice-rich layers, taliks, patterned ground, slopes, wetlands, lakes, and drainage networks. A single-column model cannot explicitly represent all of these features. Land-surface and Earth-system models therefore need subgrid schemes that account for soil texture, organic matter, ground ice, topography, snow redistribution, vegetation effects, and lateral water movement (Jan et al., 2020). Mechanistic studies of permafrost degradation, thaw settlement, and future climate impacts show that soil-property uncertainty and boundary-condition uncertainty can strongly shape projected outcomes (Sun et al., 2022; Xavier et al., 2024; Streletskiy et al., 2025; Zhou et al., 2025). Detailed THM models can support this effort by identifying which small-scale processes control large-scale fluxes and which can be safely simplified.

The concrete research product should be a set of reduced-order THM closures and benchmarking protocols for land-surface and Earth-system models. These products should include parameterizations for freeze–thaw effects on hydraulic conductivity, infiltration partitioning, runoff generation, groundwater recharge, thaw settlement, and soil thermal properties, together with guidance on when mechanical or chemical effects must be included. Such upscaling would help connect detailed freezing-soil physics to regional and global predictions of permafrost hydrology, water resources, infrastructure risk, and climate feedbacks.

7.4 Uncertainty-aware inference and reporting protocols

The fourth priority is to make an uncertainty-aware inference routine. Freezing-soil models contain uncertainty from soil parameters, constitutive closures, initial conditions, boundary forcing, numerical settings, and model structure. In permafrost

https://doi.org/10.5194/egusphere-2026-4674
Preprint. Discussion started: 7 August 2026

and seasonal freezing applications, boundary uncertainty from snow, vegetation, rainfall timing, groundwater, surface energy balance, and future climate scenarios can be as important as uncertainty in internal soil parameters (Walvoord and Kurylyk, 2016; Xavier et al., 2024; Zhou et al., 2025). Yet many studies still report a single deterministic simulation without showing whether the target prediction is robust.

Uncertainty should be propagated to decision-relevant outputs rather than only to internal parameters. Depending on the application, these outputs may include frost depth, thaw depth, active-layer water storage, runoff ratio, infiltration capacity, groundwater recharge, solute concentration, frost-heave magnitude, thaw-settlement probability, pipe strain, slope stability, or probability of exceeding a deformation threshold. Sensitivity analysis should identify whether uncertainty is dominated by the SFCC, permeability reduction, mechanical parameters, boundary forcing, or numerical assumptions. Bayesian calibration, ensemble simulation, surrogate modeling, and data assimilation can support this process, but they should be used only when the available observations can constrain the uncertain parameters (Roghangar and Hayley, 2025; Zhou et al., 2025).

For uncertainty analysis, a shared reporting protocol should distinguish measured, assigned, and calibrated parameters; document priors and parameter ranges; report conservation and convergence checks; and propagate uncertainty to target outputs rather than only to intermediate state variables. At minimum, this protocol should require a clear distinction between measured, assigned, and calibrated parameters; reporting of parameter ranges and priors; conservation and convergence checks; sensitivity analysis; uncertainty propagation to target outputs; and transparent discussion of model structural uncertainty. Such a protocol would improve comparability across studies and reduce overconfidence in models calibrated to a single observable.

7.5 Interfaces, ice lenses, cracking, and freeze–thaw damage

The fifth priority is to represent localization, interfaces, and damage better. Many important freeze–thaw impacts occur at discontinuities: soil-layer boundaries, organic–mineral interfaces, frost-susceptible lenses, ice-rich layers, trench backfill contacts, pavement layers, pile–soil interfaces and contacts, cracks, and preferential flow paths. Standard continuum THM models often smear these localized processes over grid cells or elements, which may be acceptable for frost-depth prediction but insufficient for ice-lens formation, cracking, differential settlement, or infrastructure damage (O'Neill and Miller, 1985; Rempel, 2010; Huang et al., 2022; Gao et al., 2023).

Phase-field, cohesive-zone, peridynamic, finite-discrete element, and hybrid continuum–discrete methods offer promising approaches for modeling ice-lens initiation, interface migration, fracture, and progressive damage. Phase-field approaches have been used to describe frost action and ice-lens growth in porous media (Sweidan et al., 2020; Suh and Sun, 2022; Gao et al., 2023), while finite-discrete element and peridynamic methods offer ways to represent fracture or discontinuous deformation in frozen media and freeze–thaw damage (Sun et al., 2024; Zhang et al., 2024b). However, these methods are computationally expensive, parameter-intensive, and difficult to validate at the field scale. Their most useful near-term role

https://doi.org/10.5194/egusphere-2026-4674
Preprint. Discussion started: 7 August 2026

may be to provide process understanding and reduced interface laws that can be incorporated into larger-scale continuum models.

For interface and damage modeling, benchmark cases should be designed around ice-lens initiation, layered-soil freezing, crack formation, thaw settlement, and soil–structure contact, with measurements of temperature, displacement, moisture redistribution, suction, ice distribution, stress, and interface evolution. This suite should include laboratory and numerical test cases for ice-lens initiation, layered-soil freezing, crack formation, thaw settlement, and soil–structure contact. It should report not only temperature and displacement but also moisture redistribution, suction, ice distribution, stress, and fracture or interface evolution. Such benchmarks would help determine when continuum THM is sufficient and when hybrid or discrete approaches are required.

7.6 Data-driven acceleration without losing physical constraints

Machine learning and data-driven methods can support the preceding priorities, but they should complement rather than replace process-based modeling. Physics-informed neural networks, emulators, Gaussian-process surrogates, and reduced-order models can accelerate calibration, sensitivity analysis, and uncertainty propagation. They can also help identify parameter patterns across large datasets or infer missing variables from multi-sensor observations. Recent applications of physics-informed deep learning to permafrost prediction show the potential of such methods for rapid multi-site prediction and uncertainty exploration (Liu et al., 2023). However, data-driven models must preserve mass balance, energy conservation, thermodynamic consistency, and physically meaningful phase partitioning if they are to be trusted beyond the calibration domain.

Machine learning might be the most useful here as a hybrid tool: it can emulate detailed THM/THMC simulations, infer closure parameters, identify structural model errors, and support upscaling when constrained by conservation laws and multi-observable data. For land-surface and Earth-system modeling, data-driven tools could help translate detailed column-scale simulations into computationally efficient subgrid parameterizations (Deck et al., 2026; Tian et al., 2026). The concrete research product should be physically constrained surrogate models that reproduce key THM/THMC outputs while maintaining conservation laws and uncertainty estimates.

Together, these priorities define a path from sophisticated local-scale models toward transferable, validated, and scalable soil-system prediction. Progress will depend less on adding complexity for its own sake than on building reusable closure libraries, benchmark datasets, reduced-order upscaling schemes, uncertainty-reporting protocols, interface and damage benchmarks, and physically constrained emulators. It needs closure libraries, benchmark datasets, reduced-order upscaling schemes, uncertainty-reporting protocols, interface and damage benchmarks, and physically constrained emulators. These products would allow freezing-soil models to support not only site-scale engineering analysis but also broader questions about permafrost hydrology, climate feedbacks, soil-water storage, salinity, environmental transport, and Earth-system change.

https://doi.org/10.5194/egusphere-2026-4674
Preprint. Discussion started: 7 August 2026

8 Conclusions

Freezing and thawing are coupled soil-system processes that regulate water storage, heat transfer, phase change, suction, hydraulic conductivity, vapor movement, solute redistribution, deformation, and damage. THM and THMC models provide powerful frameworks for representing these interactions, but their reliability depends on transferable closures, multi-observable validation, numerical robustness, and transparent uncertainty reporting.

The central challenge is not to maximize process complexity, but to select a model structure that is defensible for the intended prediction. Thermal models may be adequate for frost depth and soil-temperature prediction; THM coupling is needed when deformation, stress, settlement, slope stability, or soil–structure interaction is central; and THMC coupling is warranted when salinity, contaminants, osmotic effects, or freezing-point depression materially alter phase change and flow. Without independent validation, added physics can increase equifinality and overconfidence rather than predictive skill.

Temperature agreement alone is not enough to support claims about water redistribution, infiltration, runoff, recharge, heave, stress, settlement, or solute transport. Models should be tested against observables relevant to the intended prediction and supported by conservation checks, convergence analysis, parameter provenance, sensitivity analysis, and uncertainty propagation.

Future progress requires community-level products: transferable closure libraries, shared multi-observable benchmarks, uncertainty-reporting protocols, hybrid interface and damage benchmarks, and reduced-order THM closures for land-surface and Earth-system models. These advances would move freezing-soil modeling from site-specific simulation toward scalable prediction of permafrost hydrology, cold-region soil function, environmental transport, infrastructure risk, and climate feedbacks.

Code and data availability

No new code was developed for this review. Code sharing is not applicable.

Author contributions

LS conceptualized the review, organized the literature, prepared the first draft, and revised the manuscript. DN contributed to literature organization, figure preparation, and manuscript revision. Both authors reviewed and approved the submitted version.

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Preprint. Discussion started: 7 August 2026

Competing interests

The authors declare that there are no competing interests.

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